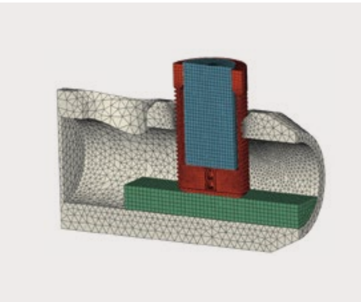
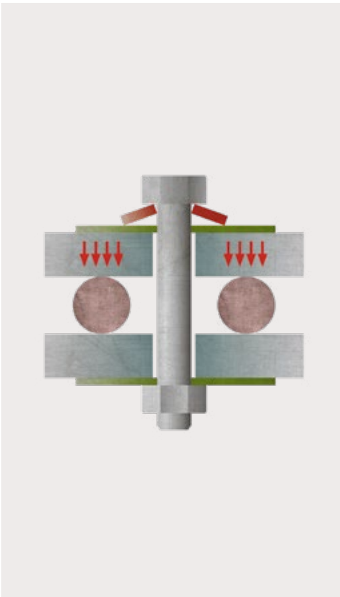
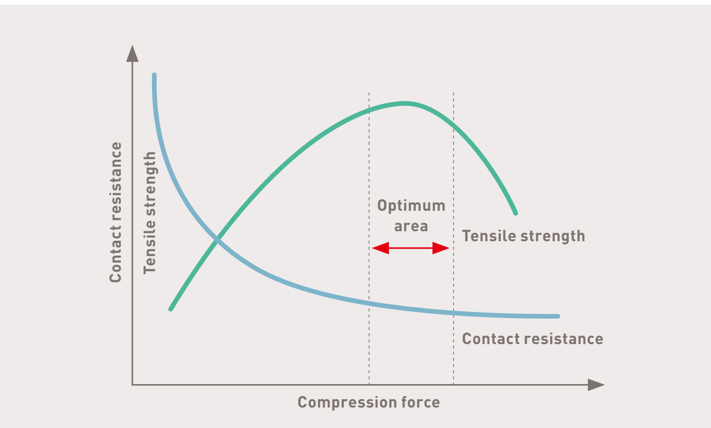
PFISTERER

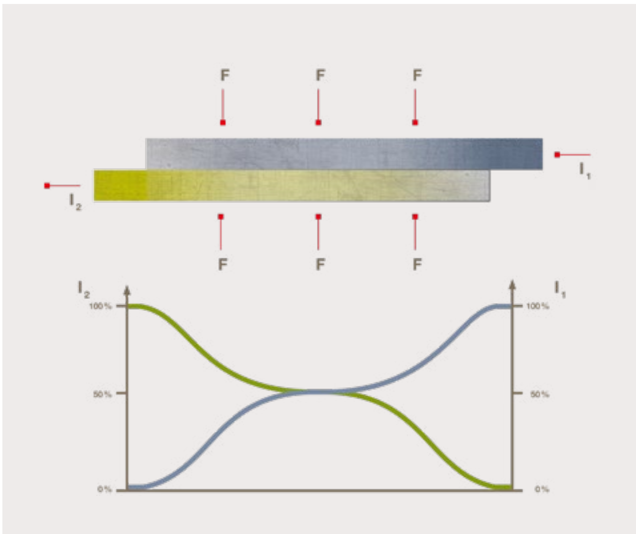
Focus on Contact

Principles of Contact Technology









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Focus on Contact
Principles of Contact Technology

Contacts are often wrongfully perceived as the weak points in electric transmission and distribution networks. The majority of all failures can be attributed to either faulty installation or to the use of connectors of lesser quality. Both can be prevented – with knowledge of the basic principles of contact technology. This series presents a practice-oriented view into the inner workings, carriage return and design criteria of contacts, various mechanical connector technologies, the mechanisms of contact aging and failure as well as options for contact quality testing. This is valuable information for anyone dealing with contacts and for those who strive to contribute to greater security of supply. This includes network planners, system managers, maintenance staff, installers and purchasers.

Quality to counter power failures

Figures prove that high-quality contacts ensure security of supply, while poor workmanship in this area causes the majority of dropouts in power grids. This first section will focus on experience with contacts of varying quality from energy markets around the world.

A Canadian energy supplier aimed to find out what exactly the typical causes for power failures were. The results of this survey from 2009: Almost 40 % of all supply disruptions can be directly attributed to faulty contacts, with an additional 9.7 % being indirectly related to contact design. No wonder: Contacts have been around since households and businesses were first connected to power grids. They have been doing their job for decades. However, knowledge about the underlying technical principles and their importance has been shrinking for years as well. There are several reasons for this phenomenon: In the past, standardized cables dominated the networks and there were connection specialists for each cable type. In recent years, however, the energy markets have been changing rapidly and energy supply companies evolved along with them. Supply areas were merged, new cable materials caught on, and the increasing energy demand was met by ever larger cable cross-sections. It is not unusual to find up to seven different cable types in a single distribution network. At the same time, installers today also act as all-round talents for the basic supply areas of energy, water and gas. What is needed now are reliable contacts that can be flexibly used in a variety of applications while being easy and safe to install.

Small cause, big damage: Improper contacts disable expensive operating equipment.

Changes in technology

For many contact manufacturers, changes in technology are nothing new. When aluminum cables largely replaced copper cables in the 1950s through the 70s, manufacturers forged new paths in contact technology. The patented SICON bolted connector by PFISTERER is a result of this shift. It presents a convincing alternative for all applications that allow for a switch from crimp connections to bolted connections. The crimping technique is very effective but it does have a history of causing power failures. The cause: The principle of crimping is based on fixed sizes. Each conductor cross-section is associated with specific sleeve cross-sections and tools. These predefined frames surpassed what market and cable technology were able to provide. Since cable costs increase with each kilometer in length, they are produced more and more efficiently. The individual wires are pressed together more tightly, thus making the cable more compact so that it requires less insulating material. Result: Something described as a 95 mm² copper cable can come in a variety of forms in practice. In addition to the various cable designs, there were now new cable cross-sections. Sleeves and tools, however, remained the same. Thus, since work in power grids is always an urgent matter, technicians tend to use the next best thing when the perfect part is not available.

Causes of power failures

A Canadian energy supplier researched the causes of power grid failures. These are the results of this 2009 survey:

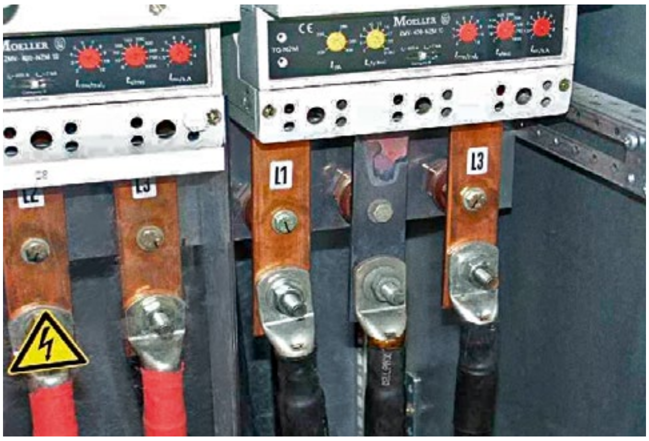
▪ Loose contacts or contact components	38,3 %
▪ Moisture	17,4 %
▪ Line disruptions (any except lightning)	10,4 %
▪ Defective or insufficient insulation	9,9 %
▪ Foreign objects / short circuits events	7,3 %
▪ Overloading / insufficient capacity	2,4 %
▪ Dust, sand and oil deposits	2,2 %
▪ All other causes	12,0 %

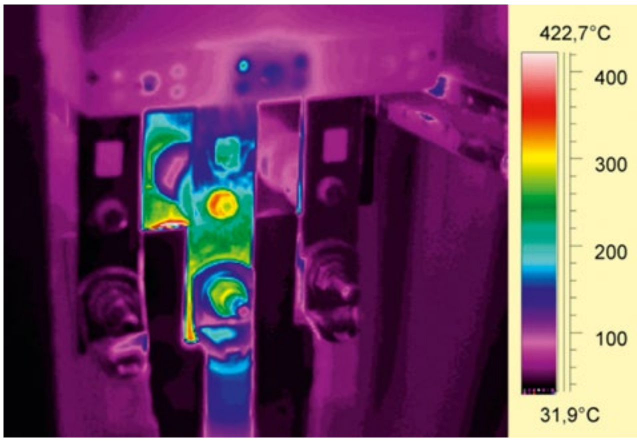
No network without contact

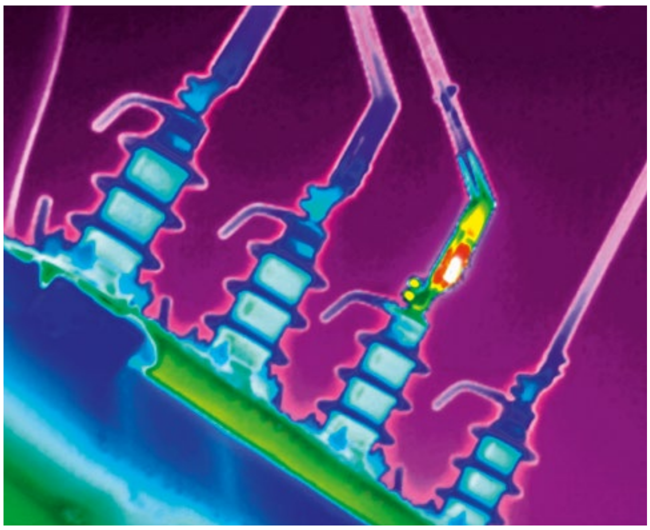
Energy demand is as high as never before. In fact, it is still on the rise. Thirty to forty year-old networks are utilized to full capacity today. This takes us to the point of the matter: the importance of contact technology for supply security. Just like communities rely on social contacts, the functioning of power grids largely depends on the effectiveness of its electrotechnical contacts. Despite high network loads, the power failure rates recorded worldwide show that requirements for contact quality still vary greatly from one country to the next. In Germany, electricity stops flowing for seven minutes per year and end user. In the US, outages amount to a total of nine hours. In Thailand, this number is 14 hours. In Bangkok alone, there were approximately 1500 MV joint failures in one year. In July 2012, Indian power grids collapsed on two consecutive days due to overloading. According to press reports, this left between 600 and 700 million people without power. Even if one could consider such enormous failures to be exceptions to the rule, high-quality contacts do pay off, even in the medium term, as the European association of cable accessory manufacturers showed using the "Total Cost of Ownership" method.

Cheap or worth the money?

When determining the "total cost throughout the entire service life", the product price is only one item. In addition to that, one needs to consider installation, maintenance and logistics as well as costs incurred by failures and compensation. A € 50 product, which may initially appear cost-effective, with a failure rate of 1 % and an installation time of one hour achieves € 115,000.00 in annual costs. A € 70 product in a higher quality design with a failure rate of 0.5 % and an installation time of one hour only costs € 97,000.00 now. The most cost-effective solution is the € 90 product with a failure rate of 0.5 % and an assembly time of half an hour: € 85,000.00 This is not exactly a negligible sum considering that operating equipment worth several millions sometimes depend on € 10 contacts. There is a reason energy supply companies and industrial groups focus more on quality again when selecting contact technologies, with criteria including material, connection technology, and contact design.







Thermal images reveal what the human eye is unable to see:
Faulty connections as a cause for significant increases in contact resistance (Source: www.ITK-Messtechnik.de)

Focus on Contact – Section 2

Force vs. Resistance. Apparent and defined contact

Section 2 shows how contacts can be used to achieve the best possible flow of current: The interdependency of contact force and transfer resistance, the step from apparent contact surfaces to defined contact points.

The joints between two metallic busbars are an important key to understanding contact technology. In order for the current to flow from one busbar to the other, their ends are overlapped. At first sight, this is an ideal contact point: two flat surfaces placed flush on top of one another, so that electricity can flow across the entire overlapping area. A look under the microscope, however, shows how deceiving this can be.

It reveals a jagged silhouette with peaks and valleys. These irregularities in the material surfaces, called roughness in surface physics, have an effect on contacts: Contact surfaces that seemingly cover 100%, as numerous measurements indicate, effectively shrink to very few metallic and therefore electrical contact points, which only make up approximately five per cent of the entire overlapping surface.

Overcoming the resistance. With force.
Just like water forces its way through a river bed blocked by debris, electricity must find a path through these tight passages. The consequence: extremely high contact resistances, which could – in the worst case – lead to melting at some points, thus damaging the contact points. In order to lower the resistances, force is exerted onto the contact point by crimping or bolting. This drives the peaks of the material surfaces into one another, extensively flattens distortions, thus creating the galvanic contact that is so important. The following applies in this case:

The more force is exerted, the more the contact resistance is lowered – though only until a typical saturation value is achieved.

Even with a further increase in force, the resistance then remains constant beyond that point. At the same time, the contact resistance does not immediately increase again once the force effect has stopped after the contact is created. Only when the contact force falls below a specific limit value – below 10 N/mm² for aluminum – contact resistance increases again.

This results in a phenomenon called contact hysteresis in technical jargon: It takes more force to make contact than to maintain it.

The right proportions. Free flow of current.

On the one hand, this knowledge results in the need for the contact force to achieve this saturation value when contact is made. On the other hand, even minimal changes in force, for example due to flow processes in the conductor material, contact resistance is increased exponentially during operation. In practice, typical causes include the following: Unsuitable sleeves or tools are used for crimping. If boltes in bolted connections are not greased, the applied torque is not sufficiently converted into the required clamping force. If the torque wrench is not properly set, the resulting torque is too low.

In additions, there are requirements for the design of contact terminals. If a contact is created with maximum-efficiency contact force, the terminal design must ensure that a minimum contact force of approx. 20% of the initial force is maintained over a period of three to four decades. It is inherent in the nature of contacts that the contact force drops over time due to various physical influences.

This reduction in contact force, also called contact aging, must be compensated by integrating elasticity in the connection. This can be achieved either through the design of the terminal or by means of additional spring washers.

Point displaces area

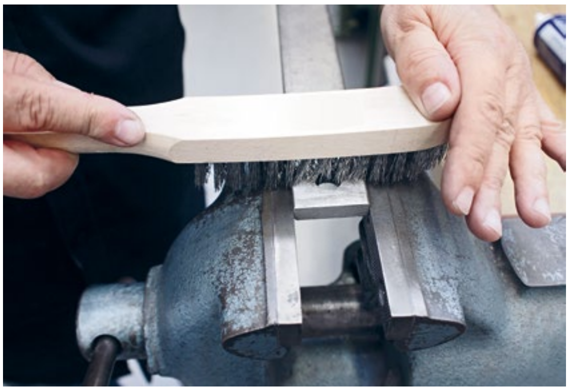
When following the path from apparent contact area to the metallic and therefore conductive contact, one can find further obstacles blocking the flow of current: If aluminum is used as a conductor material, it only leaves a fraction of the mechanical contact area that is actually conductive. The reason for this is that upon contact with atmospheric oxygen, a reaction takes place on the aluminum, which adds a non-conductive oxide layer. Since the beginning of the 1960s, when the widespread use of aluminum as conductor material became commonplace, failures happened more and more frequently. They were caused not only by contacts disintegrating due to intense flow and settling processes and lack of elasticity, but also because of the oxide layer on the aluminum. Suitable terminals for aluminum were not yet available at that time.

Today, self-passivation is common for the cost-effective, lightweight and thus popular material with corresponding contact terminal designs: Where the aluminum conductors must be contacted, the oxide layers are broken. The teeth of some tapping terminals, for example, not just break through the insulation but also through the conductor surface. In progressive bolted connectors, it is broken by blades integrated in the terminal body. Both of these products are an example for a rather new paradigm shift in contact technology: away from large apparent contact surfaces towards predefined contact points or lines.

Practical tip: Tightening bolts only calms your conscience.

Some errors persist. Such as the widespread assumption that the tightening of bolts promotes the longevity of contacts. Terminals with shear bolts prove otherwise: They are designed to eliminate the perceived need for tightening, and are used more and more frequently. This practical tip shows what matters most when installing a bolted connector to ensure reliable functioning throughout its entire life cycle.

1. In addition to choosing the proper terminal and suitable material for the conductor, the cleanliness of the contact area is crucial. This is best cleaned with a wire brush.



2. To protect the surface from re-oxidizing, it is treated with a contact protection paste – particularly with easily oxidized aluminum connectors. For a permanently reliable contact, the bolt also has to be clean.

3. It is also greased so that the applied torque results in the optimal contact force. Since this important step is often overlooked, some manufacturers supply the bolts already greased or with a special coating that provides the necessary lubrication in place of the grease.

Lastly, when tightening the bolts, the specified torque must be applied – this can be found in the installation manual or printed on the terminale.

Focus on Contact – Section 3

Why contacts age. And why they last for decades anyway.

Contacts age. However, they are designed to transmit power reliably for decades, across the innumerable interfaces within the energy network. The third section shows how these requirements match up with the facts, with a focus on the aging mechanisms at play in contacts as well as effective remedies to combat them.

The initial resistance marks the beginning of aging in every contact. The higher this initial resistance is at the time a mechanical contact is manufactured, the shorter the life of the connection. Because electrical resistance grows with an increasing thermal load. Since almost all of the physical and chemical properties of materials are temperature dependent, at least to some degree, heat promotes aging in most materials.

The effect of the initial resistance was examined as long ago as 1958 by J.A. Greenwood and J.B.P. Williamson in their paper on temperature-dependent conductors, ("Electrical Conduction in Solids. II. Theory of Temperature-Dependent Conductors", Royal Society Publishing): Where the initial resistance is 10 micro-ohms (μΩ), a mechanical connection can have a service life of up to a century, whilst at 100 μΩ it will be a maximum of fifty years.

One connection – two materials.

It doesn't take much to massively increase the initial resistance: For example, when a contact is operating in a tight cable trench, soil or other particles can contaminate the contact, or crimped contacts can suffer from the wrong combination of sleeve material and conductor material. In addition to impeccably clean and professional operations, knowledge of the different conductor and connector materials is imperative. This is another important aspect with consequences that go beyond merely limiting the initial resistance.

The main materials used in the power supply industry are still copper and aluminum, although the recent rises in the price of copper together with the trend towards larger cable cross-sections are fueling the use of cheaper and lighter aluminum. So across the world, different conductor and connector materials are making contact with one another, for example, when a copper wire network is extended using aluminum conductors. This presents a challenge to the manufacturers of contacts, to produce a component which can be used with copper and aluminum conductors alike.

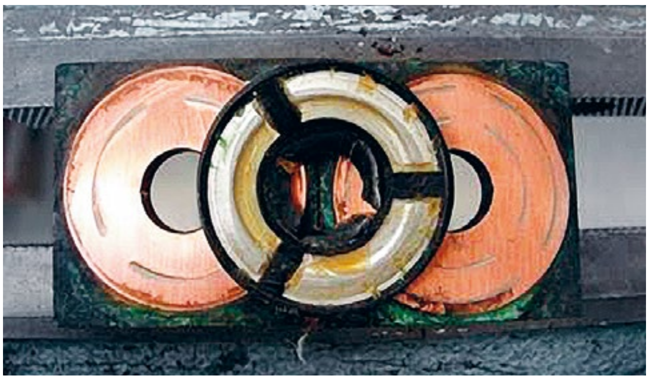


Figure 1: Al Elast contact disks for defined contact areas

The pitfalls of thermals

The following classic installation error demonstrates how two materials thermally react in different ways: If an aluminum conductor is crimped into a copper sleeve, the premature failure of the contact is inevitable, even if the sleeve size is properly selected. Once electricity passes through the connection, it heats up and the aluminum conductor expands more than the copper sleeve can yield. As the electrical load increases, the mechanical stress between the conductor and the sleeve continues to rise, until it exceeds the yield strength of the aluminum – the conductor over-expands and no longer returns to its original shape upon cooling.

After several heating and cooling cycles, the unwanted result is achieved – the minimum contact force is no longer reached and the electrical contact is degraded until there is total failure. The only remedy with crimping technology is the right combination of sleeve and conductor material, as shown in Table 1. When terminals are in use, the different thermal expansion coefficients of copper and aluminum play a role as well. Often aluminum cables are connected to copper terminals. When heated, the conductor expands and returns to its original size on cooling. This process – called thermal breathing – can be equated with micro-movements by the conductor. The resulting aluminum abrasion debris oxidizes immediately and forms a non-conductive coating at the contact points, causing premature contact failure.

Intelligent terminal designs, such as Durelast terminals with U-bolts prevent this movement by way of a sufficiently high contact force on the conductor, a technical trick also utilized in railway engineering: As a result of heating, rails expand in a longitudinal direction. The resulting forces are directed into the ground, and thus compensated for, by the strong clamping forces generated by the ties mounted at short intervals.

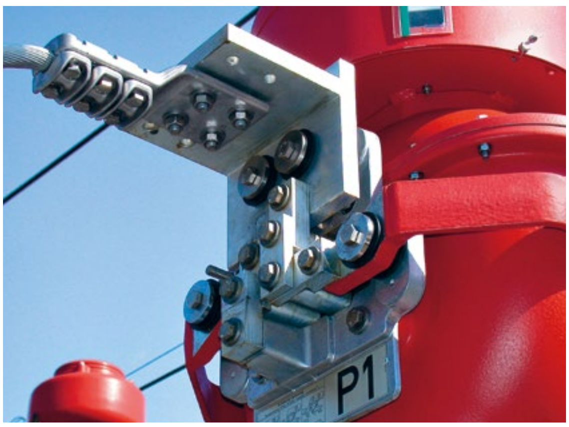


Figure 2: Protection against corrosion: Al Elast contact disks hermetically seal contact points

Flow. Recover. Force.

The correct dosage of contact force is determined by the flow and recovery processes in the materials, which result in a natural reduction in the clamping force. The contact force in any pair of mechanically connected materials reduces over time – or more precisely, by 20 to 30 % just a few minutes after the initial installation. Nevertheless, it is possible to produce contacts that have a life span of ten to 50 years.

Understanding contact hysteresis provides an approach to solving the problem. It takes more force to make a contact than to maintain it (for further details, please see Section 2). This means that the functioning of a contact is only at risk if the remaining contact force falls below a minimum value of, for example, 30 % of the initial force.

For this not to occur during its entire service life, despite flow, recovery and thermal breathing, elasticity has to be structurally designed into the body of the terminal, for example in the form of springy, permanently elastic contact elements (Fig. 3). Another remedy is to introduce additional elasticity by using springy washers. In the case of a bolted connection for example, these are positioned between the bolt head and the washer, which in turn rests on the rail to be connected.

Crimping technology: The right combination. Permanent contacts.

With crimped connections, the right combination of materials also decides whether the contact will have a long or short life span. The correct choice of sleeves and conductor material is indicated by the plus sign. The minus sign indicates a classic assembly error.

	Aluminum sleeve	**Copper sleeve**
Aluminum conductor	+	–
Copper conductor	+	+

Water. Electricity. Corrosion.
Electrolytic corrosion is another effect that drives contact aging where copper and aluminum are used in combination. Because of their molecular structure, the two metals have different potentials in relation to the neutral state: At –1.66 V, aluminum is significantly more electronegative, while on the other hand copper is slightly electropositive at +0.34 V.

If the metals touch, and a conductive medium such as water is present at the point of contact, they act as a cathode and an anode: The potential difference of the two metals is 2 V, and depending on the conductivity of the electrolyte, this drives a weak flow of current that corrodes the more electronegative metal. The aluminum becomes pitted, contact points disappear and the remaining contact area is undermined. To prevent this, the design should separate different metals from one another in situations where they could come into contact with an electrolyte.

Here, a brush stroke of insulating resin just few millimeters wide at the junction of the two materials is sufficient, as the –2 V voltage cannot generate a current even over this short strip of insulation. Another insulation method is to inject small plastic parts. For connecting planar surfaces of aluminum with ones made of aluminum, copper or bronze, for example, PFISTERER has developed the Al Elast Contact Disks (Fig 1).

Three aging effects – one solution.
These are positioned between the connection surfaces on the contact bolt. During assembly, their concentric annular cutting edges penetrate through the oxide layers on the connecting faces and create clean metallic contact surfaces. At the same time, the outer polyurethane elastomer sealing ring closes under compression, hermetically sealing the contact point so that electrolytes can no longer penetrate (Fig. 2).

After assembly, the contact force decreases here too, as a result of flow and recovery processes, but the contact disk brings more than sufficient elasticity into the bolted connection because of the staggered arrangement of the annular cutting edges. The concept of the contact disks recognizes that as many aging mechanisms as possible should be simultaneously controlled and resisted, because they can trigger one another or multiply each other's effects.

Each thermal expansion may accelerate the flow and recovery processes. These processes, together with vibration, trigger mechanical movements which promote the wear of material just as oxidation and corrosion do. And that is only part of the spectrum of negative synergies that contribute to even more aging mechanisms. Their interaction may be complex, but their negative effects are clear to see: high temperatures, increasing electrical resistance, decreasing contact force – all harbingers of contact failure.

Reliable at full capacity.
Finally, each terminal must be designed and utilized in accordance with its expected loads. The higher the constant power load, the faster the component ages. More and more situations occur where connections have been in operation for thirty years, and are therefore already in an aged condition, but are now being placed under greater load due to the higher utilization of the grid as it transmits increasing power. This is especially true in areas where the proportion of energy fed into the grid is from renewable sources, where often the networks are already at full capacity. Conclusion: When striving for permanently reliably connections, the relevant aging mechanisms should be taken into account so that the corresponding countermeasures can be reflected in the specifications. Or even easier: Order contact technology from manufacturers who know that aging is not a new problem but who take a practice-oriented approach to developing solutions instead.

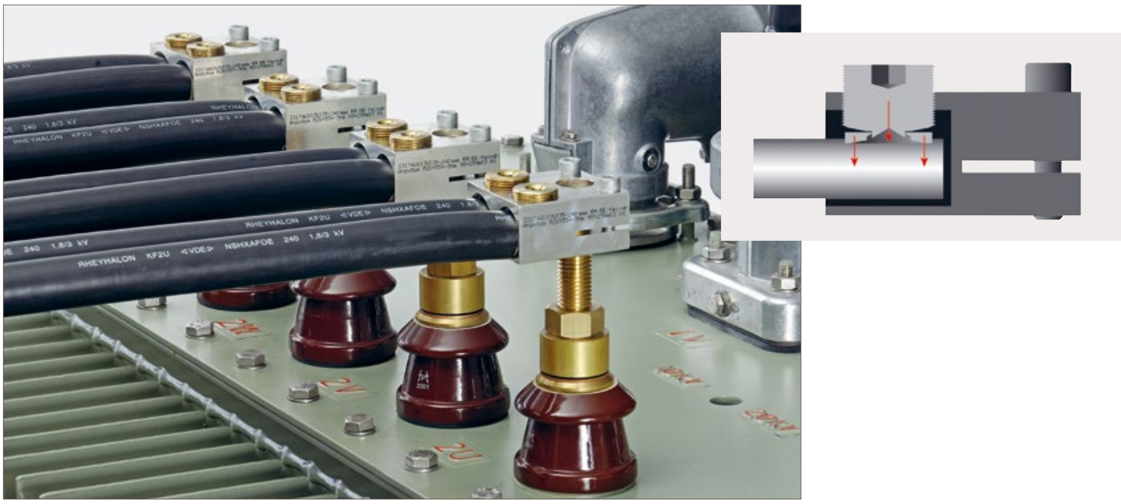


Figure 3: Bolted terminals with spring elements compensate flow and settling processes, such as this 2DIREKT transformer terminal clamps

Focus on Contact – Section 4

Long-lasting contacts thanks to the right design and installation

Knowledge is only useful when it is implemented. This second report on the principles of contact technology demonstrates, with the aid of terminals that have been in service for a long time, how the life expectancy of conductor connectors can be improved, with lifetimes of up to four decades and longer being achieved, despite the natural aging of the contact. The preconditions for this are that the connectors are designed according to the right principles and are installed correctly.

The general rules for the design of a connector are wide and varied and the trade-offs are complex, as demonstrated by the following design principles. On the one hand, the design must ensure specific contact properties are adhered to under all operating conditions, while on the other, production costs must remain within acceptable limits. Fulfilling both rules confronts the manufacturer with diverging requirements, even when he is selecting materials:

Steel, for example, is cheaper than aluminum. Moreover, with a stronger steel terminal, the required initial force to contact a conductor can be produced more easily than with an aluminum terminal. However, taking account of the need for a durable connection, steel loses its appeal: Steel connectors offer a higher resistance to current as it flows through the contact points. The result: Higher temperatures that promote the acceleration of the contact (for details, please see Section 3). The choice of materials also depends on the need to prevent, as far as possible, a permanent mechanical deformation of the connector body when the contact is being made. Doing so would affect the mechanical functions of the terminal and speed up the processes of creep, flow and settling which weaken the contact (for details, please see Section 3). Another important factor is the length, thickness and width of the connector components – with the right choice, the required contact force can be achieved without permanent plastic deformation of the connector body. And even with metallic coatings, it is important to find the right balance: The coating thickness and material must be chosen so that electrical properties such as low contact resistance can be achieved, there is a corrosion protection effect and costs remain reasonable.

Tolerances without tolerance

The sophisticated interaction of materials and design is manifested most clearly in the central factors of contact force and resilience. The contact force must be large enough to minimize the initial resistance that exists when the contact is made. Furthermore, sufficient contact force must remain throughout the entire life of the connection and the temperature-induced elongation of the conductors must be held in check, otherwise this will lead to micro-movements between the conductor and the contact parts, leading to mechanical abrasion and fretting and eventually to contact failure (see Section 3).

At the same time, the material and design should be such that the system can "breathe thermally". When heated, aluminum expands more than other metals. Result: If aluminum conductors are connected with a "rigid" copper or steel terminal, they do not have enough space to stretch, the conductor flows away but does not return to its original shape on cooling. Over several heating and cooling cycles, the electrical contact degrades gradually until total failure occurs. To master this balancing act between force and flexibility, contact equipment manufacturers need to learn to understand stretching, as there has been a widespread replacement of copper conductors by aluminum conductors. In the time of this changeover, PFISTERER developed the V-terminal with integrated resiliency – then a novelty, now a standard product. It allows for thermal breathing, firstly by using aluminum for the clamping body, as aluminum conductors and the terminal body have the same thermally induced expansion behavior (inherent elasticity). Secondly, the clamping body is deformed as the bolt is tightened at defined points so that elastic deformation occurs, which acts like a prestressed spring (design elasticity). Configuring the way in which contacts are made provides sufficient contact force using bolted technology, which also prevents the longitudinal movement of the conductor in the terminal. And sometimes optimal force is too much force. For example, when spring washers are inserted between the bolt and the connector body, bringing elasticity. Where connectors are made of aluminum or plastic, this effect is removed if the installation has been carried out incorrectly: When the bolt is tightened, it creates a high pressure load on a relatively small area, and under the tightening pressure, the spring washer located here burrows into the "soft" connector body, so that the required spring function is lost. The only solution in this situation: to place a flat steel washer between the connector body and the spring washer. This distributes the force over the entire contact area and prevents the washer sinking in (see Fig.2).

Optimum force. Suboptimal results?
Another finding: Sufficient contact force is not enough. For example, when aluminum is used, it oxidizes easily. Here, the contact zone must be designed so that the non-conductive oxide layers of the contact edges or teeth are penetrated. This method results in a purely metallic contact, ensuring the unhindered flow of current from one conductor to another (see Section 2). Another important criterion is the arrangement of the contact edges or teeth in the terminal area. The Donati rule for current commutation shows that they should ideally be positioned where the natural commutation is highest (see Fig. 1).

And sometimes optimal force is too much force. For example, when spring washers are inserted between the bolt and the connector body, bringing elasticity. Where connectors are made of aluminum or plastic, this effect is removed if the installation has been carried out incorrectly: When the bolt is tightened, it creates a high pressure load on a relatively small area, and under the tightening pressure, the spring washer located here burrows into the "soft" connector body, so that the required spring function is lost. The only solution in this situation is to place a flat steel washer between the connector body and the spring washer. This distributes the force over the entire contact area and prevents the washer sinking in (see Fig. 2).

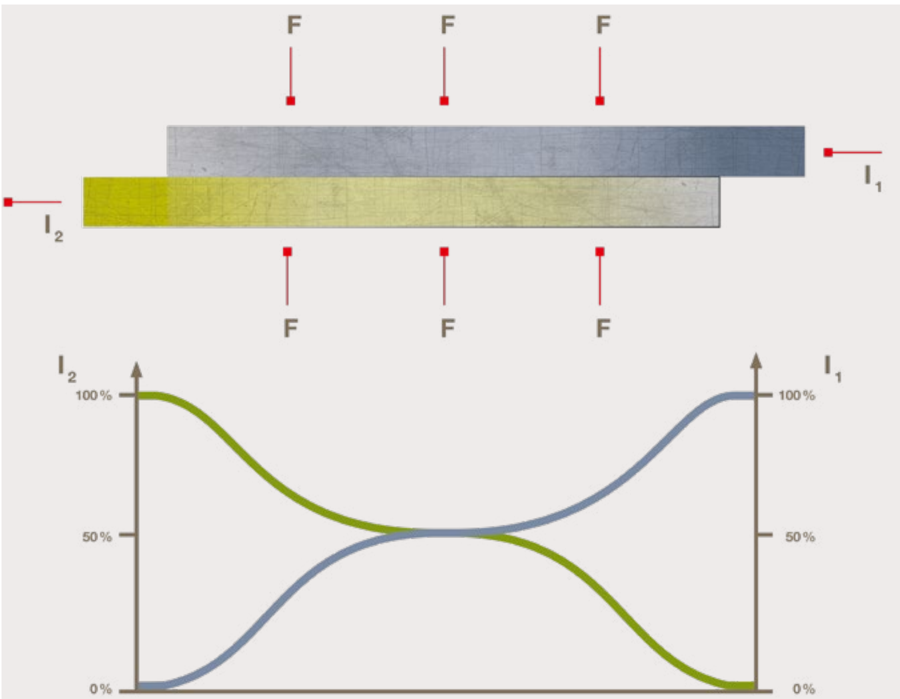


Figure 1: Ideal arrangement of the contact elements. Donati's rule of current commutation shows that the current density of a connection is not the same at all points: The commutation takes place for the most part at the beginning and at the end of the overlapping surfaces of the conductors. Ergo: The contact areas (zones, lines, points) are placed as close as possible to the beginning or end of the terminal.

Proper installation – lower risks

And even when the vital elasticity is present through design, installation errors can endanger the long-term stability of the contact. One rule for installation is: Remove contamination and oxide layers on the contact areas by cleaning and brushing. In addition, use contact greases or pastes – especially under critical environmental conditions. They protect the actual contact zones against the ingress of air, water and salt and thus against oxidation and corrosion. Added to this is that in the case of bolted connections, it is only the proper lubrication of the bolt that can ensure the optimal conversion of the applied torque into the required contact force. How significant the loss of force can be when the grease is forgotten or wrongly applied can be seen in Table 1 page 17.

Since installation is often carried out under difficult conditions and with time constraints, manufacturers of contact technology endeavor to eliminate installation errors through suitable connector designs, or at least minimize their consequences. So, for example, some manufacturers only supply pre-greased bolts. Another method is giving a metallic coating to the terminals or contact zones. Tin coatings are an economic solution that provides added reliability, if insufficient cleaning and greasing has been carried out. When penetrated by the contact teeth, the waxy tin retreats and closes up around the contact points again after the contact has been made. The electroplating process may automatically remove any oxide layers that may be present on aluminum surfaces.

Many findings – one terminal

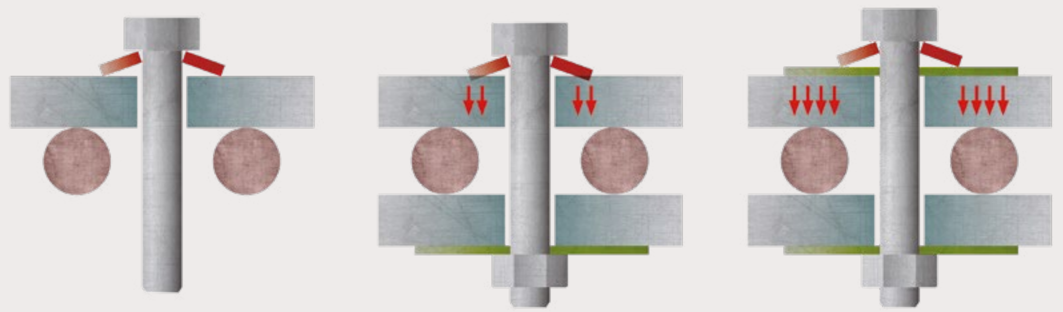
The implementation of these and other findings were already carried out in the 1960s in the ISO tapping clamps from PFISTERER (Fig. 3): The application-specific matching of bolt, bolt greasing and torque results in the required initial force being achieved. When tightening the bolt, the contact teeth "bite" into the conductor insulation and the conductor, thus creating defined, bare contact points. The shape of the metallic contact plates (elasticity) guarantees a permanent contact force. Contact plates are tin plated to create improved and reliable contacts with slightly oxidized aluminum conductors.

The contact plates are embedded in a plastic connector body in a touch-proof manner, reducing costs and improving reliability. In addition, a steel plate is integrated into the connector body directly below the bolt heads. Without this, the plastic body would be exposed to excessively high mechanical loads in the small area under the bolt head. This design is still the basis for more advanced tapping terminals such as the ISICOMPACT from PFISTERER, where the pressure plate is also designed to act as a spring element.

One specification – many parameters

The construction principles illustrated by the ISO tapping terminal are used in many design rules, which are reflected in the specifications of both manufacturers and users. The long term transmission capability of a contact, for example, is often defined by the initial force that has to be

Figure 2: A classic installation error.



1. A spring washer is inserted between the bolt head and a connector body made of aluminum or plastic.

2. Under the tightening pressure, the bolt sinks into the "soft" connector body and loses its resilience.

3. Solution: A flat steel washer is placed between them (right). It distributes the initial force that has been introduced over a wider area and prevents the bolt from sinking in.

applied to produce the connection, or over the length of the existing lines of contact, or the surface of the contact points that have been created.

One user specification, for example, calls for a 120 N initial force to be transmitted per ampere at a conductor capacity of 1000 A in the terminal of an outdoor switching station. In order to meet this, the manufacturer must take account of the various influences that affect one another, such as the materials used for the bolt, nut and washer, their surface characteristics (uncoated, galvanized, greased), the pitch of the bolt thread, the number of bolts and the tightening torque.

From initial values to the design

This process is carried out with the help of a table of empirical data. Starting with a standard bolt made of hot dip galvanized steel, size M12 and strength category 8.8 results in a nominal torque of 80 Nm (see page 17 Table 2), which is incorporated as a neutral factor of 8.0 in the calculation of the design of a bolted connector.

If an aluminum nut and A-2 washer are chosen, this combination of materials gives a required initial force equal to the clamping force of 3.8 kN per 10 Nm of tightening torque, for a thread greased with Vaseline (see page 17 Table 3). Multiplying these two values gives an initial force of 30.4 kN per bolt. To achieve the required 120 kN, four bolts are used, which results in 121.6 kN, meeting the specification.

Fine tuning and innovation

It is different if the user requests the use of M12 bolts in steel group A2 or A4 and strength category 80. These have a lower nominal torque of 75 Nm (Table 2, page 17). In addition, the different material combination is causing the clamping force of each bolt (Table 3, page 17) to drop to 2.9 kN per 10 Nm tightening torque. The result: the required initial force cannot be achieved with four bolts for Al nuts and A2 washers.

For an experienced design engineer, this is not a problem since the numerous influences with their respective tolerances allow for adaptation. Innovative manufacturers strive to exceed the required long term transmission capability of a contact anyway: In addition to the principles mentioned here, their latest generation of connectors achieve even greater efficiency with higher safety and greater flexibility in use.

- Integrated steel washers for optimal force distribution
- Elasticity by shaping the contact plates
- Contact teeth for defined contact points
- Connector body in plastic for contact protection
- Greasing bolts supports the conversion of torque into contact force

Figure 3: Even in an ISO branch terminal from the 1960s, all the design criteria for modern terminals were taken account of.

Contact forces from bolts

Bolt	Greasing	Force in kN with torque 56 Nm	80 Nm
A2 F70	without	21,8	28,6
A2 F70	Vaseline	19,8	27,4
A2 F70	M 50 G	29,3	39,6
8.8 hdg	without	17,1	25,7
8.8 hdg	Vaseline	24,8	31,7
8.8 hdg	M 50 G	21,9	32,1
8.8 electropl. tin.	without	18,9	22,9
8.8 electropl. tin.	Vaseline	32,5	47,0
8.8 electropl. tin.	M 50 G	29,4	43,0

Table 1: Details that have a big impact. If there is a failure to lubricate the bolt or it is performed incorrectly, the torque introduced cannot be sufficient to create the required contact force. Result: A loss of force of up to over 50%.

Tightening torques

Threads	Tightening torques for bolt materials in Nm	
	■ Unalloyed or alloyed steels ■ hot dip galvanized (hdg) ■ Strength category 8.8 ■ RP 0.2 MIN. = 640 N/mm²	■ Rust and acid resistant steels, ■ steel group A2 or A4 ■ Strength category 80 ■ RP 0.2 MIN. = 600 N/mm²
M 6	9,5	9
M 8	23	22
M 10	46	43
M 12	80	75
M 14	125	120
M 16	195	180
M 18	280	260
M 20	390	370

Table 2: Tightening torques for different bolt materials

Clamping forces in kN for each 10 Nm of tightening torque, thread greased with Vaseline

Bolt	Nut material	Washer	M8	M10	M12	M16
St hdg	St	St hdg	4,5	3,6	3,0	2,3
St hdg	Al	St hdg	4,8	3,8	3,2	2,5
St hdg	Al	A2	5,7	4,5	3,8	2,9
St hdg	Cu/Rg/Ms	St hdg	4,5	3,6	3,0	2,3
A2/A4	St	A2/A4	4,3	3,4	2,9	2,2
A2/A4	A2/A4	A2/A4	4,1	3,3	2,8	2,1
A2/A4	Al	A2/A4	4,3	3,4	2,9	2,2

Table 3 lists the required clamping forces for select material combinations as a function of tightening torque for a thread greased with Vaseline.

Focus on Contact – Section 5

From proven contact technology to innovative connectors

The fifth section provides an overview over the classic connection technologies crimping, plugging and bolting and proves: Progressive terminals can do more than just withstand natural contact aging. They make installation easier, reduce the risk of failure, improve occupational safety and work in a broader spectrum of applications.

When looking back on the history of contact technology leading up to today, one can visualize a wide field of options. It includes all mechanical connections of conductors in electric power grids, more specifically cables and overhead lines. To connect these, three techniques are in use around the world: Crimping, plugging and bolting. The three techniques are applied to varying degrees for the three basic forms of contacting: connecting, joining and branching (Fig. 1). The traditional techniques welding and soldering, however, have almost disappeared in the last few decades.

Crimping made to measure

The crimping technology principle is based on the radial and axial distortion of the sleeve and the conductor ends in it by means of crimping. Two methods are commonly used in this process: form-controlled symmetric crimping (for example round or hexagonal crimping, Fig. 2) and force-controlled asymmetric crimping (for example deep groove crimping). The latter is not approved for contacts used with overhead lines since the individual wires are pressed more tightly under those circumstances, and as a result they flow further in a longitudinal direction (axial distortion).

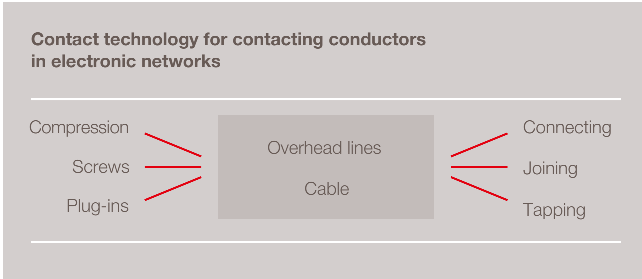


Figure 1: Overview over the vast field of contact technology today: starting with the three most important techniques to types of conductors to be connected as well as the three prevalent basic connection methods.

Figure 2: Contacts with long-term reliability require optimal transverse conductivity in the conductor. To achieve this, not only the exterior layers of the conductor assembly when crimping, but also its interior layers. This image shows optimal crimping via symmetric crimping: All individual wires show the characteristic angular distortion.

This makes the conductor thinner at the contact point (cross-section shrinkage) and lowers its mechanical strength. Overhead lines are exposed more severely to a number of tensile forces as a result of their own weight and vibrations from wind and weather influences, so they must exhibit particular tensile strength. Taking these tensile forces into consideration presents a challenge for contact technology manufacturers as they as tasked with balancing to opposing processes in all technologies, but especially in crimping.

On the one hand, the resistance to be bridged by the current drops with increased contact force, which is an effect manufacturers strive for. This is because the thermal load of a contact increases with the higher resistance, which accelerates aging (for details see Section 3).

On the other hand, the conductors are deformed too severely when the force on a contact gets too high. However, if their mechanical strength is too low, they tear with higher tensile forces. The solution: the contact force is set in a way that the connectors meet both the electrical and mechanical requirements equally (Fig. 3).

Plug-in technology for removable contacts

Practice has proven that this works: Since the crimping technique has become a staple – in addition to bolting – in Europe in the 1960s, it is now used worldwide, primarily to connect and join conductors with cross-sections between 16 and 2500 mm². The important finding that multiple smaller and defined contact points can achieve a higher contact quality than a single large area (Detail info 1, see also Section 2), is what crimping technology and the more recent plugging technology have in common. This prevailed in the 1970s and 80s when cables were used more often and when the demand for touch-proof connections increased. As a result, this requires fully enclosed contact systems that can be removed again after the initial contact has been created.

A more progressive solution for this problem can be found in dry pluggable and touch-proof CONNEX cable connection system: A connector is mounted onto the end of the cable to be connected. The connector is then plugged into an integrated adapter bushing on site. Today, all types of plug-in connectors are used primarily for connection, followed by joining. Individual products also facilitate the more rare branching via plugging, for example branch tees. The development and design of the plug-in connectors is based on the principle of elastic line contact (Fig. 4).

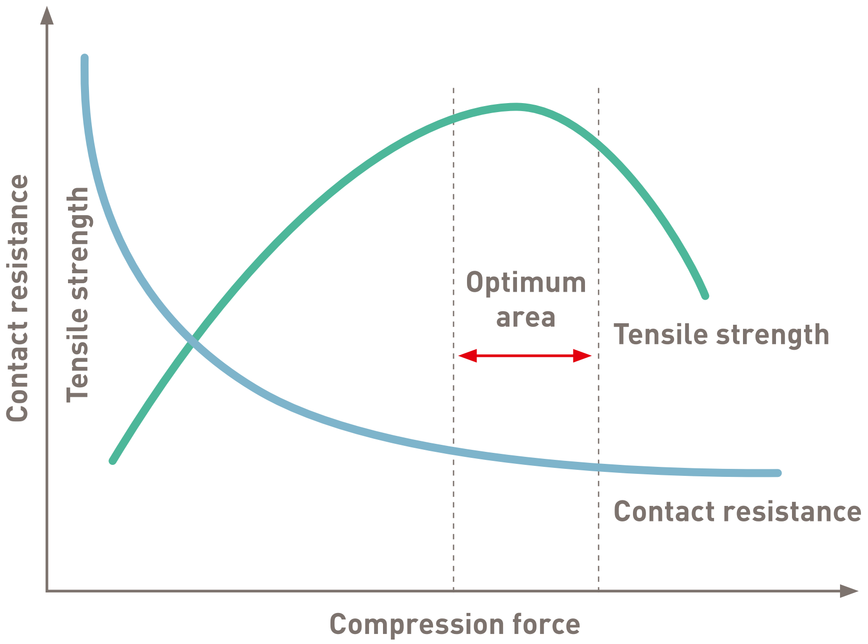


Figure 3: Crimping technology design criteria balance electric and mechanical requirements:
For crimping, the contact force must be chosen in a manner that reduces contact resistance if possible and maintains the highest possible tensile strength in the connection at the same time.

Figure 4: In plug-in connector design, the contact points are defined as contact lines as well and springs are added for high elasticity to ensure that the connection can last for a service life of multiple decades.

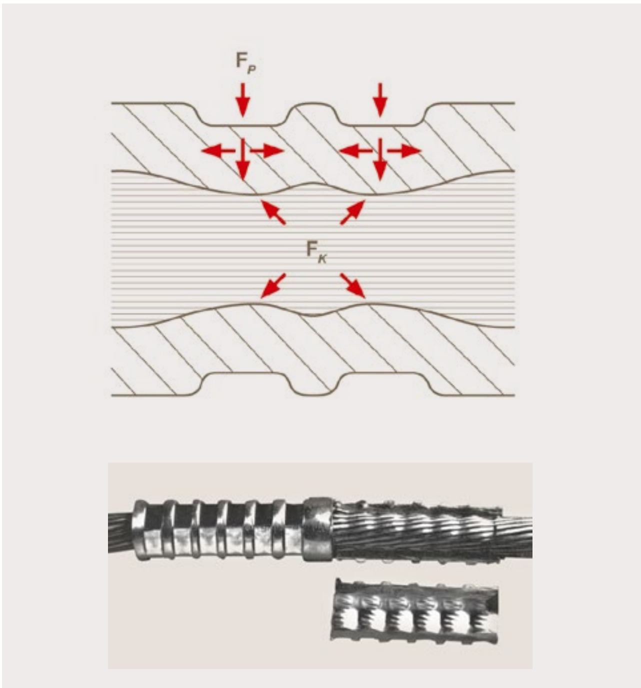
Bolted technology:
Traditional and present time usage

The oldest technique in contact technology is bolting with a number of different terminals (Fig. 5) for joining, connecting and branching. We differentiate between to basic methods: the older bare contact bolted technology originating from overhead line applications and the newer insulated bolted technology. The requirements for overhead line terminals may be lower in some cases because overhead lines are surrounded by air and cooled by the wind. This is in contrast to lines installed underground, where the insulation retains heat. To prevent the insulated cable terminals used under these circumstances from aging prematurely (Section 3) or even overheating, they must fulfill more stringent contact technology requirements. All bolted connectors have in common that the contact force is generated by the bolts (for design regulations in bolt design, see Section 4).

Figure 5: Bolted technology is not only the oldest contact method with its large variety in connector designs, but it also features the most advanced terminals used today.

Detail info 1:

Tests have shown that multiple defined contact points are better than one large contact area. This knowledge is implemented in crimping technology, for example by means of multiple crimping: Where the edge of the crimping tool presses into the sleeve and conductor, edges are formed as well. These serve as contact lines via which the current flows from one conductor to another in a controlled manner. In addition: Due to the crimping force, the conductor creeps out, expands in a longitudinal direction and compresses in the spaces of the individual crimping points. The elasticity is stored in these bunched up areas. This causes the fixed conductors to be pressed against the crimping edges, namely the contact lines, with a certain force under varying thermal conditions. As a result, the required minimum contact force is maintained throughout the entire service life of a connection.



A key component: The transition from the overhead line to the test cable – using a modular assembly made up of elements of the HV-CONNEX system.

Just like in crimping and plugging, contact technology manufacturers attempt to utilize basic knowledge and experience in practice settings when designing advanced terminals for bolted technology. Successfully. Using innovative bolted terminals, such as ISICOMPACT, makes installation easier while increasing occupational safety at the same time. They are more cost-effective to manufacture and suitable for multi-purpose applications, which increases their range of possible uses. Bolted connectors have the following characteristics: an insulated and therefore touch-proof design thanks to a connector body made from plastic and insulation displacement contact elements (Section 4) as well as the one-bolt technology with torque release.

The SICON connection concept is another example. Its development was triggered by changing market requirements (Section 1): In the past 30 years, the number of different cable designs and cross-sections has multiplied, while installer profiles shifted from specialist to all-rounders. The development of elastic plastics first introduced multi-purpose joints to the market. The resulting demand for flexible connectors that can be mounted easily and safely cannot be satisfied by the common solutions. The crimping technique is not suitable due to its inherent design which allocates fixed tools and sleeve cross-sections to different conductor cross-sections. This not only requires an abundance of materials and tools but also specially trained staff. The principle of modern bolt technology, however, has the potential to meet today's demands, though conventional bolted connectors do not live up to these standards due to their weak points.

New technology, new challenges

One of them: Applying optimal levels of contact force cannot be guaranteed because this process depends on two uncertain factors. One the one hand, it is dependent on the installer's subjective evaluation to assess if and when sufficient force has been introduced. On the other hand, the torque wrenches used for this purpose are not always helpful either. Another disadvantage: the bolts protruding from the connector body complicate joint attachment. The first optimization took place when multi-stage shear bolts were used. Corresponding to their name, they shear off when a contact is created, which makes the application of joints easier. They shear at predetermined breaking points when certain predefined torques are reached.

However, this novelty also has its limitations. The prevailing demand on the market has been that a terminal must cover a cross-section range between 50 and 240 mm². This encompasses the seven cross-section sizes 50, 70, 95, 120, 150, 185 and 240 mm² and therefore seven different nominal diameters. The multi-stage shear bolts, however, have a maximum of three breaking points so that at least four cross-section sizes are not optimally covered. On the other hand, seven predetermined breaking points on one bolt are not feasible because each breaking point weakens the load capacity of the thread.

The biggest disadvantage of multi-stage shear bolts: The technically only way to design them is so that the first predefined breaking point facing the conductor shears off at the lowest defined torque, and the last breaking point closest to the bolt head shears off at the highest defined

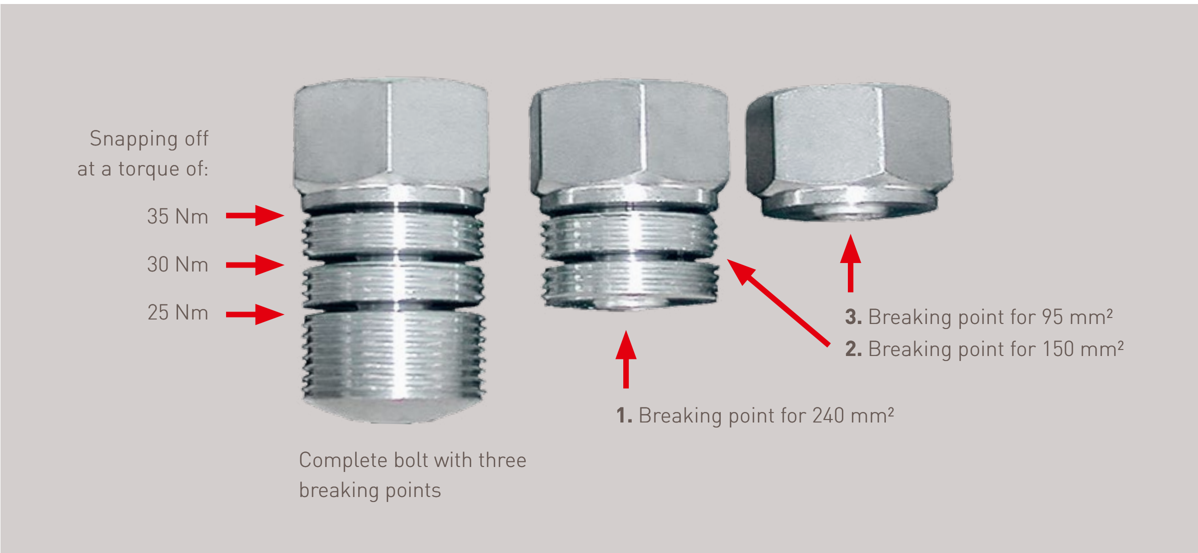
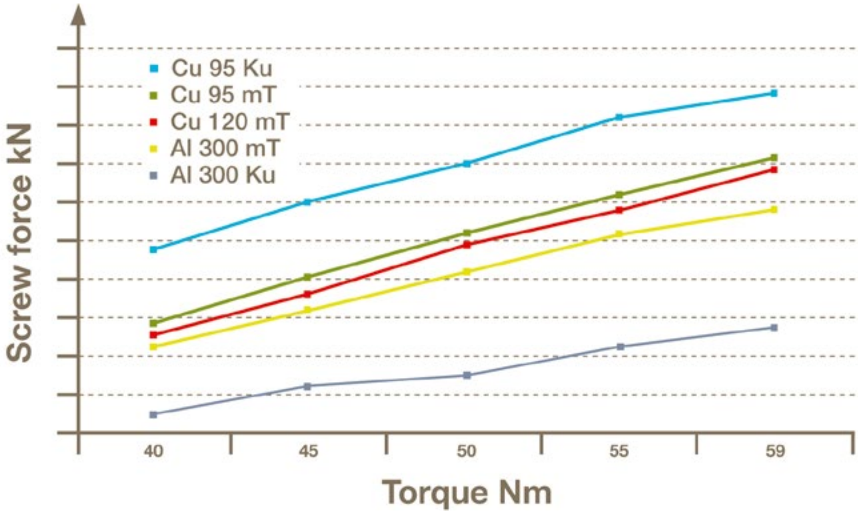


Figure 6: Disadvantage of shear bolts with multiple breaking points: Due to its design, the highest defined torque (35 Nm) must be applied at the third breaking point, while the lowest defined torque (25 Nm) is applied at the first breaking point. Due to the torque control force transmission, the smallest conductors (up to 95 mm²) are exposed to a higher contact force, while the bigger conductors (up to 240 mm² are contacted with a lower contact force.



torque (Fig. 6). The result: Whenever the bolt must be bolted in all the way – such as when connecting the smallest possible conductor cross-sections – the highest torque is applied and vice versa. Thus the smallest conductors are exposed to the highest contact force and the biggest conductors experience the lowest contact force.

Not only that: Only part of the applied torque is converted into contact force. The other part is converted into friction forces. One of them is the inevitable thread friction. As a natural counterforce to the contact force, it increases and decreases proportionally to it and can therefore be managed with conventional connectors. This is not the case for head friction. In classic bolted connectors, head friction takes effect between the bolt head and the conductor surface. As a result, it fluctuates greatly because in this constellation it is dependent upon the conductor material, conductor hardness and the overall state of the conductor surface. When using a standard connector on aluminum conductors, for example, head friction is very high. Thus it also poses the risk of not allowing for sufficient contact force. The opposite applies when the same connector is paired with a copper conductor. In that case, the head friction is significantly lower. The risk in this scenario, however, is that too much contact force being introduced can cause the thread to tear or the individual wires to be damaged too severely. This is without having taken the important factors of conductor hardness and conductor surface into account.

Detail-info 2:

For bolted connectors with an integrated pressure disk, the head friction takes effect between the pressure disk and the bolt, thus essentially between functional elements whose quality is determined by the manufacturer of the bolted connector. This makes the conductor's head friction nearly independent, able to be calculated by the manufacturer and to be integrated in the definition of torques. Result: A bolted connector with a pressure disk (mT) can create the required constant contact force (three center lines) even for conductors with highly fluctuating friction coefficients, such as copper conductors and aluminum conductors. This does not apply to domed bolts (Ku) that have a rounded bolt top: In this situation, the head friction takes effect between the bolt and the conductor, thus depending on the conductor material, conductor hardness and conductor surface, all essentially fluctuating factors that the manufacturer has no control over. The result: Depending on the conductor, the applied torque is converted into contact force more or less (top and bottom lines) and an optimal contact force is not guaranteed.

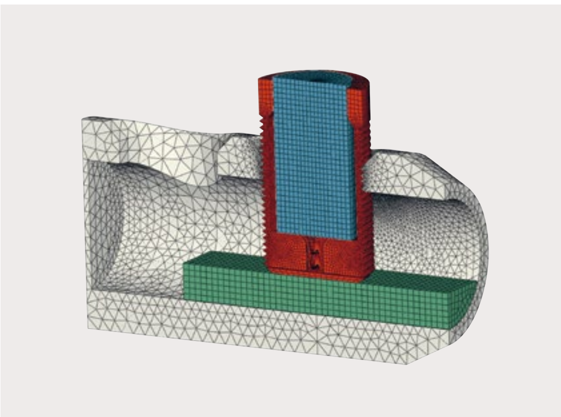
The advantage of modern bolted connectors

The bottom line: a conventional connector alone cannot do justice to different types of conductors. This is aggravated by the fact that in multi-stage shear bolts the detrimental arrangement of torque and breaking points cannot be reversed due to its design. The sum of these effects is devastating: The contact force – a factor of vital importance for any connection – cannot be reliably defined with the means presented.

This cannot be said about SICON, the latest development in the field of bolted connectors. The two most important technical innovations of the patented connection system for conductor cross-sections between 25 and 2500 mm²: The stepless design of the shear bolt as well as an integrated pressure disk at the end of the bolt. These two characteristics together ensure optimum contact forces with the use of different conductors regardless of their qualities (detail info 2). They furthermore allow even fine stranded class 5 conductors to be used for contacts without causing any damage. Detail info 3 explains how exactly it works. To develop these important functional elements, the forces and tensions in the connector must be controlled. They are calculated and visualized by means of the Finite Element Method (FEM). Individual bolted connector functions are analyzed this way as well (Fig. 7). By now, the use of SICON in all voltage levels has shown that the connection system meets the current market demands (multi-purpose application, easy installation, higher installation quality) and that it takes basic knowledge into account (Sections 2 to 4). In the SICON design, the latter looks as follows: A thread integrated in the conductor duct creates predefined contact lines. The entire connector body is tin-plated and the conductor duct has been greased at the factory in order to protect the contact from oxidation and to ensure good long-term performance. The choice of materials as well as the defined relationship between conductor hole diameter and wall thickness of the connector body furthermore ensure elasticity: When the bolt is tightened, the connector body is automatically distorted in a permanently elastic manner so that it acts as a pre-stressed spring. This counters flow and settling processes and allows the system components to breathe thermally. All of these characteristics keep natural contact aging in check.

How long will the contact last?

The question of the actual long-term durability arises with connector in all different designs. Their target service life of four to five years, however, makes real-time tests unfeasible. For this reason, type testing of new developments includes aging tests in accelerated processes. This at least gives some insight as to whether the connector is in principle suitable and reliably able to function long-time in its task in the power grid. On-site testing, however, aims to predict the residual service life of connectors already in use. A look back onto recent years brings up another question in this context: Are there any reliable methods for this? The sixth and last section with a focus on type testing and on-site testing will provide the answers.



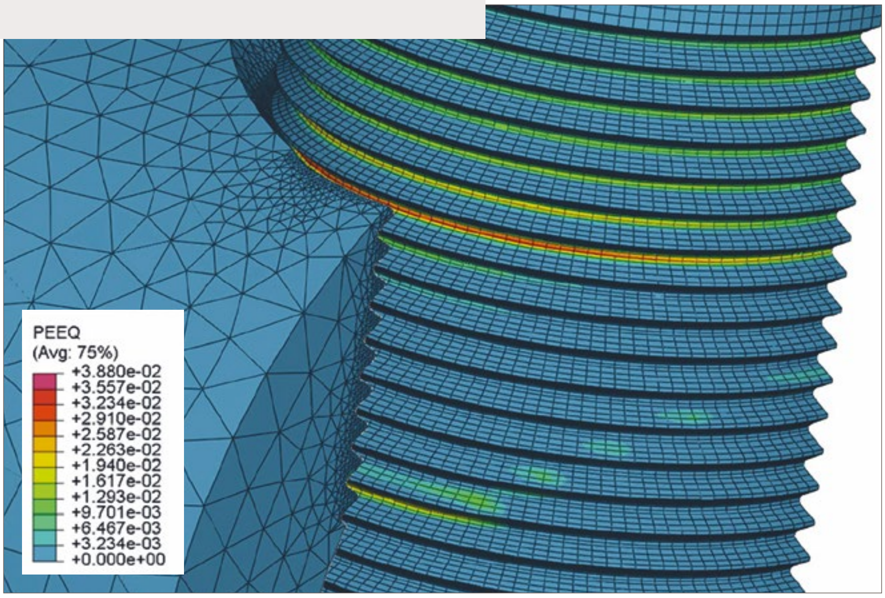
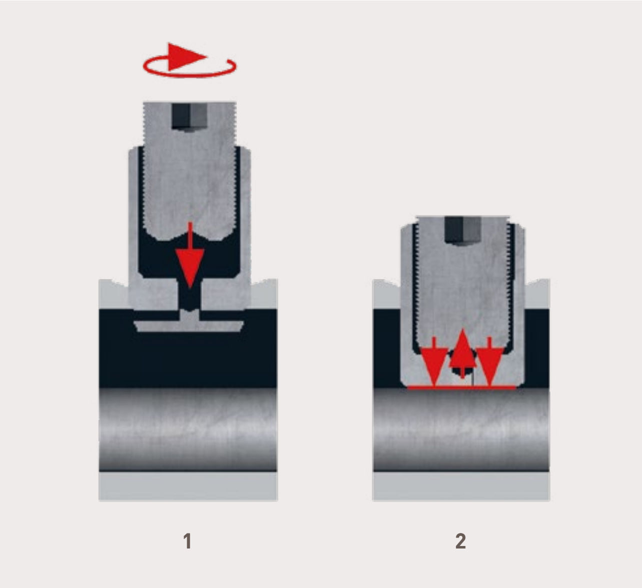
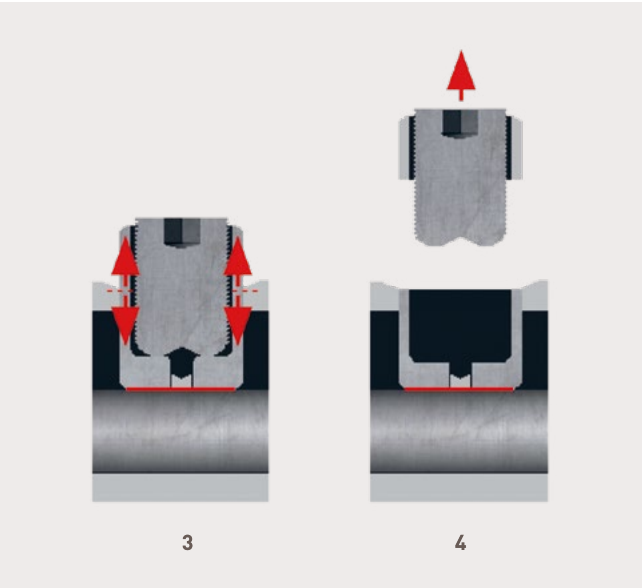


Figure 7: The FEM simulation on the left shows the forces and tensions at work in a SICON bolted connector. The FEM analysis confirms the mode of operation of its stepless shear system: The first free thread turn of the SICON bolt that protrudes from the thread of the connector body is also the area with the highest mechanical load. Ergo: This is the place where the stepless bolt shears off automatically when the optimal contact force is achieved – even without predetermined breaking points.





Detail info 3:
The SICON bolt principle

1. The SICON bolt consists of a threaded pin, a threaded sleeve with inner and outer threads as well as a friction disk at the end of the bolt. Thanks to the stepless design of the bolt, the contact force can be built without interruptions by steps or notches in the bolt. When the SICON bolt is tightened with a standard hexagon wrench, the threaded pin turns in the threaded sleeve until it touches the bottom of the sleeve.

2. From this point on, the threaded sleeve turns as well until the friction disk at the end of the bolt touches the conductor to be connected. The friction disk disengages from the bottom of the bolt, and the bolt continues to turn on the disk. While doing so, the disk remains motionless on the conductor surface since the friction between the disk and the conductor is significantly higher than the head friction between disk and bolt. Advantage: The head friction at the conductor itself stops, and the torque of the bolt is converted into contact force by the conductor nearly independently (Detail info 2). This force presses the conductor against the opposing wall of the connector body, which essentially creates the terminal connection. At the same time, the friction disk protects the conductor from damage caused by the contacting process.

3. The SICON bolt continues to turn until the breakaway torque is reached. Then the interaction between tensile stress and contact force comes into play. As a result from the bolt being tightened, both forces are created as two equally strong and opposing forces according to the law of mechanics that states that force equals counterforce. The contact force is exerted onto the conductor, while the tensile force works in the opposite direction onto the threaded sleeve of the SICON bolt. As soon as the tensile stress associated with the optimal contact force is built up, the breakaway torque is reached: the tensioned bolt is axially stretched in a predefined area of the threaded sleeve until it shears off.

4. The SICON connector is designed in a manner that the highest point of the tensile stress is always wherever the threaded sleeve protrudes from the thread of the connector body. If viewed from the outside, the first free thread turn thus also acts as the breakaway edge (Fig. 7). Ergo: The SICON bolt always shears off below the surface of the terminal body and does so without leaving protruding bolt parts with sharp edges. This eliminates the previously necessary step of filing as the risk of disruptive electrical discharge due to metal shavings is no longer a problem. Compared to conventional shear bolts, the SICON bolt also shears off very gently and nearly without jolting.

Focus on Contact – Section 6

How long will the contact last?

Is a new connector always suitable for decades of use? How long is the residual service life of connectors already in use? The first question can be answered through type testing, whereas the second one is the subject of on-site tests. Section 6 addresses both of these approaches with a focus on aging effects in contacts.

Figure 1: An analysis of the thermal image shows that the bolts are by far the hottest area in the tested terminal set-up. This means that the current flows through the bolts rather than the contacts – a precursor to contact failure.

A typical form of on-site testing of above-ground connections, or more specifically their contact quality, is thermal imaging. This imaging method reveals infrared radiation which serves as the basis for the interpretation of temperature distributions. Thermal imaging cameras today are technically advanced and typically feature excellent resolutions. The crucial issue is that these thermal images must be analyzed in a professional manner. This requires basic knowledge about contact technology. One of the most important principles for the analysis of thermal images states: The higher the resistance in a connection, the shorter its service life is. The reason for this is that high resistances are always associated with corresponding high temperatures, which in turn promote natural contact aging (Section 3). Areas of the image that show higher temperatures could thus be an indicator of bad contact quality.

Clear thermal image – complex analysis

The measured temperatures, however, must always be seen in relation to additional factors: If a significant current flows through the connection at the time the thermal image was taken, an increased temperature might be absolutely justified, whereas it would have to be considered critical for a lower current. Ambient temperatures can affect the evaluation as well: A higher temperature in a connector that is also heated by direct sunlight must be assessed differently than a connector evaluated in cold winter temperatures. Another factor to take into consideration is the emission factor which varies depending on the surface characteristics of the connector: uncoated aluminum radiates differently than soiled or oxidized aluminum.

There is yet another principle of contact technology that is also reflected in the standard requirements for type testing according to IEC 61238-1 and IEC 61284: The connector must not be warmer than the conductor. The application of this principle not only requires extensive image sections but also knowledge about and experience with the system in which the connection in question will be utilized, or more specifically with the position of the connector in this system (Fig. 1).

If this and other necessary information is assumed as a given during interpretation, the thermal images taken after several years of operation can at least answer the following question: Is the connector inconspicuous or is it already in a critical state? However, this approach is unable to provide reliable answers that go beyond this rough analysis of the status quo. A one-time snapshot neither allows past developments to be reconstructed nor does it give any insight into future trends. It still fails to provide useful information on the number of years it takes for the quality of contacts in operation to decline or the actual remaining service life of a connection. However, even though negative findings regarding an urgent problem are relative, this approach does at least offer the opportunity to do one thing: If a connection was clearly revealed to be critical, it can be replaced immediately.

Saving systematically

A systematic use of thermal imaging in select critical areas can not only result in higher grid and supply security but also lead to cost benefits. A prerequisite in this approach – in addition to professional interpretation of the images – is that the thermal images are taken when a connection is commissioned and that the most important data, such as current and ambient temperature at the very least, are recorded in the process. This fingerprint is then used as the baseline for subsequent thermal images taken at specific intervals, for example every five years, including data collection and documentation.

Just this fingerprint alone can provide valuable insights. If, for example, the bolts were not tightened enough during initial installation of a bolted connector, the image would show this flaw. The comparison of current thermal images and data with older ones (Fig. 2) could indicate trends that would allow for foresight and thus cost-effectiveness in network maintenance. For example, if transformers or insulators are scheduled for replacement, the required turn-off time could be optimally utilized by simultaneously replacing any connections in the vicinity that show a clear negative trend.

Exact resistance? Big effort!

While the temperature factor in thermal imaging only approximates the physical resistance value, a number that plays a central role in contact quality, resistance measurement, which is also commonly used, calculates the value directly via voltage and current and can therefore be considered more accurate. Different methods are used in this approach:

Resistance measurement under operating voltage is only performed on overhead lines. Since the on-site measurement of the operating current is associated with significant effort, the network control station generally reports the current operating current to the testing team on site via radio. Even if the probability is low, this constellation still poses the risk of inaccuracies. While the measurement only takes approximately 20 seconds, one cannot eliminate the possibility of grid capacities fluctuating during this time, which would automatically change the operating current during measurement. By far the bigger challenge is the attachment of the measuring instrument – an imposing apparatus that is transported to the connection on rollers via the overhead lines and remote control. Days can pass before this point is reached. First, the measuring instrument must be lifted up. Then long insulating rods are used to position it on the overhead line, which is under operating voltage during this procedure.

In light of this effort, this approach only seems feasible in very few special scenarios, for example when a previously taken thermal image detects symptoms of a possible failure in an important nodal point but is unable to prove it beyond a doubt. Resistance measurement under operating voltage can provide insight before making the much more costly decision to replace the part, which would also involve the overhead line being taken off the grid. Regardless of which decision would be made in this situation or similar ones, for this type of resistance measurement, it is important to keep in mind the following: It measures the current value, which allows the current contact quality to be evaluated, if measured and interpreted correctly, but it does not provide information about previous or future developments.

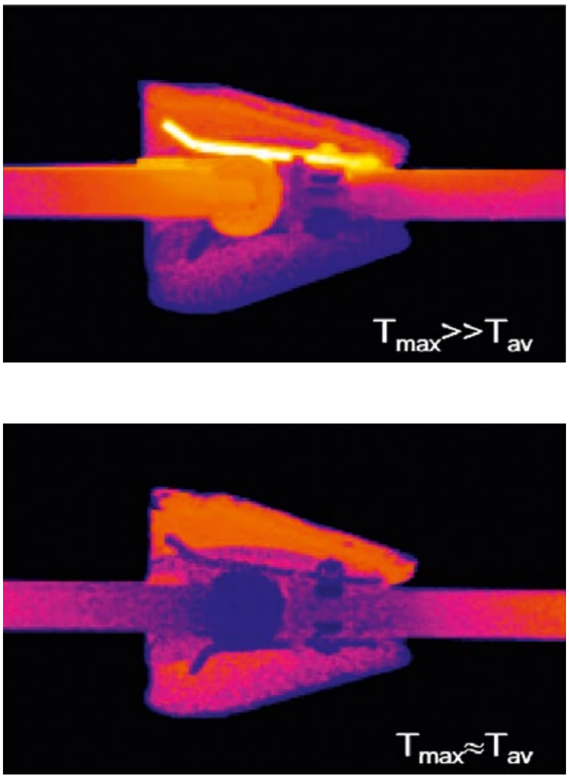


Figure 2: A comparison of the two infrared images clearly shows the difference between a critical contact (above) and a new contact (below).

High operating current – low measuring current

One of the situations in which resistance measurement is used without operating voltage is if there are recurring failures and reconstruction of a larger grid section is being considered. A used connector will serve as a specimen. This connector was removed from the grid along with 2 to 3 m of conductor on both ends of the connector. It is then typically examined in the lab, though in rare cases also on site, under direct current. For this purpose, there is a large selection of ohmmeters on the market which usually work with measuring currents between 5 and 500 mA.

However, these low measuring currents are proven not to be suitable for the assessment of heavy current contacts, which are exposed to 500 to 1000 A. If necessary, a small current can find its way even without noticeable resistance via very few contact points, even if the majority of the contact is actually unusable. Therefore the direct measuring current must be at least 50 to 100 A and be able to be realized at a reasonable expense.

The principle that the best measuring technology is useless without professional analysis of the measured values applies here as well. Comparing the connector resistance to the resistance behavior of the uncut conductor is a good strategy here. For this purpose, the relationship of the connector resistance to the resistance of a conductor piece the same length as the connector is determined. According to IEC 61238-1, this value is called resistance factor. The closer this value is to the ideal ratio of 1 to 1, the better the contact quality is (compare subsequent explanations regarding resistance calculations in type testing according to IEC 61238-1).

Click without force

Another typical form of on-site testing is to gage the contact quality of bolted connectors by the remaining contact force. Even though the contact force is not the only deciding factor, it is a key component of contact quality, which makes it suitable as a test indicator. Keep in mind: The lower the contact force, the higher the resistance, which accelerates natural aging (Section 3).

This method does not detect the contact force itself but instead attempts to determine it in directly via the measurement of the auxiliary quantity residual torque. The popularity of this method lies in its simplicity: The measuring instrument used here is a simple torque wrench preset to the target torque, which is adjusted to the bolt in the connector, which generates the contact force (Section 4). The wrench is placed on the bolt and then tightened. More often than not, the wrench clicks exactly when the target torque is reached. This often leads to the conclusion that the initially exerted contact force is still present and that the contact is functional. However, this assumption is often wrong.

The explanation lies in the word "torque": The generally valid relationship between torque and force assumes a movement of the bolt. However, after many years in use, the bolt mechanism stiffens due to soiling, mechanical damage or corrosion – a completely normal process not to be confused with the unrelated permanent elasticity of the connector system. It is in line with the universal standard for connectors, which is "connect it, switch it on and forget about it." In regards to bolts this means that their mobility is not a requirement for permanent contact quality beyond the moment when the initial contact is created. A look at torque measurement reveals: If there is no motion, then the relationship between torque and levered force and the clicking of the torque wrench are of no significance. From a physical point of view, this relationship can only gain importance again if the retarding static friction is overcome. Theoretically, this could be achieved with a significantly higher torque. However, how should this be adjusted when considering that the static friction varies from one bolt to the next?

Furthermore, if the torque is too high, the bolt may suffer damage. Even if the bolt could be moved, there are other factors that affect the relationship of torque and force, such as the initial bolt greasing. These factors can neither be reproduced in on-site testing nor calculated in a manner that allows for reliable conclusions about the residual contact force to be drawn from the torque alone. Regardless of which approach is taken in this process, the conclusion is always the same: Torque measurement is not suitable for assessing contact quality.

On-site testing? With reservations.
Ergo: Aside from the fact that torque measurement per se is unsuitable, the on-site tests shown here have both strengths and weaknesses. If users are aware of them, they can weigh them with respect to measuring methods, room for interpretation and effort involved. While doing so, it is always important to keep in mind: Neither method can determine the remaining service life of a connector in use accurately. This is why it is even more important that only those products are used that have generally proven their suitability for long-term use. Though this may be standard in Europe, it is not necessarily a given in the rest of the world.

Hardness test according to IEC 61238-1
Even though the required contact service life of several decades does not allow for real-time tests, cable connectors can already prove their suitability even before commissioning by passing a type test according to IEC 61238-1. Due to the responsibilities of the standards boards to low and medium voltage, the application of this standard is limited. However, there are users that have all of their connectors tested based on this standard. Though there are special test standards for HV connectors, none of them apply the same high level of strictness to the requirements for the aging resistance of cable connectors.

In the test according to IEC 61238-1 (see Fig. 3 for test set-up), the aging behavior is simulated in accelerated processes by means of 1,000 heating cycles or load cycles. The load exerted in these tests is equivalent to typical operating loads over 40 years or longer.

This approach is based on the Arrhenius equation, which states – put briefly – that high absolute temperatures shorten the service life of contacts. Contact aging is further accelerated by temperature fluctuations caused by load changes as they trigger flow and settling processes (Section 3).

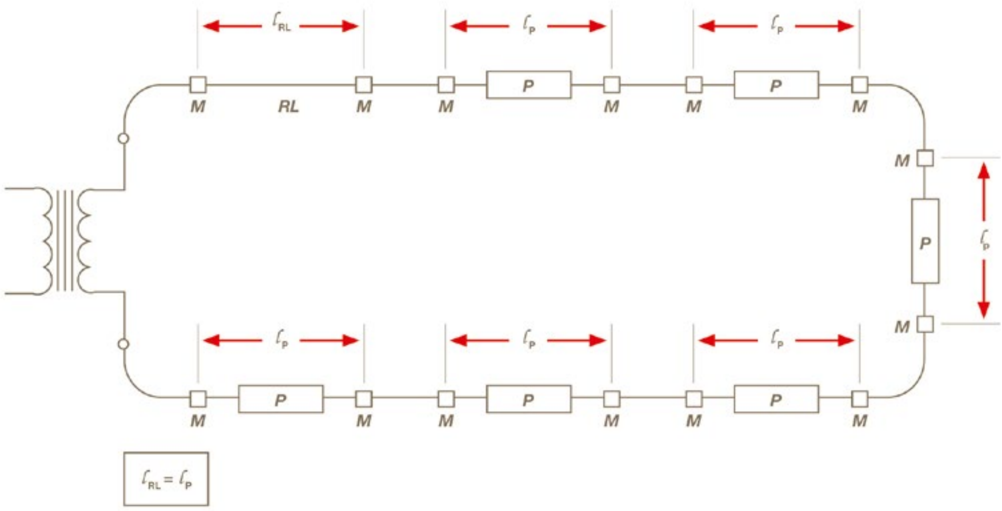


Figure 3: Test circuit set-up in aging test according to IEC 61238-1 with six specimens (P), reference conductor (RL) and measuring points (M).

Both a high absolute temperature and temperature fluctuations are simulated through heat cycle sequences (Fig. 4). Meanwhile the temperatures of the specimens and the reference conductor are measured regularly. According to IEC 61238-1, connector loads must not exceed those of the reference conductor under current. Connector resistances are determined at the same time.

Something that is currently unique in the test according to IEC 61238-1 is that the transverse conductivity of the connected conductors is considered as well. This reflects how well the connector can contact the individual wires in the conductor in all conductor positions, thus ensuring that they have a high level of transverse conductivity. They key factor in assessing connector resistances is resistance factor k. This factor is calculated from the ratio of reference conductor resistance to contact resistance. According to the standard, this value must remain consistent and below 2 for all specimens (Fig. 5).

Type testing depending on type of terminal and application

The aging test of overhead lines and switchgear terminals based on temperature fluctuations is performed in accordance with IEC 61284. Since these terminals are exposed to lower thermal loads due to their bare design and areas of application (Section 5), their test parameters have been adjusted accordingly: Instead of 1000 heating cycles, only 500 are required, while the temperature of the reference conductor must be 70 K above the ambient temperature. In principle, however, the test methods and assessment criteria of IEC 61284 are identical with IEC 61238-1, from which they were derived.

The results of testing according to IEC 61284 confirm a number of basic principles of contact technology, including this one: If an even current flows through a connector which was designed in line with the required principles and installed correctly, the temperature of the connector is always lower than that of the reference conductor. This disproves the widespread misconception that connectors are always hotspots in the network (Fig. 6).

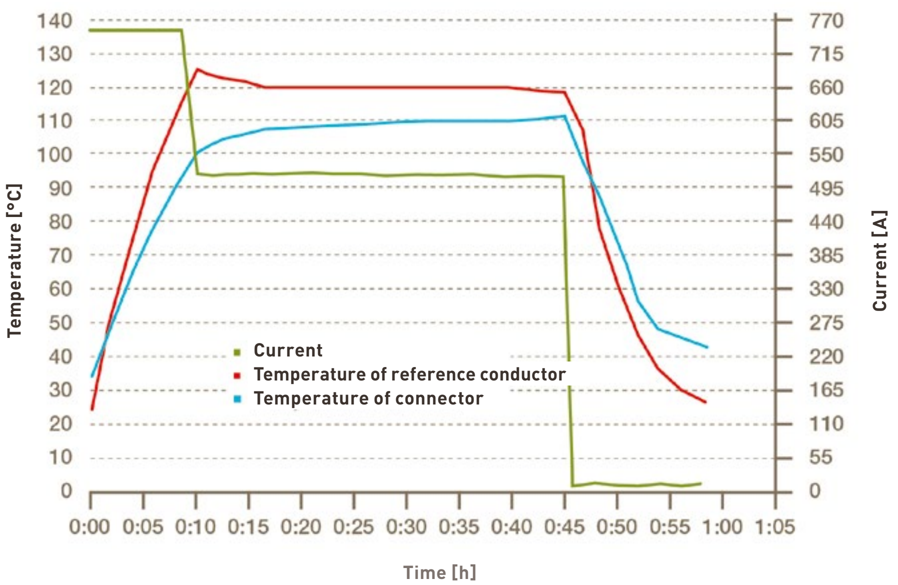


Figure 4: Temperature and current curves during a heating cycle in an aging test according to IEC 61238-1: A heating cycle consists of three phases: In the first phase, the reference conductor is heated to 120 °C. Then the temperature is held at a consistent level for over 30 minutes, and finally the conductor is cooled down to room temperature again. For the test, a total of 1000 of such cycles are performed consecutively. The heating cycle featured here shows the normal temperature behavior of a connector: While under current, its temperature remains below that of the reference conductor.

Resistance factor k in six specimens during an aging test acc. to IEC 61238-1

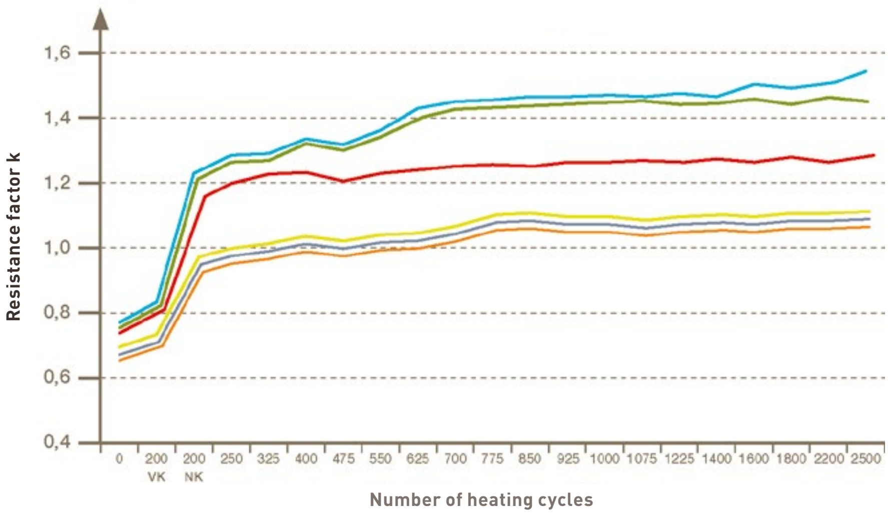


Figure 5: The resistance curves of the six specimens shown here illustrate that their resistance factors remain consistent and below as required by IEC 61238-1, and they do so far beyond the 1000th heating cycle.

Comparison of temperature curves of conductors and connectors

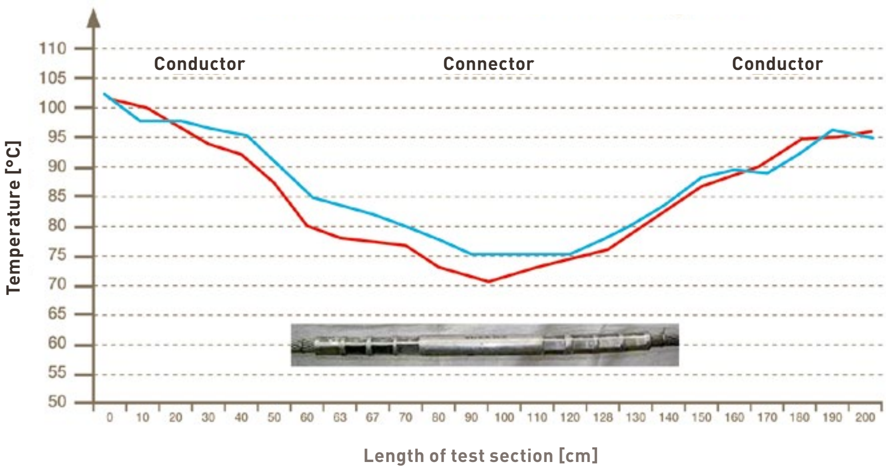


Figure 6: The temperature curves of two connectors and their conductors as recorded in a type test according to IEC 61284 show: If the connector has been designed in line with the required principles and installed correctly, the connector temperature is below that of the conductor, assuming that the flow of current is even. The reason: The parallel connection of conductor cable and connector sleeve ensures that both the conductor and the connector conduct the electricity in the connector area, which allows the flow of current to utilize twice the cross-section. This in turn lowers the resistance. In addition, the overall bigger surface can emit more heat this way.

If the aging tests according to both standards are to provide reproducible results, additional age-accelerating factors at play in real usage scenarios must be excluded. Oxygen, moisture and salt penetrating the contact area, for example, can promote aging (Sections 3 and 4). For this reason additional type testing according to IEC 60068-2-52 (Fig. 7 and 8), geared toward the intended area of application, is recommended for outdoor connectors.

Conclusion: Safety through specification

The highest possible level of safety can be achieved if connector specifications are worded in accordance with these empirical values. Connectors should therefore meet at least the following three design criteria: Defined contact points, sufficient elasticity and contact protection grease (Sections 2 to 4). In addition, connectors should pass type testing in accordance with the above mentioned standards. Fortunately, users are not alone in requesting these standards. A number of manufacturers develop and produce all of their products – not only large components for high voltage applications but also smaller terminals for medium and low voltage contacts – in line with standards and state of the art. This effort pays off. A comparison of investment costs and overall costs over the entire life cycle shows (Fig. 1): If you focus on quality, you end up saving not only effort but also money.

Figure 8: Conductors and connectors after ten weeks of salt resistance testing according to IEC 60068-2-52

Figure 7: Salt resistance test according to IEC 60068-2-52: The specimens (before cyclic salt spray) are positioned in a test chamber with a volume of 3 m³ and then sprayed with a salt water solution (5% NaCl). One test cycle lasts 24 hours (2 h of spraying and 22 h of drying). Meanwhile the specimens are subject to cyclic alternating current loads (I_{on} = 220 A/for 1 h, I_{off} = 0 A/for 2 h).

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