Electric Field Distribution in Bolted Busbar Assemblies with Longitudinal Slots

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Abstract: - This paper discusses how the design of high power bolted busbar assemblies influences the change of current density distribution when one or three longitudinal slots are introduced in the area between the bolt holes in an effort to increase significantly the true contact area in the contact interface between the busars, reduce the contact resistance and improve the reliability in the assemblies performance. The slotted variants are compared with the classical no slotted cases by the help of several computer models, based on the finite element method. Additionally, the Joule heat distribution in the buses is investigated.

Key-Words: - bolted busbar connections, current density distribution, longitudinal slots, Joule heat distribution

1 Introduction

An efficient connection is defined as one which exhibits minimum contact resistance, both at initial assembly and in the long run. Operating experience with high-voltage power systems has shown that defective electrical connections are involved in many circuit or equipment failures. Increasing the real contact area, that is a fraction of the apparent contact area, determined by the dimensions of the buses and their overlapping, reduces the contact resistance and increases the reliability of the contact assembly performance.

2 Theoretical background

In order to increase the real contact area, Boychenko and Dzektser [1] have shown that changing the connection design can be equally effective in increasing the contact area. In other words, by cutting slots in the busbar in the area between the bolt holes, 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 of the classical case and is mechanically and electrically more stable when subjected to current cycling test [2], [3]. 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 idea is developed by M. Braunovic [2] in typical high voltage 700 kV power connectors used for connections of stranded 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 two or three segments. Numerous reports from the field showed that in the old connector design, contact resistance between the current-carrying part and conductor was unstable and often lead to unacceptable overheating 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.

The 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 longitudinal slots into the current carrying parts (pads). The observed improvement was associated with a more uniform stress distribution under the bolts in the sectioned joint segments and significantly lower tendency to misalignment.

The contact behavior of these connectors is investigated in [3] and the new design of high power bolted busbar connectors, introducing one or two longitudinal slots 4 mm wide and 72mm long leads to rise in max contact pressure of 21% for the connector with one slot and 11.6% for the two slotted connector. The max contact penetration increases with 20.7% for the connector with two sectors and 15.7% for this one with three sectors. Therefore, the true area of metal to metal contact is maximized within the electrical interface and that leads to reduced contact resistance and more efficient performance of the connectors of new design.

Introducing of longitudinal slots for bolted busbar connections is proposed in [4] too. These examples for busbar conductors of rectangular section are illustrated in Fig. 1.

![Fig.1. Longitudinal slots in straight joints a), angle joints b) and T-joints c)](image)

The investigated connections in this work are of new design that is with sectioned busbars that have two and eight bolt holes. The busbars are modified by cutting slots 2 mm wide and 80mm long as seen in Fig.1. Bolt hole diameter is 13.2mm for the 12.7mm bolt diameters. The thicknesses of the connection’s busbars are 10 and 20mm and are made of copper. The behavior of these connections is compared with the same connections, having no slots in their busbars.

The mechanical changes, associated with the contact penetration depth and the contact pressure, in the contact area between two busbars in a bolted busbar connection are studied by the help of the finite elements simulation tool ANSYS Workbench [5]. 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 design could be introduced for this connection. Typical bolted busbar connections with longitudinal slots are shown in Fig. 2.

![Fig.2. Bolted busbar connections with longitudinal slots- a) straight joint with 3 slots, b) angle joint with 3 slots and c) T-joint with 1 slot](image)

It was established that the new design of high power bolted busbar connections of straight joint, introducing
one or three longitudinal slots 2 mm wide and 80mm long leads to rise in max contact pressure of 15.4% for the connector with one slot and 21.6% for the three slotted connection. The max contact penetration increases with 14.1% for the connector with two sectors and 10.13% for this one with four sectors.

Similar results are obtained for the angle joint connections. The max contact pressure for the connection with one slot rises with 15.2% and for connection with 3 slots – with 17.6%. The max contact penetration is increased with 15.9% for connection with 2 sectors and with 10.3% for 4 sectors connection.

The data for T-joint connections show that the max contact pressure for connection with 1 slot increases with 17.1% and for the connection with 3 slots – with 19.6%. The max contact penetration rises with 12.9% for connection with 1 slot and for connection with 3 slots it increases with 16.9%.

3 Problem Formulation

The aim of this paper is to investigate how the design of high power bolted busbar assemblies influences the change of current density distribution when one or three longitudinal slots are introduced in the area between the bolt holes in straight, angle and T-joints in an effort to increase significantly the true contact area in the contact interface between the busbars, reduce the contact resistance and improve the reliability in the assemblies performance. The slotted variants are compared with the classical no slotted cases by the help of several computer models, based on the finite element method. Additionally, the Joule heat distribution in the buses is investigated.

4 Problem Solution

The amount of heat generated in a conductor is proportional to its resistance and to the square of the current it carries, while the temperature rise depends on the rate at which the heat is dissipated through convection, radiation, and conduction.

Allowable current density in a bus is the amount of current that the bus can carry per square inch or cross-sectional area without exceeding the permissible temperature rise. For both ac and dc buses, densities may vary from values of 9.3.10^5 and 1.09. 10^6 A/m^2 in heavy current-carrying copper buses to 1.86.10^6 and 2.17.10^6 A/m^2 in light buses under favorable conditions. For aluminum, densities of 75 percent of the above values are usually permitted [6].

Current conduction analysis is used to analyze a variety of conductive systems. Generally, the quantities of interest in a current conduction analysis are voltages, current densities, electric power losses (Joule heat).

Several computer models smooth the research progress of the current density and Joule heat distribution changes that take place within the bolted busbar connection, due to the introduced longitudinal slots (sectors). The FEA package ANSYS 12.1 is employed in the analysis of the electric field and the Joule heat distributions. The model is meshed with the SOLID 232 element - a 3-D, 10-node, tetrahedral current-based electric element. The element has one degree of freedom, voltage, at each node and is based on the electric scalar potential formulation. It is applicable to the low frequency time-harmonic quasistatic electric field analyses.

The current density distribution in bolted busbar straight assembly with 1 slot a) and without slot b) is shown in Fig. 3.

Fig.3 Current density distribution in straight assembly with 1 slot a) and without slot b)

Fig.4 illustrates the current density distribution in the bolted angle assembly with 3 slots a) and in classical case b).

Fig.5 presents the current density distribution in the bolted T-joint assembly with 3 longitudinal slots a) and without slots b).

Fig.4 Current density distribution in bolted angle assembly with 3 slots a) and in classical case b)
Fig. 4 Current density distribution in angle assembly with 3 slots a) and without slots b).

Fig. 5 Current density distribution in the bolted T-joint assembly with 3 longitudinal slots a) and without slots b).

Fig. 6 Joule heat distribution for T-joint connection a) without slots and b) with 3 slots in one of the buses.

Another very important characteristic is the heat generated by the current flow. Joule heat distribution in the connection is illustrated in Fig. 6 for T-joint a) without slots and b) with 3 slots for the case when the both buses are slotted.
Additionally the cases when the 2 buses in the connections are slotted are investigated and all the cases are as follows:

- Assembly 1 – straight unslotted assembly;
- Assembly 1a – straight assembly with 1 slot in one of the buses;
- Assembly 2 – straight unslotted assembly;
- Assembly 2a - straight assembly with 3 slots in the 2 buses;
- Assembly 3 – angle unslotted assembly;
- Assembly 3a - angle assembly with 1 slot in one of the buses;
- Assembly 3b - angle assembly with 2 slots in the 2 buses;
- Assembly 4 - angle unslotted assembly;
- Assembly 4a - angle assembly with 3 slots in one of the buses;
- Assembly 4b - angle assembly with 6 slots in the 2 buses;
- Assembly 5 – T-joint unslotted assembly;
- Assembly 5a – T-joint assembly with 1 slot in one of the buses;
- Assembly 5b – T-joint assembly with 2 slots in the 2 buses;
- Assembly 6 - T-joint unslotted assembly;
- Assembly 6a – T-joint assembly with 3 slots in one of the buses;
- Assembly 6b – T-joint assembly with 6 slots in the 2 buses;

Additionally the cases when the 2 buses in the connections are slotted are investigated and all the cases are as follows:

Table 1 Comparison of $j_{\text{max}}$ and $J_{\text{max}}$ for connections with and without longitudinal slots

<table>
<thead>
<tr>
<th>Assembly</th>
<th>$j_{\text{max}}$, A/m$^2$</th>
<th>%</th>
<th>$J_{\text{max}}$, J</th>
<th>%</th>
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<tr>
<td>Assembly 1</td>
<td>$1.29 \times 10^6$</td>
<td>100</td>
<td>14871</td>
<td>100</td>
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<tr>
<td>Assembly 1a</td>
<td>$1.8 \times 10^6$</td>
<td>140</td>
<td>41052</td>
<td>276</td>
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<tr>
<td>Assembly 2</td>
<td>$3 \times 10^6$</td>
<td>100</td>
<td>84283</td>
<td>100</td>
</tr>
<tr>
<td>Assembly 2a</td>
<td>$3 \times 10^6$</td>
<td>100</td>
<td>83102</td>
<td>98.6</td>
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<td>Assembly 3</td>
<td>$1.8 \times 10^6$</td>
<td>100</td>
<td>30490</td>
<td>100</td>
</tr>
<tr>
<td>Assembly 3a</td>
<td>$2.25 \times 10^6$</td>
<td>125</td>
<td>50854</td>
<td>167</td>
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<tr>
<td>Assembly 3b</td>
<td>$4.5 \times 10^6$</td>
<td>250</td>
<td>207632</td>
<td>681</td>
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<tr>
<td>Assembly 4</td>
<td>$1.8 \times 10^6$</td>
<td>100</td>
<td>30848</td>
<td>100</td>
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<tr>
<td>Assembly 4a</td>
<td>$2.25 \times 10^6$</td>
<td>125</td>
<td>51355</td>
<td>166</td>
</tr>
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<td>Assembly 4b</td>
<td>$9.02 \times 10^6$</td>
<td>501</td>
<td>844057</td>
<td>2736</td>
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<tr>
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<td>100</td>
<td>20626</td>
<td>100</td>
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<td>121</td>
<td>31761</td>
<td>154</td>
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<td>300</td>
<td>200912</td>
<td>974</td>
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<td>100</td>
<td>31175</td>
<td>100</td>
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<td>100</td>
<td>33515</td>
<td>107</td>
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<tr>
<td>Assembly 6b</td>
<td>$9 \times 10^6$</td>
<td>500</td>
<td>821141</td>
<td>2634</td>
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</table>

An assessment of the max values of the current density $j_{\text{max}}$ and Joule heat $J_{\text{max}}$ for the connections with and without slots is given in Table 1.

5 Discussion and conclusion

Based on the results in Table 1, it is established that the max current density is about 40% higher for the single slotted busbar case, and up to 5 times higher when both busbars have longitudinal slots. Similarly, for the max. Joule heat, the increase is up to 2.7 times for the single slotted busbar case and up to 26 times when both busbars are slotted.

Regions with max current density, the so called hot-spots, are concentrated on some edges, at the ends of the longitudinal slots and in the transition zone between two busbars. These regions occupy negligibly small busbar surface space (below 0.1%). Their temperature should be checked since due to some standards (e.g. IEEE Standard 27-1974 or ANSI C37.20C.1974) [6], it is limited to a certain value. If the permissible temperature is exceeded, then some special measures should be taken (e.g. silver coating of busbars ends or reduction of the current carrying capacity).

For bolted busbar connections of angle or T-joint type, a significant non-uniform current density distribution is observed in the connections, which is evident from the supplied figures. In some busbars, the volume of the non loaded regions occupies more than 60% of the busbar volume. The non-uniformity in the distribution is confirmed through the software application Adobe Photoshop.

References: