Effect of Connection Design on the Contact Resistance of High Power Overlapping Bolted Joints

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Abstract—**The effect of design changes on the contact resistance of overlapping bolted/pad joints was investigated. It was found that slanting the edges of the bus-bars/pads under 45° and making slots in the overlapping areas significantly reduce the contact resistance of a joint and improve its mechanical integrity. These improvements are results of enlarged contact area and creation of a uniform current distribution at the contact interface.**

Index Terms—**Connector design, contact area, overlapping bolted joints.**

I. INTRODUCTION

THE main function of the sub-station is to provide a point in the electrical system where energy can be tapped from the transmission lines, transformed to lower voltage and directed via busses to switches and circuit breakers for the purpose of either protecting the various circuits in emergencies, or switching circuits according to load, need for maintenance, etc. Furthermore, since the sub-station is at the end of a transmission line, the degree of reliability of the sub-station components should be no less than that which was built into the transmission line itself. Hence, connectors intended for use in substations should be designed in such a way as to assure an uninterrupted service under all operating and environmental conditions. A well-designed and properly installed connector should provide a connection as dependable as the conductors it joins.

Of the many types of connections used in sub-stations components, overlapping bolted joints are the most widely used. They are versatile, dependable, and economical. Among the design parameters required to assure the connector reliability the following are certainly the most important for assuring the connector electrical and mechanical integrities.

Electrical efficiency results, although not always, from design considerations. The contact joint resistance, which, in turn, is a function of the contact area and distribution of the conducting spots in the interface between the contact members, largely determines the connector electrical efficiency. The surface finish and the magnitude of the applied force and manner in which it is applied, generally determine the contact area and distribution of the conducting spots.

Mechanical strength. A well-designed connector should have adequate mechanical strength to maintain its mechanical integrity since under operating conditions it is subjected to the loads imposed by ice, wind, and the expansion and contraction strains arising from the extreme conditions of load cycling and ambient temperature changes. A properly designed and installed connector should withstand the stresses to which the connector is normally subjected during the life of the joint.

Ease of installation is also important, not only because of the economic advantage of reducing installation time, but also for providing a greater assurance that the connector will be installed properly.

Corrosion resistance. Sub-stations are very often built close to large industrial complexes that are often located in the areas in which the atmosphere might be highly corrosive. Hence, in order to maintain the reliable performance, the connector should have the ability to withstand the environmental attacks. This is particularly important in the case wherever aluminum is the conductor, and even more so when aluminum is being joined to copper.

II. FACTORS AFFECTING JOINT PERFORMANCE

A comprehensive review of factors affecting the connector performance and detailed analysis of the degradation mechanisms of power connections is given elsewhere [1]. At this point, it is convenient to consider briefly some of the factors affecting the contact resistance of bolted overlapping connectors as well as design changes used to improve the joint performance and maintain its reliability.

It has been established [2] that real surfaces are not flat but comprise many asperities. Hence, when contact is made between two metals, surface asperities of the contacting members will penetrate the natural oxide and other surface contaminant films, establishing localized metallic contacts and, thus, conducting paths. As the force increases, the number and the area of these small metal-metal contact spots will increase as a result of the rupturing of the oxide film and extrusion of metal through the ruptures. These spots, termed a-spots, are small cold welds providing the only conducting paths for the transfer of electrical current.

The real contact area A_r, often referred to as "conducting contact area", is only a fraction of the apparent contact area A_a, as illustrated in Fig. 1. The relationship between the applied normal load F_c, hardness of the metal H and the apparent contact area A_a is given by

$$F_c = \xi H A a. \tag{1}$$

The hardness H in this expression represents a measure of the ability of a metal to resist deformation due to point loading; ξ is the pressure factor and depends on the amount of deformation of
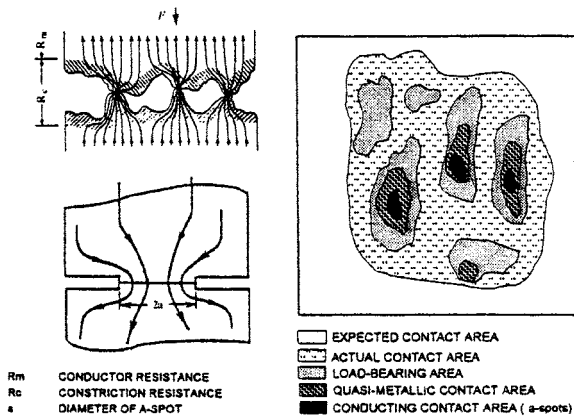
Fig. 1. Schematic of current constriction and real contact surface.

the asperities and is equal to 1 in most practical contact systems. On the other hand, Holm [2] has shown that hardness (H) is related to the yield stress (σ_y) by

$$H = 3\sigma_y. \tag{2}$$

Hence, the conducting contact area will be only a small fraction of the calculated real contact area, generally considered to be much smaller than 1%.

It should be pointed out that the electrical interface of an a-spot is far different from the single circular contact spot. In fact, the true metal-to-metal contact is limited to a cluster of microspots, within the nominal contact spot, where the contacting materials extrude to touch each other through cracks in their oxide film as demonstrated by Williamson in the case of aluminum connections [3]. Current passing across a contact interface is therefore constricted to flow through these a-spots. Hence, the electrical resistance of the contact due to this constricted flow of current is called "constriction resistance" and is related to the basic properties of metals such as hardness and electrical resistivity [2]

$$R_c = \frac{\rho_1 + \rho_2}{4a} \tag{3}$$

where ρ_1 and ρ_2 are resistivities of the contacting metals, a is the radius of the conducting contact area. If the two contacting metals are the same, then the constriction resistance becomes

$$R_c = \frac{\rho}{2a}. \tag{4}$$

Since the metals are not clean, the passage of electric current may be affected by thin oxide, sulfide and other inorganic films usually present on metal surfaces. Hence, the total contact resistance of a joint is a sum of the constriction resistance (R_c) and the resistance of the film (R_f)

$$R = R_c + R_f$$
$$R_f = \frac{\sigma}{\pi a^2} \tag{5}$$

where σ is the resistance per area of the film. Both tunnelling and fritting are considered as operative mechanisms for the cur-
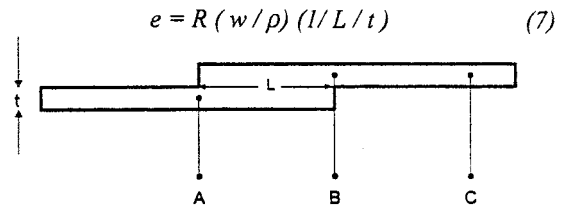
rent transfer across the film. In most practical applications, the contribution of these films to the total contact resistance is of minor importance, since the contact spots are usually created by the mechanical rupture of surface films.

From the above discussion it is clear that electrical paths of current will be fewer and the current will be distributed more uniformly if there are more contact spots. Hence, surface roughness is of great significance, since a rougher surface having many sharp asperities has a greater probability of having many metal-to-metal contacts and also, the ability to penetrate its counterpart at much lower loads than a smooth surface with a consequently larger current-carrying area. Consequently, contact surfaces finished with rough abrading will have appreciably lower contact resistance than those smoothly machined [4]–[6].

From these rather elementary considerations, it is clear that one of the most important requirements for good connector performance is for the real area of contact to be sufficiently large so that even with initial and long-term deterioration, a reserve of contact area is still available to prevent overheating conditions in the joint. Unfortunately, present knowledge and understanding of various aspects relating to the failure mechanisms of electrical contacts are insufficient to assess with any degree of accuracy just how large the true area of contact should be in any given type of joint.

In the case of a bolted overlapping joint, it has been shown that current lines are distorted at the joints as a result of which, the resistance of even a perfectly made overlapping joint (no interface resistance) is higher than that of a bar of the same length as the joint. This is known as "streamline effect" and is determined by the ratio between the overlap and busbar thickness.

Fig. 2 illustrates a thin strip busbar of uniform width (w), and thickness (t). Thus the strip is shaped like an overlapping joint but is void of contact surfaces along AB, except through the part of its length AB where the thickness is $2t$. A current (I) is passed through the busbar from end to end. The voltage drop is measured between A and B, and between B and C whereby distance $AB = BC$. Hence

$$V_{AB} = RI \text{ and } V_{BC} = R_B I$$
$$e = \frac{V_{AB}}{V_{BC}} = \frac{R}{R_B} \tag{6}$$

where e is the streamline effect, R is the total resistance of a joint and R_B is resistance of equal length of a busbar and is given as

$$R_B = \rho \left(\frac{L}{wt} \right). \tag{7}$$

$$e = R\,(w/\rho)\,(1/L/t) \tag{7}$$

Fig. 2. Schematic of an overlapping joint without contact interface.
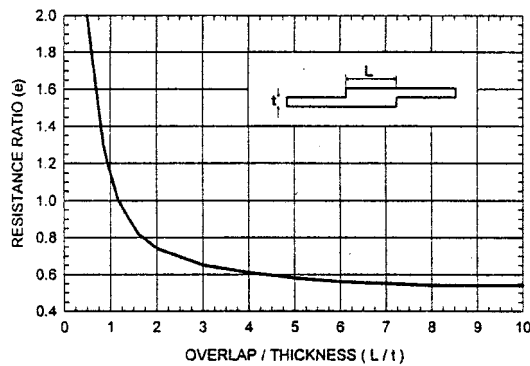
Fig. 3. Effect of current distortion ("streamline effect") on the contact resistance of an overlapping joint.

Hence, the streamline effect e becomes a function of the ratio L/t, i.e.

$$e = R\left(\frac{w}{\rho}\right)\left(\frac{1}{\left(\frac{L}{t}\right)}\right). \qquad (8)$$

Melsom and Booth [7] have tested a number of different busbar combinations and obtained the results shown in Fig. 3 which allows to calculate the resistance caused by the streamline effect of a perfectly made overlap in relation to the resistance of an equal length of a single busbar. From this figure it appears that the streamline effect rapidly decreases until the overlap/thickness ratio reaches a value of 2 when its decrease is slowed down and practically stabilized upon passing a value of 6. In other words, upon reaching this value, the current distortion is minimized and the current lines become parallels. Consequently, the optimal overlap length in a bolted joint should be 5–7 times the busbar thickness.

However, to meet all requirements, and for the sake of convenience, it is common practice to make overlaps equal to the width of the bus bar. Although this procedure is usually satisfactory for busbars of ordinary dimensions, it may not provide sufficient joint contact area on busbars that have a high thickness-to-width ratio. Hence, as a rule of thumb, the minimum overlap should be from 8 to 10 times the bar thickness. Furthermore, since the actual area of contact is much less than the total area of overlap, the determination of overlap on the basis of the width alone is reasonably safe practice only if the current density in the contact surface does not exceed 1/3 to 1/4 of the current density in the busbar cross section.

Donatti [8] has studied extensively bolted overlapping joints and found that the current tends to traverse the contact surface at the end points of the joint while the passage of current in the intermediate region is minimal. It was also shown that when the two conductors of substantially different resistance values are in contact, the current will pass across the contact interface almost exclusively at the end of the better conductor, the remaining contact interface being almost inactive.

Consequently, to reduce current density in the joints, it is useless to increase the contact surface by extending its length, since this does not change the current distribution to an appreciable extent. Rather, increasing the width of the contact surface was found to be more beneficial.
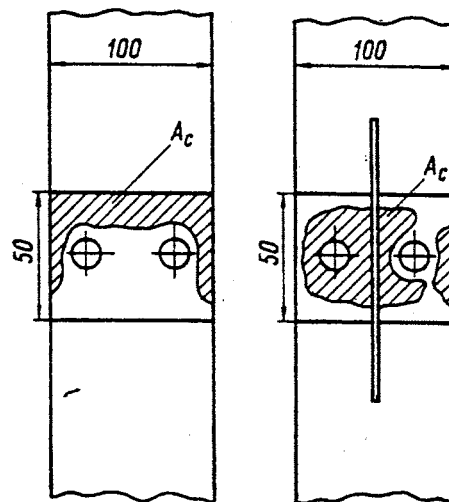

Fig. 4. Effect of making a slot in the overlapping busbar joint. The contact area of a joint with slots (B) is 1–5 to 1.7 times larger than that without slots (A).
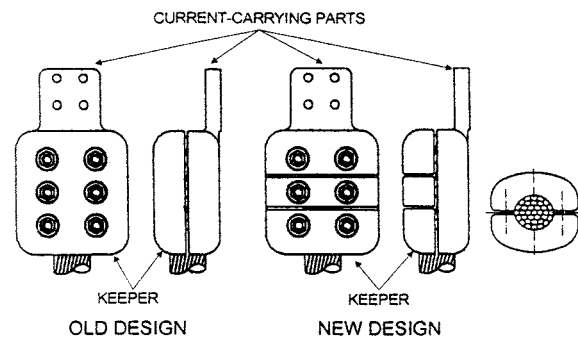

Fig. 5. Typical high voltage (>700 kV) power connectors.

Boychenko and Dzektster [9] have shown that changing the connection design can equally be effective in increasing the contact area. In other words, cutting slots in the bus-bar in a manner as shown in Fig. 4, the actual surface area of a joint can be increased by 1.5 to 1.7 times of that without slots. The contact resistance of a joint configuration with slots (B) is 30–40% lower than that of (A) and is mechanically and electrically more stable when subjected to current cycling test (Fig. 4). The beneficial effect of sectioning the bus-bar is attributed to a uniform contact pressure distribution under the bolt, which, in turn, creates a larger contact area.

Fig. 5 depicts typical high voltage (>700 kV) power connectors used for connections of stranded 4000 MCM conductors and for connecting a variety of power equipment at the sub-station site. These connectors are made of two parts: keeper and current-carrying member comprised of a grooved section and flat end (pad, tongue). The conductor is secured in the groves by either high-strength aluminum (7075 grade) or steel bolts. Keeper and current-carrying part are made of cast or wrought aluminum.

In the case of an old connector design, the keeper is made of a solid block of cast aluminum while in the new connector design; the keeper is sectioned into three segments. Numerous report from the field showed that in the old connector design, contact resistance between the current-carrying part and conductor was unstable that often lead to unacceptable overheating
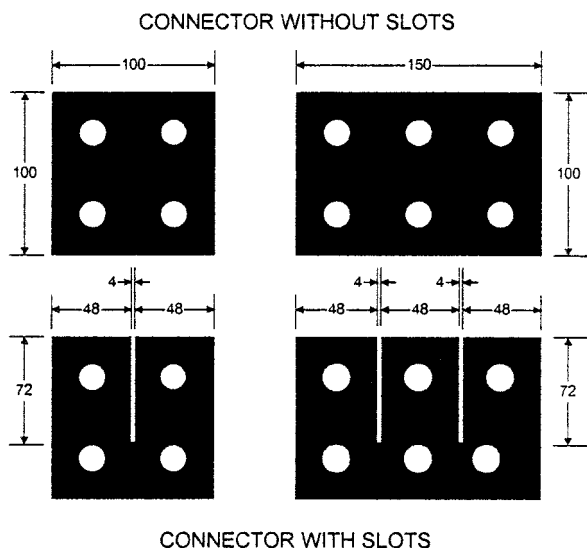
CONNECTOR WITHOUT SLOTS

CONNECTOR WITH SLOTS

Fig. 6. Schematic of the contact surfaces of the connector current-carrying pads without and with slots. Bolt-hole diameter is 13.2 mm for the 12.7 mm diameter bolts. All dimensions are in mm.

Fig. 7. Schematic of the bolted joint configurations and positioning of the voltage probe leads for the contact resistance measurements.

of the joint as a whole. This was associated with the inability of a relatively large and rigid keeper to maintain a good contact between the conductor and current-carrying part of a connector. Sectioning the keeper mitigated the problem and significantly improved both mechanical and electrical stabilities of a joint. Beneficial effect of sectioning was associated with a more uniform stress distribution between the keeper and conductor that assured a larger contact area at the conductor-connector current carrying interface.

It is rather surprising that no attention was given to the flat section of the current-carrying part (pad, tongue) since its rigidity, surface finish and misalignment when bolted to another rigid pad, is often a cause of impaired current transfer and thus higher contact resistance. Hence, it is the objective of this work to determine as to whether further improvement for this type of power connection can be realized by modifying the design and surface finish of current-carrying pad (tongue).

III. EXPERIMENTAL DETAILS

A. Connectors

The connectors used in this work were of the new design, that is, with sectioned keeper part, whose current-carrying pads had four- and six-bolt hole. The connectors used were with intact current-carrying pads (no slots) and with pads modified by cutting slots 4 mm wide and 72 mm long as seen in Fig. 6. The thickness of the connector pads was 25 mm. The connectors were made of 356 grade aluminum with typical electrical resistivity value of 50 nΩm. The busbars were made of the same grade aluminum.

B. Contact Resistance Measurements

Series of contact resistance measurements were carried out on the overlapping joints between the connector pads and busbars of the same material and dimensions. The joint configuration consisted of steel bo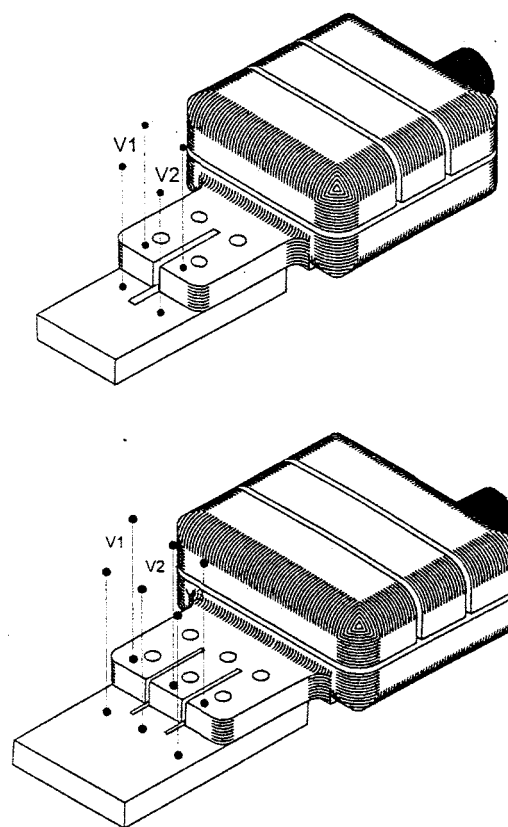lt and thick flat washers and high-spring constant Belleville (disc-spring) washers. In order to maintain elasticity of the joint, flat and Belleville washers were placed on both side of the overlapping bolted joint [10].

Thick flat washers (3–4 mm thick) were used to avoid possible buckling that might be provoked by the forces generated by edges of Belleville washer. The flat washer diameter was 1.4 times larger than that of Belleville washer. Such a large flat washer was used to provide and maintain a more uniform stress distribution under the washers. The tightening torques was 60 Nm.

The contact resistance was derived from the voltage drop measured between the potential leads positioned on the connector pads and busbars as shown in Fig. 7. Although this figure depicts only the positioning of the voltage drop leads for the connectors with slots, the same arrangement was used for the connectors without slots. The current applied across the connector pad-busbar joint was 150 A dc. The voltage drop was measured using HP3442 data logger whose output was transferred to HP7451 microprocessor for computer processing. The voltage drop was measured every 20 s over a period of 1 h.

The voltage drop leads consisted of multi-strand, fine-gauge wire cords welded to the spring-loaded, gold-plated pins. The pins were inserted into small holes drilled into the connector pad and busbar about 10 mm from the edge of the connector pad. Hence, the total spacing between the potential leads at all measuring locations was about 45 mm. The resistance derived from the voltage drop measurement across this spacing can be considered as a measure of the true contact resistance between the

connector pad and busbar since the bulk contributions arising from the connector pad and busbar are essentially insignificant. An estimate of the bulk contributions to the overall resistance measured across the busbar-pad contact was approximately 0.1 $\mu\Omega$. The resolution of the voltage measuring system was about 1 μV, leading to a resistance resolution of 0.01 $\mu\Omega$. This resolution was sufficient to detect small resistance changes associated with the connector resistance arising from different surface preparation and connector configuration.

Each reported resistance value is the average of the two and three readings made across the contacting members of the four and six bolts connectors respectively. The contact resistance measurements were carried out on the connector-pad/busbar combinations whose contacting surfaces were given different surface finish: as received, brushed, brushed and lubricated, machined, machined and lubricated. These tests were repeated three times always using new connectors and busbars. The reproducibility of the results obtained was in the range 5–10%.

C. Surface Preparation

The contacting surfaces of the connectors and busbars intended for the contact resistance measurements were first degreased by wiping these with the cotton swabs soaked in a 50/50 mixture of freon and methanol and then roughened using two surface preparation methods.

In the first, roughening of the surface was achieved with a stainless steel brush that had 7 mm trimout and density of 100 wires/cm^2. The wires were bent in the middle thus allowing brushing in one direction only Abraded contact surfaces were cleaned by wiping them with cotton swabs soaked in a freon/methanol mixture and then brought into contact and joint assembled.

When lubricant was used, the abrasion was done through the thin layer of compound (grease) spread over the contact surfaces. The contaminated compound was not removed but was left on the contact surfaces. The so-prepared contacting surfaces were then brought into contact and joint assembled. The compound used for this purpose was Penetrox A-13 [9]–[11].

The other method involved machining of the contact surfaces on a milling machine. The spacing between the teeth was 1 mm. The machined surfaces were then wiped with swabs soaked in mixture freon/methanol, brought into contact and joint assembled. For the lubricated combinations, a thin layer of compound was spread over the machined surfaces that were then brought into contact and joint assembled.

IV. RESULTS

The results of contact resistance measurements are shown in Figs. 8–13. These figures depict the evolution of the contact resistance as function of elapsed time, approximately 60 min. The results of the contact resistance measurement are also summarized inTable I showing the joint contact resistance of connectors with four-bolt and six-bolt joint configuration with and without slots and different surface finish. The contact resistance values listed in Table I are the mean values of all the readings taken over a period of 1 h.
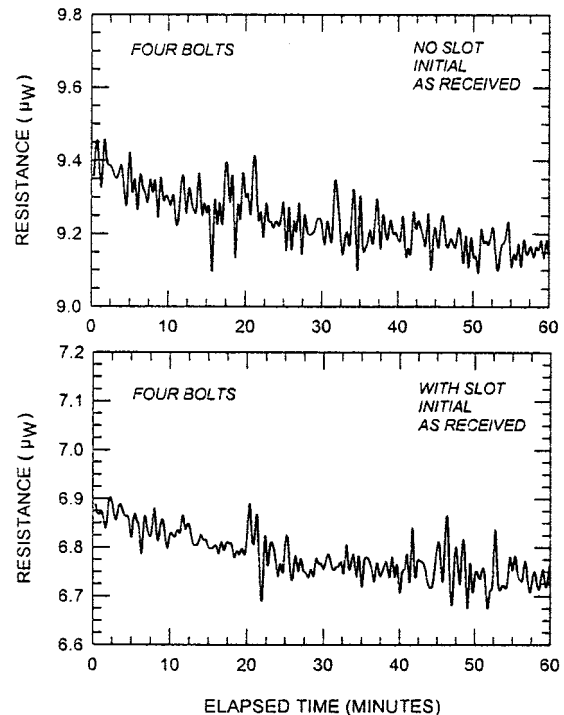

Fig. 8. Evolution of contact resistance with time of a four-bolt connector pad-busbar joint without and with slots. Surface finish: as received.
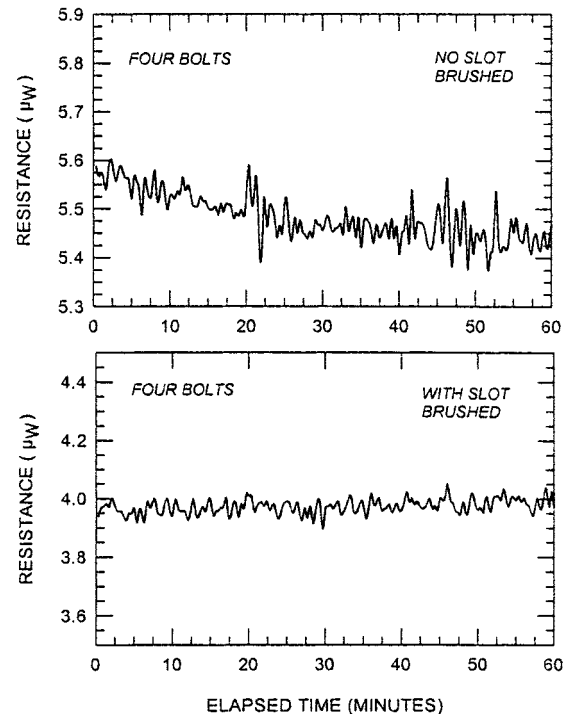

Fig. 9. Evolution of contact resistance with time of a four-bolt connector pad-busbar joint without and with slots. Surface finish: Brushed.

From the results shown in Figs. 8–13 and Table I, two important features characterize the contact resistance behavior. The primary feature is that sectioning, that is cutting the slots into the connector current carrying parts (pads), result in a very pronounced decrease in the contact resistance. In the case of four-bolt joint configuration, the contact resistance is
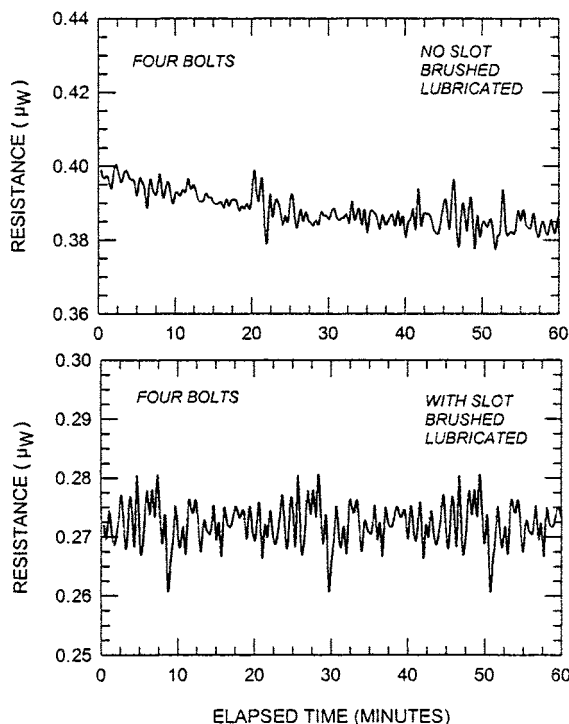
Fig. 10. Evolution of contact resistance with time of a four-bolt connector pad-busbar joint without and with slots. Surface finish: Brushed + Lubricated.
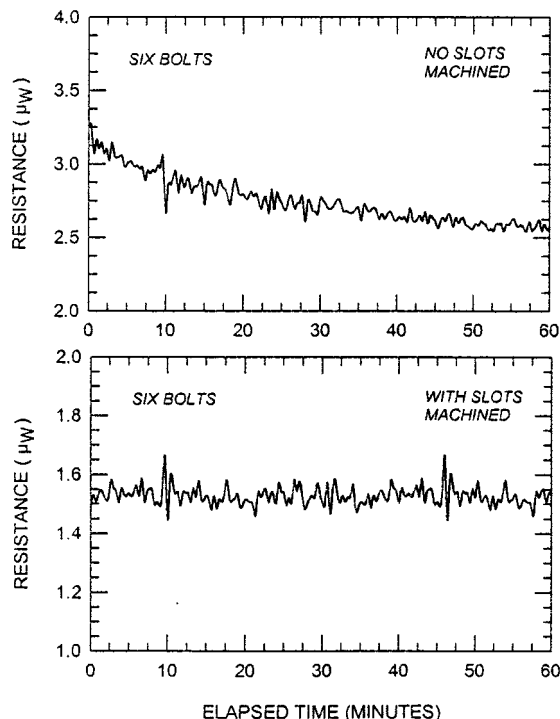

Fig. 12. Evolution of contact resistance with time of a six-bolt connector pad-busbar joint without and with slots. Surface finish: Machined.
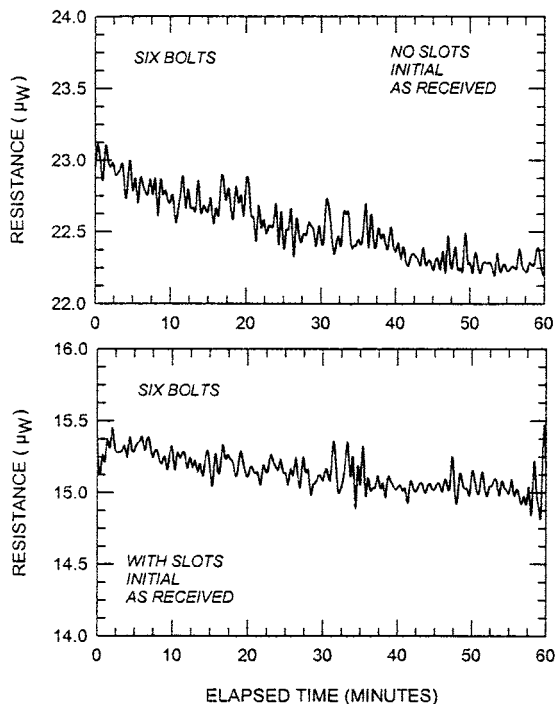

Fig. 11. Evolution of contact resistance with time of a six-bolt connector pad-busbar joint without and with slots. Surface finish: as received.
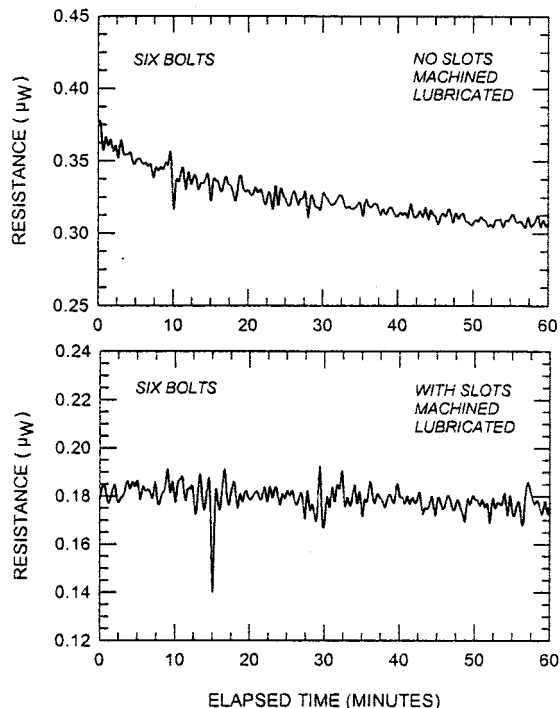

Fig. 13. Evolution of contact resistance with time of a six-bolt connector pad-busbar joint without and with slots. Surface finish: Machined + Lubricated.

decreased by 25–30% while in the six-bolt joint configuration this decrease is in the range 30–45%.

The second feature is that surface preparation has equally an important effect as the sectioning of the current-carrying parts. It appears that the best result, meaning the lowest contact resistance, was obtained when the surfaces were machined and lubri-

cated. The worst case was when the contact surface was not given any surface treatment. However, even in this case, sectioning of the pads had a beneficial effect since the contact resistance of the connectors with slots was 30–50% lower than that without slots.

An interesting feature of the results shown is that the contact resistance of connectors without slots and irrespective of surface

TABLE I
MEAN VALUES OF JOINT CONTACT RESISTANCE OF CONNECTORS WITH
FOUR- AND SIX-BOLT CONFIGURATION. R_s-CONTACT RESISTANCE OF
CONTACTING MEMBERS WITH SLOTS n. R_{ns}-CONTACT RESISTANCE
OF CONTACTING MEMBERS WITHOUT SLOTS

FOUR-BOLT CONFIGURATION

SURFACE FINISH	NO SLOTS	WITH SLOTS	R_s / R_{ns}
As received	9.19	6.70	0.73
Brushed	5.48	3.97	0.72
Brushed + Lubricated	0.39	0.27	0.69

SIX-BOLT CONFIGURATION

	NO SLOTS	WITH SLOTS	R_s / R_{ns}
As received	22.52	15.20	0.68
Machined	2.74	1.55	0.56
Machined + Lubricated	0.32	0.18	0.56

finish shows tendency to decrease with time (elapsed time) and become stable after approximately 40–50 min. Such behavior was not observed in the connectors whose current-carrying parts (pads) were sectioned, i.e., with slots. Their contact resistance remained stable from the beginning until the end of measurements. Some plausible explanations for the observed difference will be given in Section V.

V. DISCUSSION

The results clearly show that sectioning, that is cutting the slots into the connector current-carrying parts (pads), results in a considerable improvement of the joint contact resistance. Depending on the surface preparation, the presence of slots in the pads can decrease the contact resistance by 30–50% as compared to that without slots. Although a detailed mechanism responsible for the observed effect is beyond the scope of this work, the results are sufficiently consistent to invoke a basic model to account for the beneficial effect of connector pad sectioning.

When two rigid busbars are pressed together, the contact between the mating surfaces will be made where the asperities on these surfaces meet thus forming discrete metal-to-metal spots where the current can flow across the interface. However, not all the spots in contact will be electrically conducting because of the presence of oxide films that is, in the case of aluminum connections, very tenacious and highly insulating.

Furthermore, since the busbars are very rigid and with surfaces that are neither perfectly flat nor parallel, a significant misalignment between the contacting surfaces will take place when the joint is made. As a result, some areas in the contact zones will be under high pressure and plastically deformed while the others will be still elastic or not in contact at all. A direct consequence of this situation is a smaller load-bearing area and thus a smaller number of conducting spots.

On the other hand, sectioning the connector current-carrying parts (pads) will create segments less rigid that will considerably reduce misalignment. Hence, when the sectioned current carrying parts are bolted, a larger load-bearing area and a more uniform stress distribution over the entire contact interface of the sectioned overlapping joint will be created. This, in turn,

will increase the number of conducting spots and thus lower the contact resistance.

In addition, sectioned current-carrying parts will make these not only electrically more stable, but also their mechanical integrity will be greatly improved due to a more uniform stress distribution under the bolts in the sectioned segments. The results of contact resistance measurements shown in Figs. 8–13 clearly demonstrate that this is, indeed, the case. However, in the bus-bars without slots, this feature was not observed. Instead, contact resistance initially decreases with a tendency of attaining a stable value after a certain time of resistance measurement had elapsed.

This behavior can be understood in terms of the dynamics of conducting spots formation. In other words, due to a nonuniform stress distribution at the contact interface caused by the bus-bar misalignment, some contact spots will be under high stress and yielding whereas the others will barely touch each other.

However, as the plastically deformed spots yield and creep, the pressure in the zones where the asperities are barely in contact will increase the asperities will rupture the oxide film and establish new conducting Spots, thus creating larger load-bearing areas and lower contact resistance. The mere fact that the contact resistance showed tendency of reaching a stable value indicates that this process will proceed until sufficient load-bearing area is created to support the applied load.

It is also interesting to note, that this behavior was observed in all connector configurations without slots irrespective of the surface finish. Hence, it appears that this type of behavior may, indeed, be characteristic of the overlapping bolted joints without slots and, most likely, due to the misalignment of the contacting surfaces.

The results of this study showed that surface preparation plays a very important role in the performance of the overlapping bolted joints. The significance and effect of surface preparation and lubrication on the contact resistance was studied and reported elsewhere [4], [10]–[12] and will not be addressed here. However, for the profound and immediate impact exerted by lubrication on the contact resistance some plausible explanations are warranted.

One possibility is that as the connection is assembled, the lubricant alleviates sliding and rotation of the surfaces (due to torsional action of the bolts) and thus more effective shearing of the oxide film on the aluminum surfaces [4]. Another possibility is that metallic additives in the lubricant used (zinc-oxide) break up the oxide film and thus increasing the metal-to-metal contacts that, in turn, results in a lower contact resistance.

It is also worth noting that machined contact surfaces showed superior performance as compared to the brushed ones as manifested by considerably lower contact resistance values. This can be attributed to a distinct distribution of the serrations having uniform height and width and thus, a more controllable load-bearing and current-conducting area (real contact area).

To estimate the size of contact zone where conduction takes place, this zone can be envisaged as a large circular composite area comprising several discrete small areas (a-spots) with composite electrical resistance R_c given as

$$R_c = \frac{\rho}{2a} \tag{9}$$

TABLE II
CALCULATED VALUES FOR COMPOSITE RADIUS (a_c) OF COMPOSITE
CONTACT AREA (A_c)

FOUR-BOLT CONFIGURATION

SURFACE FINISH	NO SLOTS		WITH SLOTS	
	a_c	A_c	a_c	A_c
As received	0.27	0.23	0.37	0.43
Brushed	0.46	0.66	0.63	1.25
Brushed + Lubricated	6.29	124.21	8.85	245.92

SIX-BOLT CONFUGURATION

As received	0.11	0.04	0.16	0.08
Machined	0.91	2.60	1.61	8.14
Machined + Lubricated	7.72	187.14	13.89	605.81

TABLE III
RATIO BETWEEN THE REAL CONTACT AREA (A_c) AND EXPECTED
AREA (A_e) $(A_c/A_e$ IN %)

FOUR-BOLT CONFIGURATION

SURFACE FINISH	NO SLOTS		WITH SLOTS	
	A_c	A_c/A_e	A_c	A_c/A_e
As received	0.23	0.0023	0.43	0.0043
Brushed	0.66	0.0066	1.25	0.0125
Brushed + Lubricated	124.21	0.0124	245.92	0.0245

SIX-BOLT CONFUGURATION

As received	0.04	0.0003	0.08	0.0005
Machined	2.60	0.0173	8.14	0.0543
Machined + Lubricated	187.14	1.2476	605.81	4.0387

where ρ is the bulk resistivity of connector aluminum alloy and a, is the composite radius. Hence, using the resistivity value $\rho = 50$ nΩm typical for the aluminum commonly used for this type of connectors, the composite radius a, and real conducting area A_c, can be calculated from

$$a_c = \frac{\rho}{2R}$$
$$A_c = a_c^2 \pi . f. \tag{10}$$

The results of calculation are shown in Table II. The dimensions of the composite radius are in mm and of composite contact area in mm^2.

From the results shown in Table II it is clear that sectioning the overlapping bolted joints combined with machining and lubricating the contact surface assured the lowest contact resistance and a very pronounced enlargement of the actual conducting area. This feature becomes even more evident from Table III depicting the ratio of the real conducting area (A_c) vs expected contact area (A_e) (See Fig. 6). The ratio values are given in (%).

The results shown in Table III confirm the well-known fact that the actual size of the area where conducting occurs is, indeed, very small, considerably less than 1%. As it can be seen, even with the most effective means of enlarging the contact area that is sectioning the current- carrying parts, the maximum gain achieved is only 4%.

On the other hand, it is also obvious that connectors whose current-carrying parts (pads) were not given any surface treat-ment nor were sectioned, had extremely small conducting area and, thus, highest contact resistance.

In summary, it can be stated that relatively minor changes in the design of high-power connectors, can bring significant improvement in their performance and stability both electrical and mechanical. In view of the wide use of overlapping bolted joints in the sub-stations and on the network as a whole, design changes, as described in this work, should be given more atten-tion in the search for reliable electrical connections.

VI. CONCLUSION

1) Results of contact resistance measurements show clearly that the electrical and mechanical integrities of bolted high-power connectors can be significantly improved by sectioning, that is cutting the slots into their current-car-rying parts (pads).

2) Sectioning the current-carrying parts, combined with machining and lubricating, produced the best results as manifested by significant enlargement of the contact con-ducting areas and considerably lower contact resistance.

3) The observed improvement was associated with a more uniform stress distribution under the bolts in the sectioned joint segments and significantly lower tendency to mis-alignment.

4) It is confirmed that surface preparation, such as brushing or machining, combined with lubrication, is a very effec-tive method of achieving low-resistance joints.

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