Bolted Busbar Connections with Particularly Slotted Bolt Holes

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Abstract **– The paper discusses how introducing particularly slotted bolt holes in bolted busbar connections could increase significantly the true contact area and reduce the contact resistance. The profile presented has 4 slots with circular holes at the ends. The slots are 3mm long and lie on mutually perpendicular axes, rotated at an angle of 45 degrees in relation to the busbar axes. This hole shape is compared with the classical one of bolted busbar connections by the help of several computer models. It has been established that the new shape case leads to a considerable increase in the contact pressure and penetration in the contact area between the busbars.**

Keywords **– bolted busbar connections, new hole shape, contact resistance, contact pressure, contact penetration**

I. Introduction

The boost to transmission and distribution lines loading is due primarily to the amplified consumption of electrical energy worldwide. This explains the elevated reliability and service requirements of high power connections in the power-utility industry. The fundamentals to reliable bare overhead high-power line connections design are given in [1] and include: maximization of true area of electrical contact, optimization of frictional forces, minimization of creep and stress relaxation, minimization of fretting and galvanic corrosion, minimization of differential thermal expansion along and normal to interfaces. Summarizing the major criteria, it is worthwhile to note that all of them can be met simultaneously if an outline could achieve a sufficiently large contact load and metal-to-metal contact area (increased number and area of α-spots) as well as sufficient elastic energy storage in the connection so as to maintain acceptable load intensity throughout the connection service life.

THE OBJECTIVE of this study is to analyze the influence that four bolt hole slots with circular ends exert on the busbars contact penetration and pressure, when the slots are arranged in pairs on mutually perpendicular axes, rotated at an angle of 45 degrees in relation to the busbar axes.

II. Theoretical Background

All joint surfaces are rough and their surface topography shows summits and valleys. Thus under the joint force F two joint surfaces get into mechanical contact only at their surface summits. Electrical current lines are highly constricted at the contact spots when passing through, as presented schematically in Fig. 1a. This constriction amplifies the electric flow resistance and hence the power loss. Obviously, the more the contact spots, the smaller the power loss at the interface of the conductors. Power connections with superior performance are designed to maximize both the number and the life of the contact spots

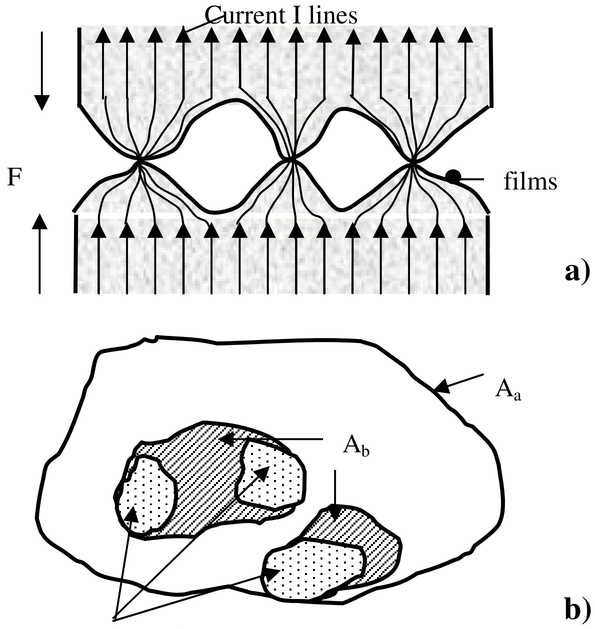

Fig. 1. a) Contact interface and the constricted current lines; b) Apparent contact area A_a, bearing area A_b with quasimetallic contact zones and α-spots

Hence the load bearing area A_b in an electric joint measures only a fraction of the overlapping, the so called apparent area A_a. Metal surfaces, e.g. those of copper conductors, are often covered with oxide or other insulating layers. As a result the load bearing area A_b may enclose regions that do not contribute to the current flow. So a fraction of A_b may have metallic or quasimetallic contact and the real electric contact area A_c, i.e. the conducting area, could be smaller than the load bearing area A_b (Fig. 1b) [2].

A conducting area is referred to as quasimetallic when it is covered with a thin (< 20 Å) film that can be tunneled through by electrons. This quasimetallic electric contact results in a relatively small film resistance R_F.

The summits of the two electric joint surfaces, being in metallic or quasi-metallic contact, form the so called α-spots where the current lines bundle together causing the constriction resistance R_c. The number n, the shape and the

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area of the α-spots are generally stochastic and depend on the material parameters of the conductor, the topography of the joint surfaces and the joint force. For simplicity it is often assumed that the α-spots are circular. Looking at one such spot, its constriction resistance R_c depends on its radius *a* and the resistivity ρ of the conductor material. Under the assumption that the bulk material above and under the α-spot is infinite in volume, the value of the constriction resistance can be calculated by means of the Holm´s ellipsoid model

$$R_c = \frac{\rho}{2a} \tag{1}$$

If a single α-spot is completely covered with a thin film, of resistivity ρ_f and thickness *s,* its film resistance R_f is given by

$$R_f = \frac{\rho_f s}{\pi a^2} = \frac{\sigma_f}{\pi a^2} \tag{2}$$

where σ_f is the tunnel resistivity i.e. the resistance of the film across one cm².

The total resistance R_1 of an α-spot, referred to as contact resistance, results in the sum of the constriction resistance R_c and the film resistance R_f

$$R_1 = R_c + R_f \tag{3}$$

III. Modeling the Bolted Busbar Connection

If the deeper contact penetration increases α-spots both in numbers and dimensions, which in turn expands the true contact area and decreases contact resistance, then a new hole-shape could be introduced for this connection. A typical bolted busbar connection is shown in Fig. 2.

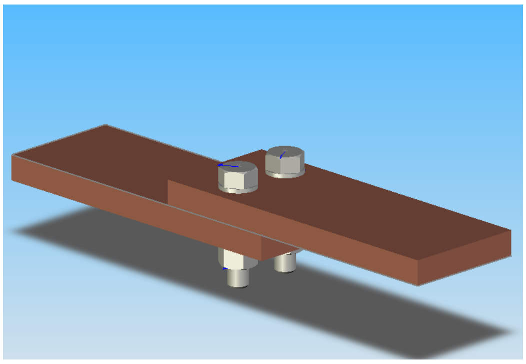

Fig. 2. A bolted busbar connection

The profile scheme of small circular holes at the slot ends arises from [3]. This new case is modeled and compared with the classical one in [4].

For that purpose there have been investigated 11 different models. The first one is a classical one of two copper busbars with 2 bolts (case 1). The next cases introduce the new concept where all bolt holes have four slots, of length 3mm arranged in such a way that the pairs of slots lie on mutually perpendicular axes that are rotated at an angle of 45 degrees in relation to the busbar axes. The slots end with small circular holes. This new shape form is presented in Fig. 3.

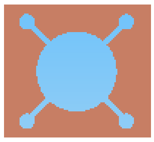

Fig. 3. New hole shape for bolts in bolted busbar connections

Table I describes the 11 investigated cases of different slot width and radius of the small circular holes.

Table I Investigated cases

Case No	1	2	3	4	5	6	7	8	9	10	11
Slot width, mm	0	0.3	0.3	0.3	0.3	0.5	0.5	0.5	0.7	0.7	1.0
Radius of the small hole, mm	0	0.3	0.5	0.7	1.0	0..5	0.7	1.0	0.7	1.0	1.0

This is suggested to decrease radial loadings on bolts that emerge after the connection is assembled, increase the contact penetration in the busbars near the bolts area and maximize the true area of metal to metal contact at the electrical interface.

Copper busbars (Young's modulus E = $1.1.10^{11}$Pa, Poisson's ratio μ = 0.34, width 60mm, height 10mm, length 160mm, busbars' overlap 60mm) are investigated. The connection has 2 holes of ∅10.5mm.

Fasteners: bolts – Hex Bolt Grade B_ISO 4015 – M10 x 40 x 40 – N, steel E = 2.10^{11}Pa, μ = 0.3; nuts – Hex Nut Style1 Grade AB_ISO 4032 – M10 – W – N, steel E = 2.10^{11}Pa, μ = 0.3; washers – Plain Washer Small Grade A_ISO 7092 – 10, steel E = 2.10^{11}Pa, μ = 0.3. Tension in each bolt F = 15000N.

Models for the contact pressure and penetration in the electrical interface between busbars are obtained using the software package ANSYS Workbench 9.

The aspect of model meshing is distinguished as a key phase for proper analysis of the problem. This is because on the one hand it is an established certainty that the reason for the good quality of physical space triangulation is closely related to the consistent mapping between parametric and physical space. On the other hand a properly meshed model will present a fairly close-to-reality detailed picture of stress distributions which is a hard task for analytical solution and is usually an averaged value. It is evident from Fig.4 and Fig.5, for the uneven allocation of pressure and penetration, that the slotted cases bring even more complexities.

The meshed model incorporates the following elements: 10-Node Quadratic Tetrahedron, 20-Node Quadratic Hexahedron and 20-Node Quadratic Wedge. Contacts are meshed with Quadratic Quadrilateral (or Triangular) Contact and Target elements.

The 10-Node Quadratic Tetrahedron element is the basic mesh constituent. It is defined by 10 nodes with corresponding *x*, *y* and *z* translations and is recognized as well suited to mesh irregular geometries especially the ones produced by CAD systems like Solid Works, the CAD-system employed here.

The 20-Node Quadratic Hexahedron and Wedge type elements are used for meshing the washers. Like the previously described element, this one possesses the same features but offers 20 nodes that allow any spatial orientation. It is assumed that using it to mesh the washers guarantees full transfer of washer deformations and loading to the busbars, the primary researched target.

In order to represent contacting and sliding between the 3-D surfaces, the Quadratic Quadrilateral (or Triangular) contact element is applied. With an 8-node surface-to-surface contact capability and taking the same parameters as the solid element to which it is connected, this contact element is given the presumed behavior and friction of the contact region. Busbars are selected to be in a bonded type contact so as not to overload the hardware with calculations and at the same time ensure a theoretically full area contact with no initial penetrations. In such a way the study could search for the percent enlargement of the busbar contact area with higher penetration and compare this value for the new slotted cases with the one for the classical not slotted case.

The Quadratic Quadrilateral (or Triangular) target segment element associates with the corresponding contact element and is used due to the 3-D behavior it offers.

Fig. 4 shows contact pressure for case 2. It is obvious that the pressure in the area surrounding the slots is increased significantly.

Contact penetration for case 10 is presented in Fig.5. The 4 particularly slotted bolt holes provide the extended high penetration zone that covers the area around the hole between the slots.

The eleven cases have been evaluated by comparing the max values of pressure and penetration for each one of them as well as the percent participation of the 8 zones according to the legends. With that end in view, all zones are set to have equal upper and lower limits. The zones of the highest pressure or penetration are set to equal lower limits while the max values define their upper limits. This comparison procedure is performed by the help of the Adobe Photoshop software, where each colored zone is identified with a certain number of pixels. The results obtained are summarized in Table II and Table III.

TABLE II CONTACT PRESSURE RESULTS

Case No	p_{max}, MPa	3.02 - 8.14, %	8.14 - 13.26, %	13.26 - 18.38, %	18.38 -23.5, %	23.5 - 28.62, %	28.62 - 33.74, %	33.74 - 38.86, %	>38.86, %
1.	43.99	21.82	15.39	13.46	11.18	12.24	12.66	11.08	2.17
2.	55.01	21.89	15.59	13.39	10.02	8.96	8.62	7.98	13.55
3.	74.3	19.89	13.94	11.88	10.12	8.36	6.58	5.54	23.69
4.	74.06	20.92	14.52	11.37	8.9	8.24	6.28	6.03	23.74
5.	71.22	19.24	12.85	11.44	10.27	8.13	6.66	6.27	25.14
6.	85.71	21.56	14.83	12.98	9.17	7.98	7.94	6.5	19.04
7.	87.04	19.25	12.22	10.68	9.84	8.64	7.11	6.47	25.79
8.	74.38	18.321	12.81	10.1	9.64	8.6	7.06	6.6	26.87
9.	93.13	19.83	13.89	11.28	11.07	9.11	7.07	7.16	20.59
10.	91.02	18.19	12.52	11.43	10.22	8.31	6.33	5.89	27.11
11.	92.76	19.58	12.47	10.63	10.74	8.25	6.96	6.18	25.19

TABLE III CONTACT PENETRATION RESULTS

Case No	μ_{max} , μm	0.0084 - 0.0168, %	0.0168 - 0.0252, %	0.0252 - 0.0337, %	0.0337 - 0.0421, %	0.0421 - 0.0505, %	0.0505 - 0.0589, %	0.0589 - 0.0673, %	>0.0673 , %
1.	0.076	20.21	15.23	13.38	11.79	12.85	13.27	11.18	2.09
2.	0.115	17.33	12.94	12.49	9.28	7.88	7.39	7.25	25.44
3.	0.278	12.13	7.6	7.46	5.68	4.39	4.93	4.85	52.96
4.	0.234	14.12	8.61	8.06	6.75	6.06	5.36	4.46	46.58
5.	0.201	13.58	8.88	7.83	6.51	6.15	6.63	5.28	45.14
6.	0.327	12.57	8.27	7.59	5.86	5.37	6.26	4.82	49.26
7.	0.283	12.42	8.34	7.29	5.37	4.96	5.55	4.48	51.59
8.	0.207	13.59	8.4	8.06	5.91	5.33	6.13	5.35	47.23
9.	0.296	22.56	7.2	6.99	5.8	4.99	5.31	4.63	42.52
10.	0.266	12.68	8.17	7.44	6	6.08	6.06	5.64	47.93
11.	0.296	13.11	8.01	7.27	5.65	5.15	5.74	4.88	50.19

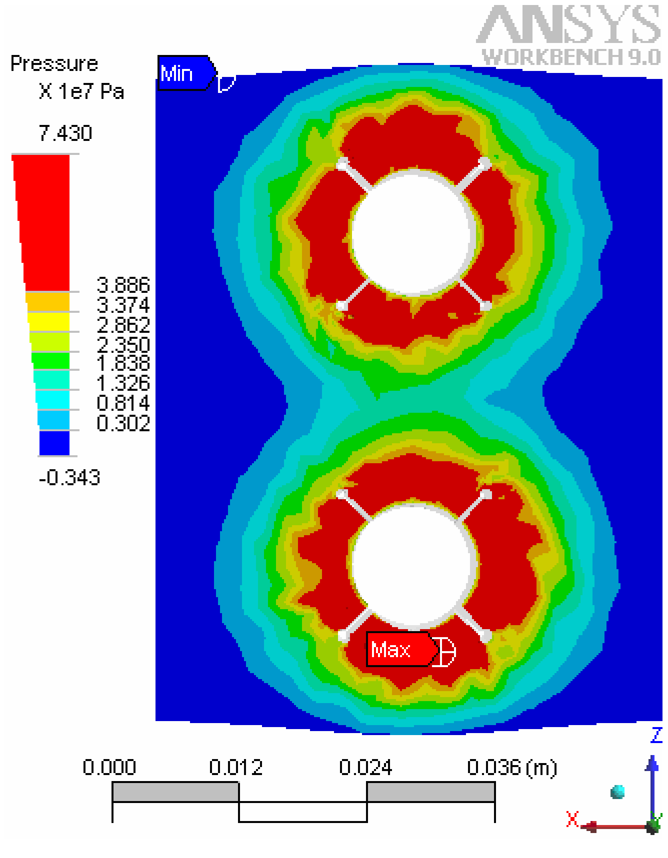

Fig. 4. Contact pressure for case 2 (new hole shape with 4 slots of length 3mm and width 0.3mm and small circular holes at the end of the slots of radius 0.5mm)

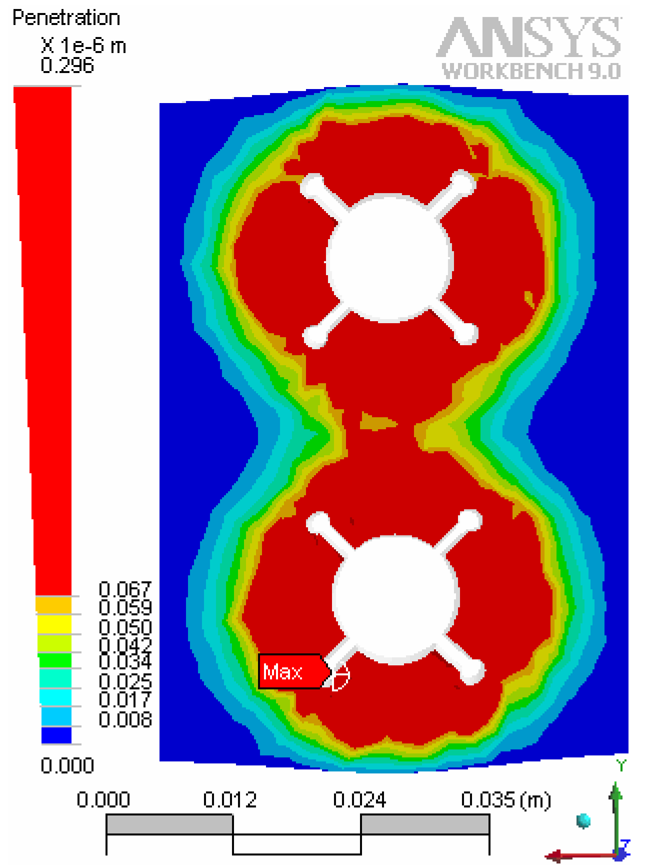

Fig. 5. Contact penetration for case 10 (new hole shape with 4 slots of length 3mm and width 1.0 mm and small circular holes at the end of the slots of radius 1.0 mm)

IV. Results and Discussion

When bolt holes of bolted busbar connections have slots ending with circular openings, then a zone of considerably high contact penetration and pressure concentration around the slots is observed. It is confirmed by the models, presented in Fig.4 and Fig.5.

Based on the contact pressure data for the eleven cases, summarized in Table II, it is obvious that, the introduced cases from 2 to 11, where four slots of 3mm length and width of 0.3; 0.5; 0.7 and 1mm, ending with small circular holes of radius 0.3, 0.5, 0.7 and 1.0 mm and lying in pairs on mutually perpendicular axes, are characterized with increased max contact pressure, that is between 12.05 and 111.7% higher than the max pressure for the classic case. The zone of contact pressure > 38.86MPa occupies between 13.55 and 27.11% of the entire contact surface, while for the classic case it occupies 2.17%.

Similar results, summarized in Table III, are obtained for the contact penetration.

The max contact penetrations, for cases 2 to 11 with the above described geometry, are between 0.115 and 0.327µm. It is between 51.3 and 330.3% higher than that for the classic case. The zone with contact penetration > 0.0673µm, occupies respectively between 25.44 and 51.59% of the entire contact surface, which is between 12 and 24.7 times higher than the relevant zone for the classic case.

V. Conclusion

When bolt holes of bolted busbar connections have 4 slots, lying in pairs on mutually perpendicular axes and ending with small circular holes, then the values of contact pressure and penetration are noticeably high in the area of busbars contact.

The deeper contact penetration increases the number of α-spots and their dimensions as well as the true contact area and this in turn reduces the contact resistance.

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