Thermal Field Distribution in Bolted Busbar Connections with Longitudinal Slots

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Abstract: - Thermal field distribution of three cases of high power bolted busbar connections – straight, angle and T-joint variants is investigated. The busbars, proposed by Asea Brown Boveri Company are shaped by one or three longitudinal slots between the bolts holes in order to decrease the contact resistance and to improve the stability of performance. Finite element (FE) models are generated to analyze the temperature distribution of the contacting busbars.

Key-Words: - Bolted busbar high power connections, Longitudinal slots, Thermal field distribution

1 Introduction

Wherever currents are transmitted in the order of a few hundred amps to a few thousand amps — or even tens of thousands of amps — problems arise at the busbar joints as a result of excessively high joint resistance.

Several variables affect this resistance, which increases with time because of ageing. The heat losses rise at the same time. Ultimately, excessive heating can lead to total failure of the joint. Service life can vary widely depending on the ambient conditions.

Progressive film buildup increases the joint resistance, heat losses and therefore the temperature of the joint, which in turn accelerates the chemical reaction producing the film buildup. This “vicious circle” of film buildup, heat loss and joint temperature can ultimately cause the busbar joint to fail totally as a result of overheating.

Busbars may be connected to each other and to electrical apparatus by bolted or clamp connections. Bolted joints are compact and efficient but have a somewhat more uneven contact pressure compared to clamped plate joints.

A review of factors that affect the connector performance and detailed analysis of the degradation mechanisms of power connections is given in [1] and [2].

There are two major factors that affect the reliability of a power joint. The first one includes the connection design and material properties. The second one is the environmental influence on the joint.

2 Theoretical background

In order to increase the real contact area, Boychenko and Dzektsir [3] have shown that changing the connection design can be equally effective in increasing the contact area. In other words, if slots are cut in the busbars, the actual surface area of a joint could be increased by 1.5 to 1.7 times the area of a joint whose busbars have no slots. The contact resistance of 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. 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 [4] 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 grooves by either high-strength aluminum (7075 grade) or steel bolts. The keeper and the 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 entire joint.
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 joint stability. 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.

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 behavior of these connectors is investigated in [5]. The new design of high power bolted busbar connectors, with one or two longitudinal slots 4 mm wide and 72mm long, raises the max contact pressure by 21% for the one slot connector and by 11.6% for the two slotted connector. The max contact penetration goes as high as 20.7% for the connector with two sectors and 15.7% for the one with three sectors.

Therefore, the true area of metal to metal contact is maximized within the electrical interface, which reduces contact resistance and makes the performance of the new connectors design a more efficient one.

Longitudinal slots for bolted busbar connections are also proposed in [6] and the shapes are shown in Fig. 1.

The influence of the longitudinal slots on the mechanical behavior, especially on the contact penetration and contact pressure in the overlapping surface is analyzed in [7] and a certain rise of these two indices is observed. The new design of high power bolted busbar connections of straight joint, with one or three longitudinal slots 2 mm wide and 80mm long boosts the max contact pressure by 15.4% for the connector with one slot and by 21.6% for the three slotted connection. The max contact penetration increases with 14.1% for the connector with two sectors and with 10.13% for the one with four sectors.

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

The data for T-joint connections, shows 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 is 12.9%

The electric field distribution in these assemblies is discussed in [8]. Current conduction analysis is applied. 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) [9], 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. 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.

![Fig.1 Longitudinal slots in a) straight joints b) angle joints c) and T-joints](image-url)
3 Problem Formulation
The aim of this paper is to investigate how the design of high power bolted busbar assemblies influences the thermal field 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.

4 Problem solution
The busbars are modified by cutting slots 2 mm wide and 80mm long as shown in Fig.1. Bolt holes diameter is 13.2mm for 12.7mm bolt diameters. Busbars are made of copper and are 10mm and 20mm thick. The behavior of these connections is compared to the behavior of the same connections but with busbars that have no slots.

The thermal field distribution is studied by the help of the FEA tool ANSYS, solving the coupled electric-thermal problem. Typical bolted busbar connections with longitudinal slots are shown in Fig. 2.

![3 slotted busbar](image1)
![3 slotted busbar](image2)

The investigated assembly consists of:
- Copper busbars (Young’s modulus $E = 1.1 \times 10^{11}$ Pa, Poisson’s ratio $\mu = 0.34$, width 80, 100 and 160mm, height 10 and 20mm, length 250mm, busbars overlap 80mm with 2 or 8 holes of Ø13.2mm
- Fasteners: bolts – Hex Finished Bolt_AI–HFBOLT 0.5-20-3-1.25-N, steel $E = 2.1 \times 10^{11}$ Pa, $\mu = 0.3$; nuts – Heavy Hex Nut_AI–HHNUT 0.5000-13-D-N, steel $E = 2.1 \times 10^{11}$ Pa, $\mu = 0.3$; washers –Flat Washer Type A Wide_AI- FW 0.5, steel $E = 2.1 \times 10^{11}$ Pa, $\mu = 0.3$.
- Tension in each bolt $F = 12559$ N.

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.

Several computer models smooth the research progress of the thermal field distribution changes that take place within the bolted busbar connections due to the introduced longitudinal slots (sectors). The FEA package ANSYS 12.1 is employed in the analysis of the thermal field distribution. The model is meshed with the SOLID226 element – 3D, 20 nodes coupled field element with up to 5 degrees of freedom per node.

The current-carrying capacity of a bus is limited by the temperature rise produced by the current and other factors [9]. Buses in generating stations and substations are generally rated on the basis of the allowable temperature rise without risk of overheating the terminals, bus connections, and joints. ANSI C37.20C-1974 (IEEE standard 27-1974) permits that the hottest spot temperature rise for plain copper buses be 30 °C above ambient temperature of 40°C, i.e. the hottest spot total temperature limit of 70 °C.
Fig. 3 shows the thermal field distribution in bolted busbar straight assembly with 1 slot a) and no slot b).

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

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

Fig. 3 Temperature distribution in bolted busbar straight assembly with 1 slot a) and without slot b)

Fig. 4 Temperature distribution in bolted busbar angle assembly with 3 slots a) and without slots b)

Fig. 5 Temperature distribution in the bolted T-joint assembly with 3 longitudinal slots a) and without slots b)
Additionally, cases where both buses in the connection are slotted have been investigated. All the studied cases are as follows:

Straight assembly
- Assembly 1 – unslotted;
- Assembly 1a – 1 slot in one of the buses;
- Assembly 2 – unslotted;
- Assembly 2a - 3 slots in both buses;

Angle assembly
- Assembly 3 – unslotted;
- Assembly 3a - 1 slot in one of the buses;
- Assembly 3b - 2 slots in both buses;
- Assembly 4 - unslotted;
- Assembly 4a - 3 slots in one of the buses;
- Assembly 4b - 6 slots in both buses;

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

An assessment of the max $T_{\text{max}}$ and min $T_{\text{min}}$ values of the temperatures and their difference $\Delta T$ for the connections with and without slots is given in Table 1.

Table 1 $T_{\text{max}}$, $T_{\text{min}}$ and $\Delta T$ for connections with and without longitudinal slots.

<table>
<thead>
<tr>
<th>Assembly</th>
<th>$T_{\text{max}}$, °C</th>
<th>$T_{\text{min}}$, °C</th>
<th>$\Delta T$, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assembly 1</td>
<td>29.772</td>
<td>29.924</td>
<td>0.152</td>
</tr>
<tr>
<td>Assembly 1a</td>
<td>28.919</td>
<td>28.762</td>
<td>0.157</td>
</tr>
<tr>
<td>Assembly 2</td>
<td>27.538</td>
<td>27.271</td>
<td>0.267</td>
</tr>
<tr>
<td>Assembly 2a</td>
<td>25.9</td>
<td>25.718</td>
<td>0.182</td>
</tr>
<tr>
<td>Assembly 3</td>
<td>30.362</td>
<td>30.346</td>
<td>0.016</td>
</tr>
<tr>
<td>Assembly 3a</td>
<td>29.608</td>
<td>29.302</td>
<td>0.306</td>
</tr>
<tr>
<td>Assembly 3b</td>
<td>28.851</td>
<td>28.541</td>
<td>0.31</td>
</tr>
<tr>
<td>Assembly 4</td>
<td>27.889</td>
<td>27.497</td>
<td>0.392</td>
</tr>
<tr>
<td>Assembly 4a</td>
<td>25.039</td>
<td>25</td>
<td>0.039</td>
</tr>
<tr>
<td>Assembly 4b</td>
<td>24.218</td>
<td>24.058</td>
<td>0.16</td>
</tr>
<tr>
<td>Assembly 5</td>
<td>27.479</td>
<td>27.185</td>
<td>0.294</td>
</tr>
<tr>
<td>Assembly 5a</td>
<td>25.755</td>
<td>25.557</td>
<td>0.198</td>
</tr>
<tr>
<td>Assembly 5b</td>
<td>24.882</td>
<td>24.669</td>
<td>0.213</td>
</tr>
<tr>
<td>Assembly 6</td>
<td>30.86</td>
<td>30.487</td>
<td>0.373</td>
</tr>
<tr>
<td>Assembly 6a</td>
<td>27.07</td>
<td>26.741</td>
<td>0.329</td>
</tr>
<tr>
<td>Assembly 6b</td>
<td>25.809</td>
<td>25.578</td>
<td>0.231</td>
</tr>
</tbody>
</table>

4 Discussion and conclusions
Based on the results in Table 1 we can conclude that in all investigated cases of new bolted busbar connections of straight, angle and T-joints type with and without longitudinal slots the thermal field is practically uniformly distributed. The difference between $T_{\text{max}}$ and $T_{\text{min}}$ is negligible (between 0.01 and 0.4 °C).

The cases with introduced longitudinal slots have slightly lower temperatures because they are better cooled, especially when both buses are slotted.

The temperature results obtained from the models were confirmed by experimental measurements with infrared camera.

The idea of introducing slots in high power bolted busbar connections is additionally developed in 3 new designs, where the slots are part of the bolt holes: slotted bolt holes - design S, slotted bolt holes, ending with small holes – design SH and groups of small holes around the bolt holes – design G. In all of these cases the contact pressure and contact penetration is about 50% higher and the experimentally proved reduction of contact resistance is significant as provided by [9], [10], [11], [12], [13], [14],[15] and [16].

References:


