New Design of Aluminum Bolted Busbar Connections

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Abstract: - The work reported describes how introducing a new design (slotted hole shape, slots, ending with small holes or groups of small holes around the bolt holes) in high power aluminum bolted busbar connections increases significantly the true contact area and therefore reduces contact resistance. The new designs, formally called S, SH and G type are compared with the classical one of bolted busbar connections by the help of computer models. It has been estimated that the new cases lead to a considerable rise of contact pressure and penetration and improve reliability and life of the connection. Additionally, contact material influence is investigated.

Key-Words: - Aluminum bolted busbar high power connections, Contact pressure, Contact penetration, New connection design.

1. Introduction
Generally, there are two factors that affect the reliability of a power connection. The first is the connection design and material and the second is the environment.
The fundamental requirements for the design of reliable high-power connections used in bare overhead lines are given in [1]. One of the main ways to increase connection reliability is to reach a sufficient true contact area (large area of metal to metal contact) and low contact resistance [2].

2. Theoretical background
The new design idea of bolted busbar connections arises from [3]. Boychenko and Dzektser have shown that changing the connection design and increasing the contact area are equally effective. In other words, if the busbars are slotted longitudinally, then the actual joint contact area increases by 1.5 to 1.7 times. Such joints have contact resistance of 30-40% lower than joints without slots. Moreover, the former are mechanically and electrically more stable when subjected to current cycling tests [4], [5]. The beneficial effect of busbar sectioning 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] and [7].
This idea is developed also in [8] and [9] and a new slotted hole shape for bolted high power connections – design S is proposed. Fig. 1 shows the hole shape of the 11 investigated cases. A significant contact pressure and penetration rise is obtained for copper (Cu) busbars.

In addition, a new slotted holes shape - slots ending with small circular holes (design SH), is developed and investigated in [10] which is illustrated in Fig. 2. Positive contact pressure and penetration results are obtained too.

However, cutting such slots in copper or aluminum busbars is a difficult procedure. Therefore, in the investigation mentioned, the slots are replaced by groups of small holes – design G [11] and [12]. Fig. 3 shows the hole shapes of the cases with two, four and eight groups of small holes.

Fig.1. Hole shapes with 2 and 4 slots

Fig.2. Hole shape with slots, ending with small circular holes

Fig.3. Hole shape with 2, 4 and 8 groups of small holes
3. Modeling bolted busbar connections

Series of overlapping contact connections are modeled and studied, and the data involved is as follows:

- Aluminium (AL) busbars (Young’s modulus $E = 0.7 \times 10^{11}$ Pa, Poisson’s ratio $\mu = 0.35$, width 60mm, height 10mm, length 160mm, busbars’ overlap 60mm with 2 holes of $\varnothing 10.5$ mm;
- Fasteners: bolts – Hex Bolt Grade B ISO 4015 – M10 x 40 x 40 – N, steel $E = 2.10^{11}$ Pa, $\mu = 0.3$; nuts – Hex Nut Style 1 Grade AB ISO 4032 – M10 – W – N, steel $E = 2.10^{11}$ Pa, $\mu = 0.3$; washers – Plain Washer Small Grade A ISO 7092 – 10, steel $E = 2.10^{11}$ Pa, $\mu = 0.3$, tightening torques of 30Nm.

For that purpose there have been investigated 11 different models categorized as design S.

- case 1 – classical case – AL busbars with 2 bolt holes;
- case 2 – 2 slots parallel to the busbar axis;
- case 3 – 2 slots perpendicular to the busbar axis;
- case 4 – mixed – busbar of case 2 plus busbar of case 3;

For cases 2 to 4 all bolt holes have two slots of length 3mm and width 1mm.

For cases 5 to 8 the busbar holes have 4 slots of length 3mm and varying width, arranged in such a way that the pairs of slots are on mutually perpendicular axes and rotated at an angle of 45 degrees in relation to the busbar axes:

- case 5 – width 0.3mm;
- case 6 – width 0.5mm;
- case 7 – width 0.7mm;
- case 8 – width 1mm;
- case 9 – the 4 slots are not rotated;
- case 10 – mixed case – the first busbar corresponds to case 8 and the second to case 9;
- case 11 – a busbar hole with 8 slots of length 3mm and width 1mm;

Fig. 4 shows case 8 contact penetration. It is obvious that the penetration in the surrounding area of the slots is increased significantly.

All eleven cases have been evaluated by comparing the max values of pressure and penetration for each one of them. The percent participation of the 8 zones according to the legends has been evaluated as well. 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 for the cases of design S are summarized in Fig. 5 and Fig. 6.

![Fig.5. Max. contact pressure and % occupation of the zone of $P > 41.33$ MPa for all cases of design S](image)

Additionally, the max. contact penetration of AL and Cu design S busbar connections is compared so as to evaluate the influence of the contact material. The results are presented in Fig. 7.

![Fig.6. Max. contact penetration and % occupation of the zone of $\mu > 0.12\mu m$ for all cases of design S](image)
The next innovative design SH introduces the new concept that all bolt holes have four slots of length 3mm, arranged in such a way that the pairs of slots lie on mutually perpendicular axes. Axes are rotated at an angle of 45 degrees in relation to the busbar axes and the slots end with small circular holes.

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

<table>
<thead>
<tr>
<th>Case No</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slot width, mm</td>
<td>0</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.5</td>
<td>0.5</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>1.0</td>
</tr>
<tr>
<td>Radius of the small hole, mm</td>
<td>0</td>
<td>0.3</td>
<td>0.5</td>
<td>0.7</td>
<td>1.0</td>
<td>0.5</td>
<td>0.7</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Fig. 8 presents contact penetration for case 8. It is evident that the penetration in the encircled zone of the slots is enlarged considerably.

The generalized results for the max. pressure and penetration along with the zones of highest pressure and penetration for the 11 studied cases of design SH are shown in Fig. 9 and Fig. 10.

The similarity in behavior of the max. contact penetration for Al and Cu busbar connections of design SH is presented in Fig. 11.
For the last innovative design type – **design G** of bolted busbar connections, there have been investigated 13 different models.

- **case 1** – classical case – AL busbars with 2 bolt holes;
- **case 2** – two horizontal groups of two holes of diameter Ø1mm and distance of 0.9mm between the holes, parallel to the busbar axis;
- **case 3** – two vertical groups of two holes of diameter Ø1mm and distance of 0.9mm between the holes;
- **case 4** – mixed case – a busbar of case2 and one of case3;
- **case 5** – eight groups of two holes of diameter Ø1mm and distance of 0.9mm between the holes, displaced at angle of 45 degrees;
- **case 6** – two horizontal groups of three holes of diameter Ø0.8mm and distance of 0.2mm between the holes, parallel to the busbar axis;
- **case 7** – two vertical groups of three holes of diameter Ø0.8mm and distance of 0.2mm between the holes;
- **case 8** – four groups (two horizontal and two vertical) of three holes of diameter Ø0.8mm and distance of 0.2mm between the holes;
- **case 9** – four groups of three holes Ø0.8mm and distance of 0.2mm between the holes, lying on two mutually perpendicular axes, rotated at an angle of 45 degrees in relation to the busbar axes;
- **case 10** – two horizontal groups of three holes of diameter Ø0.9mm and distance of 0.1mm between the holes;
- **case 11** – two vertical groups of three holes of diameter Ø0.9mm and distance of 0.1mm between the holes;
- **case 12** – four groups (two horizontal and two vertical) of three holes of diameter Ø0.9mm and distance of 0.1mm between the holes;
- **case 13** – four groups of three holes Ø0.9mm and distance of 0.1mm between the holes, lying on two mutually perpendicular axes, rotated at an angle of 45 degrees in relation to the busbar axes;

The cases are again 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 and therefore reduce the contact resistance.

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

The summarized results for the max. pressure and penetration as well as the areas of the highest pressure and penetration for the 13 studied cases of **design G** are shown in Fig. 13 and Fig. 14.
The influence of the contact material (aluminum and copper) on the max. contact penetration of busbar connections for design G is illustrated in Fig. 15.

![Fig. 15. Comparison between the max. contact penetration for aluminum and copper busbar connections](image)

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, Fig. 8 and Fig. 12, for the uneven allocation of penetration, that the new 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 cases with the one for the classical (no slots and perforations) 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.

4. Discussion and conclusions

1. Based on the contact pressure data for the eleven cases, summarized in Fig. 5, it is obvious that the cases of design S are characterized with increased max. contact pressure, that is between 13.2 and 262.7%, and is higher than the max. pressure for the classic case. The zone of contact pressure >41.33MPa occupies between 4.51 and 10.71% of the entire contact surface, while for the classic case it occupies 0.15%.

Similar results, summarized in Fig. 6, are obtained for the contact penetration. The max. contact penetrations for cases 2 to 11, with the above described geometry, are between 0.147 and 0.47µm. It is correspondingly 5 and 236% higher than that for the classic case. The zone with contact penetration >0.12µm occupies respectively 3.27% and 14.51% of the entire contact surface, which is 25 to 117 times more than the relevant zone for the classic case.

2. Fig. 9 illustrates the generalized data for the max. contact pressure of the 11 investigated cases design SH. The increased max. contact pressure values vary between 65.75 and 96.64 MPa. The part of the contact surface with max. contact pressure >41.33MPa occupies between 10.36 and 23.42%, and for the classic case it occupies 0.15%.

The summarized data for contact penetration are presented in Fig. 10. The max. contact penetration is in the range 0.22-0.5 µm, which is 1.83-41.7 times higher, than for the classic case 1. The zone with the highest contact penetration >0.12 µm occupies 19.05 to 46.28% of the real contact surface, while for the classic case the zone is figure is about 0.12%.

3. Based on Fig. 13 for design G, it is obvious that in the extraordinary mixed case 4 the max. pressure is 88.5MPa. This value almost doubles the value of the classical case. Additionally, the zone of pressure > 41.33MPa occupies 18.71% of the entire contact area while in the classical case it is 0.15% (125 times larger).
The other superb cases are 2, 3, 5, 6, 7 and 12. In all of them, the zone of pressure >41.33MPa is almost 100 times larger than that in the classical case. Once more, the best case - mixed case 4 (Fig. 14), the max. contact penetration is 0.58\(\mu\)m. This value is approximately 4 times the penetration of the classical case. The part of the contact area with penetration > 0.14\(\mu\)m occupies 41.12 %, while for the classical case it occupies 0.13% (300 times larger) in comparison with the classical case.

Some other first-rate cases are 2, 3, 6, 7 and 12, where the % occupation of the zone of penetration >0.14\(\mu\)m is more than 300 times the value for the classical case 1.

4. The max. contact penetration for copper and aluminum busbar connections is compared. The results are presented in Fig. 7, Fig. 11 and Fig. 15. Based on them, it is evident that the max. contact penetration is higher for the aluminum bolted busbar connections which is due to the lower hardness of aluminum. Additionally, it is experimentally proved that the major decrease of the contact resistance in aluminum joints is approximately 50% [13].

References:


