Effect of Perforation in High Power Bolted Busbar Connections

Raina T. Tzeneva[1] and Peter D. Dineff[2]

Abstract **-The work reported describes how introducing perforation groups of two or three small holes in a proper way around the bolt holes in high power bolted busbar connections increases significantly the true contact area and therefore reduces contact resistance. The new design is compared with the classical one of bolted busbar connections by the help of several computer models. It has been estimated that the new case leads to a considerable rise of contact pressure and contact penetration in the contact interface between the busbars.**

Keywords **–Bolted busbar high power connections, Contact penetration, Contact pressure, Contact resistance, Groups of small holes, New hole shape.**

I. INTRODUCTION

Steadily increasing energy consumption in densely populated regions imposes severe operation conditions on transmission and distribution systems which have to carry greater loads than in the past and operate at higher temperatures.

Power connections are generally the weak links in electrical transmission and distribution systems – both overhead and underground systems.

Mainly, there are two factors that affect the reliability of a power connection. The first is the design of the connection and the material from which it is fabricated. The second is the environment to which the connection is exposed.

The fundamental requirements for the design of reliable high-power connections used in bare overhead lines are given in [1]. The fundamental design criteria for power connectors are: maximization of electric contact true area, optimization of frictional forces with conductors (buses), 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 connection design criteria, mentioned above it is worthwhile noting that all the criteria can be met simultaneously by working out an outline that achieves a sufficiently large contact load, a large area of metal-to-metal contact and sufficient elastic energy storage in the connection to maintain an acceptable connector's contact load throughout the service life of the connection.

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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.

For this reason, it is essential to keep in mind that the load bearing area in an electric joint is only a fraction of the overlapping, known as apparent area. Metal surfaces, e. g. those of copper conductors are often covered with oxide or other insulating layers. As a consequence, the load bearing area may have regions that do not contribute to the current flow since only a fraction of may have metallic or quasi-metallic contact and the real area of electric contact, i.e. the conducting area, could be smaller than the load bearing area (Fig. 1b) [2].

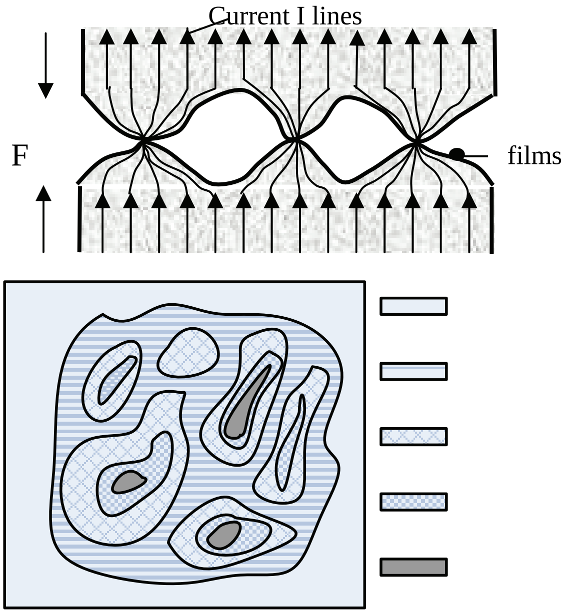

Fig. 1. a) Contact surface and current lines; b) Contact area with α- spots

A conducting area is referred to as quasi-metallic when it is covered with a thin (< 20 Å) film that can be tunneled through by electrons. This quasi-metallic 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 area of the α-spots are generally stochastic and depend on material parameters of the conductor material, 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 single circular α-spot its constriction resistance R_c depends on its radius a and the resistivity ρ of the conductor material.

III. MODELLIN BOLTED BUSBAR CONNECTIONS

In this paper, the mechanical changes, associated with the contact penetration depth and the contact pressure, in the contact area between two busbars in a high power bolted busbar connection are studied by the help of the finite elements simulation tool ANSYS Workbench. If a higher 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.

The new slotted hole shape arises from [3]. Boychenko and Dzektser have shown that changing the connection design can equally be effective in increasing the contact area. In other words, cutting longitudinal slots in the busbar, 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 joint configuration with slots is 30-40% lower than that without slots and is mechanically and electrically more stable when subjected to current cycling tests [4], [5]. The beneficial effect of sectioning the busbar is attributed to a uniform contact pressure distribution under the bolt, which in turn, creates a larger contact area. This case is investigated in [6].

This idea is developed in [7], [8] and a new slotted hole shape for bolted high power connections is proposed. Fig. 2 shows the hole shape of the investigated 11 cases. Significant rise of the contact pressure and contact penetration is obtained.

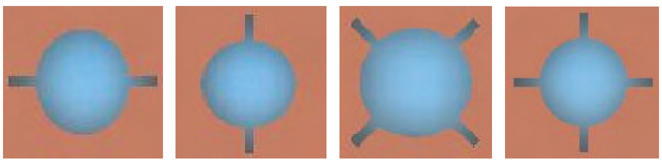

Fig. 2. Hole shape with 2 or 4 slots

Additionally a new shape of slotted holes in which the slots end with small circular holes is raised and investigated in [9] and illustrated in Fig. 3. Positive results for the contact pressure and contact penetration are obtained too.

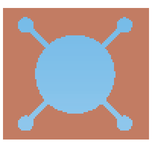

Fig. 3. Hole shape with slots, ending with small circular holes

But to cut these thin slots in copper or aluminum busbars is a difficult procedure and in this investigation the slots are replaced by groups of two or four small holes.

For that purpose there have been investigated 13 different models.

<u>case 1</u> – the classical case – copper busbars with 2 bolt holes;

<u>case 2</u> –two horizontal groups of two holes of diameter Ø1mm and distance of 0.9mm between the holes, parallel to the busbar axis;

<u>case 3</u> – two vertical groups of two holes of diameter Ø1mm and distance of 0.9mm between the holes;

<u>case 4</u> – mixed – one of the busbars in the connection is of case 2 and the other is of case 3;

<u>case 5</u> – eight groups of two holes of diameter Ø1mm and distance of 0.9mm between the holes, displaced at angle of 45 degrees;

<u>case 6</u> – two horizontal groups of three holes of diameter Ø0.8mm and distance of 0.2mm between the holes, parallel to the busbar axis;

<u>case 7</u> – two vertical groups of three holes of diameter Ø0.8mm and distance of 0.2mm between the holes;

<u>case 8</u> –four groups (two horizontal and two vertical) of three holes of diameter Ø0.8mm and distance of 0.2mm between the holes;

<u>case 9</u> – four groups of three holes Ø0.8mm and distance of 0.2mm between the holes, laying on two mutually perpendicular axes, rotated at an angle of 45 degrees in relation to the busbar axes;

<u>case 10</u> – two horizontal groups of three holes of diameter Ø0.9mm and distance of 0.1mm between the holes ;

<u>case 11</u> – two vertical groups of three holes of diameter Ø0.9mm and distance of 0.1mm between the holes;

<u>case 12</u> - four groups (two horizontal and two vertical) of three holes of diameter Ø0.9mm and distance of 0.1mm between the holes;

<u>case 13</u> - four groups of three holes Ø0.9mm and distance of 0.1mm between the holes, laying on two mutually perpendicular axes, rotated at an angle of 45 degrees in relation to the busbar axes;

Fig. 4 shows the hole shapes of the cases with two groups of small holes (cases 2, 3, 6, 7, 10 and 11).

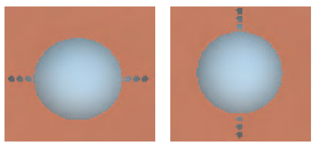

Fig. 4. Hole shape with 2 groups of small holes

Fig. 5 presents the new hole shapes with 4 and 8 groups of small holes (cases 8, 9, 12, 13 and 5).

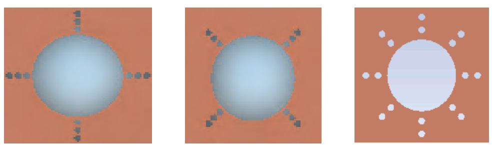

Fig. 5. Hole shape with 4 and 8 groups of small holes

The cases are 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; maximize the true area of metal to metal contact in an electrical interface.

The investigated assembly consists of:

- ❑ 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 with 2 holes of Ø10.5mm;
- ❑ Fasteners: bolts – Hex Bolt GradeB_ISO 4015 – M10 x 40 x 40 – N, steel E = 2.10^{11}Pa, µ = 0.3; nuts – Hex Nut Style1 GradeAB_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 are studied for contact pressure and penetration within the busbars electrical interface.

Fig. 6 shows contact pressure for case 11. It is obvious that the pressure in the surrounding area of the perforation is increased significantly.

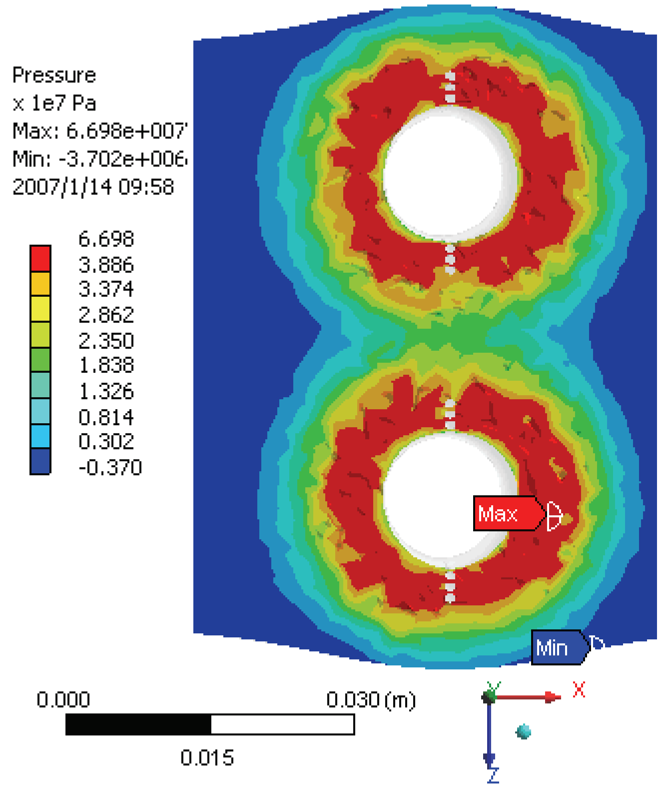

Fig. 6. Contact pressure for case 11 with 2 vertical groups of 3 small holes

Contact penetration for case 12 is shown in Fig.7. When the 4 groups of small holes are introduced the high penetration zone expands covering the region between the perforations.

All the thirteen 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 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 Fig. 9 and Fig. 10.

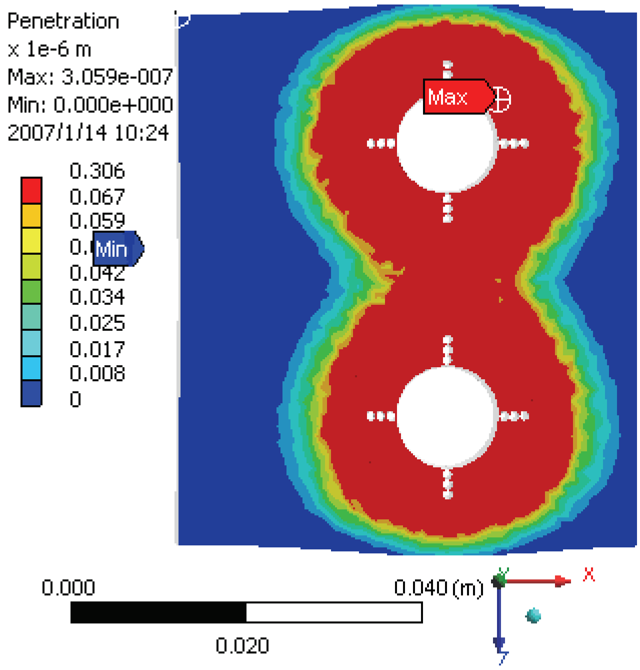

Fig. 7. Contact penetration for case 12 with 4 groups of 3 small holes

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.6 and Fig.7, for the uneven allocation of pressure and penetration, that the perforated 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.

IV. Discussion and Conclusions

When the busbars have groups of small holes around the bolt holes then there emerges a zone of significantly high contact pressure and contact penetration around the perforations. It is confirmed by the models, presented in Fig. 6 and Fig. 7.

Contact pressure data for the thirteen cases are summarized in Fig. 9.

Based on Fig. 9 and Fig. 11 it is obvious that in the extraordinary mixed case 4 the max. pressure is 88.73MPa. This value is 2 times the value of the classical case 1. Additionally the zone of pressure > 38.86MPa occupies 20.83% of the entire contact area while in the classical case it is 1.75% (12 times larger).

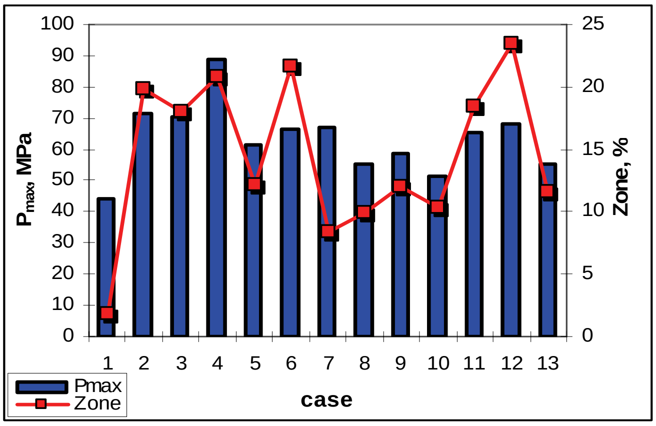

Fig. 9. Max contact pressure and % occupation of the zone of P > 38.86MPa for all cases

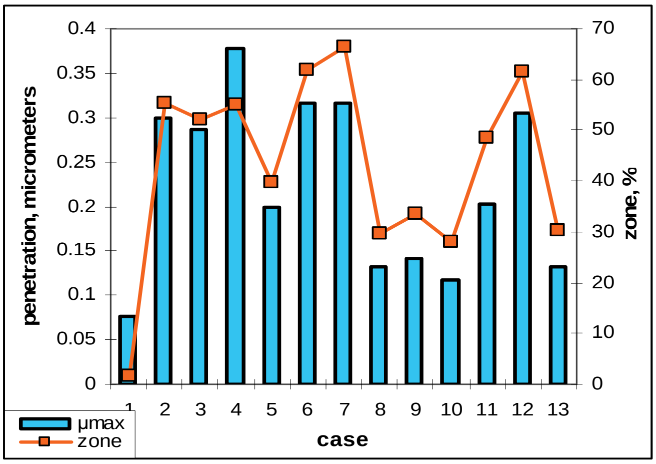

Fig. 10. Max contact penetration and % occupation of the zone of μ > 0.0673μm for all cases

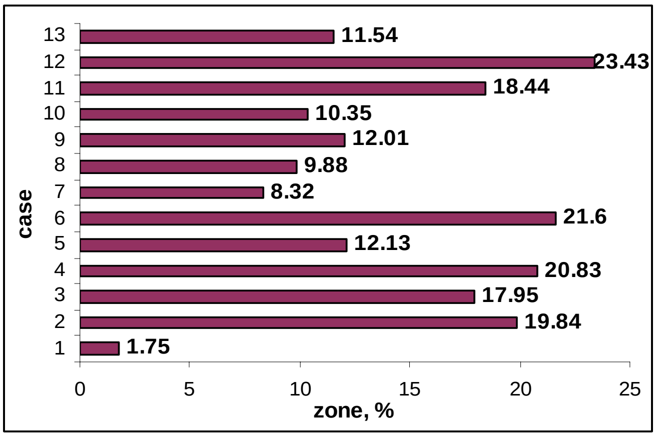

Fig. 11. Percent occupation of the P > 38.86MPa zone for all cases

The other excellent case is 12 with max. contact pressure of 67.92MPa and % occupation of the zone of pressure > 38.86MPa – 23.43% (13.4 times larger than that for the classical case 1).

The results for the contact penetration are summarized in Fig. 10 and Fig. 12.

Again in the best mixed case 4 the contact penetration is 0.377μm. This value is approximately 5 times the penetration of the classical case 1 (Fig. 12). The part of the contact area with penetration > 0.0673μm occupies 55.04 %, while for the classical case it occupies 1.69% (32.6 times larger) by comparison with the classical case.

Another excellent case 12 has max contact penetration 0.306μm and % occupation of the zone of penetration >0.0673μm – 61.44% (36.35 times the value for the classical case 1).

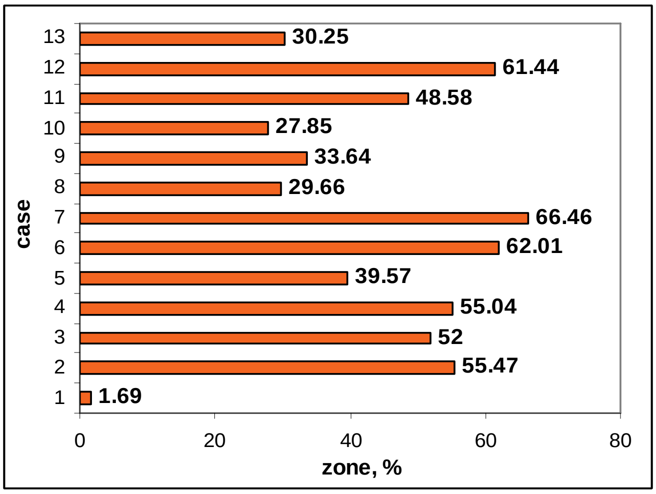

Fig. 12. Percent occupation of the μ > 0.0673μm zone for all cases

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