Electrical Performance of Conductive Bolted Joints of Copper & Aluminum Busbars

SAMARJIT BHATTACHARYYA[1], DR. A CHOUDHURY[1], PROF H.R. JARIWALA[1], M.S. SHETTY[2], RAJULKUMAR[2*]

[1]Department of Electrical Engg, S.V.National Institute of Technology, Surat-395007, India
Phone: 91-261-2201564 , Email address: samarjit.bhattacharyya@gmail.com
[2] Engineer*, Reliance Industries Limited, Surat , India

Abstract: *In the electric power industry, the aluminum /copper bolted joints are often used in different applications. Both the materials have different thermal expansion coefficients. As a consequence, substantial clamping pressures are needed in addition to having regard to surface preparation and bolting torques. Belleville washers are frequently used to compensate for thermal expansion and contraction in such joints. This paper describes and compares performance of different combinations of 1350 aluminum /copper bolted joints .*

Keywords— *Copper Bus bar, Aluminum Bus bar, Streamline effect, Interface resistance, Silver Plating, Belleville Washer, Contact resistance.*

1. INTRODUCTION

It is well known that special attention has to be paid to the preparation and assembly of aluminum surfaces to obtain stable low-resistance in aluminum/aluminum joints, whereas copper/copper joints are much less sensitive in this regard. It is therefore, to assumed that the aluminum/copper interface lies between these two extremes in terms of need for care during assembly. However, practical experience in service has not always supported this view and aluminum/copper joints needs special attention.

The resistance of a joint is affected mainly by two factors:

a) Streamline effect or spreading resistance Rs, the diversion of the current flow through a joint.
b) The contact resistance or interface resistance of the joint Ri.

The total joint resistance Rj=Rs+Ri

The above equation is valid only for a d.c current. Where a.c. currents are flowing, the changes in resistance due to proximity and skin effects in the joint zone will also be taken into account.

Further the role of changes in thermal and electrical resistance that can occur in a clamped joint is very important as both can affect the contact force and current flow across the joints. This is specially true in case of joints between two dissimilar metals Copper and Aluminum.

A purely metallic contact joint occurs only in vacuum. In free air oxide layers form on the contact surfaces.

The hardness of the contact material also affects the resistance to current flow across the joint. Current flows across constricted areas where these rough surfaces make contact.

The two main reason of degradation of aluminum/copper joints are:

a) Direct oxidation
b) Interfacial shear tension

Our aim in this paper is to optimize the above mentioned factors in case of Copper-Aluminum joints in order to achieve excellent joint efficiency.

2. PROBLEM FORMULATION

Here in this paper different Aluminum and Copper bus bar combinations are considered for measuring contact resistance.

In each case milli-volt drop across the busbar joints at different loads will be measured. Lower the voltage drop lower will be the contact resistance for the same load.

Different factors that will determine the efficiency of the joint with possible remedies are as follows:

a. Streamline effect
b. Effect of oxides in contact resistance
c. Condition of the contact surfaces

a. Streamline effect:

The distortion of the lines of current flow at an overlapping joint between two conductors affects the resistance of the joint. In case of an overlapping joint between two flat copper bars the streamline effect is dependent only on the ratio of the length of the overlap to the thickness of the bars and not on the width. Hence the efficiency of an overlapping joint does not increase as the length of the overlap increases and from the electrical point of view no advantage is to be gained by employing an unduly long overlap.

b. Effect of oxides in contact resistance:

In free air, oxide layers form on the contact surfaces. This oxidation layers are one of the main reason of degradation of aluminum/copper joints.Petroleum greases are used to slow down the formation of oxide layers. If the petroleum layer is very thin the contact resistance is negligible or nearly equal to the resistance in a vacuum.

Holm (2) determined that the contact resistance can be neglected if the thin film layer is less than 10^{-6} cm thick. He termed this layer quasimetallic. The low resistance can be explained by tunnel effect. Electrons can penetrate the thin film without energy loss, as if they are passing through a tunnel. If the layer is thicker, electrons lose energy and the resistance to current flow increases.

If there is a thick film on the contact surfaces, there is additional resistance present. The extra resistance is known as Fritting Resistance Rf. This occurs when the petroleum coating is greater than 10^{-6} cm thick or an oxide or sulfide film develops on the contacts. This thick layer can be penetrated if the electrical field force is great enough. Field strengths of 10^{-5} to 10^{-7} V/cm will overcome this thick layer. This breakdown is known as A fritting. Once the thick layer begins to dissolve, the area of spot contact begins to increase and the resistance is lowered. The second step is called B fritting. Most power contacts have sufficient electrical fields to cause both A and B fritting. Therefore, the contact resistance is temporarily low, as if only a thin film is present.

This oxide formation can rapidly destroy un plated copper contacts. Silver plated contacts are more resistant to the formation of this oxide film since silver does not form a stable oxide. Contact surfaces should be flattened by machining and thoroughly cleaned before carrying out silver plating. However if sulphides are present in the environment, a thick sulphide film will form on silver contacts.

c) Condition of the contact surfaces:

The condition of the contact surfaces of a joint has an important bearing on its efficiency. The surfaces of the copper should be flat and clean. Current flows across constricted areas where these rough surfaces make contact.

The surface area of the constrictions depends on:

i) Hardness of the material

ii) Amount of contact force.

i) Hardness of the material:

Contact hardness is expressed by the amount of force needed to cause permanent deformation.

Contact hardness is determined by pressing a round ball into the surface of the contact. The pressure causes the surface to deflect a certain distance while a load is applied. After the pressure is removed, a permanent indentation is left in the surface. The difference between the two lines of deflection d is the elastic deformation. The depth of the permanent deflection is the plastic deformation D. (fig-4)

The contact hardness is expressed by the amount of force needed to cause permanent deformation.

For a radius of ball r. $D = \frac{d}{r}$

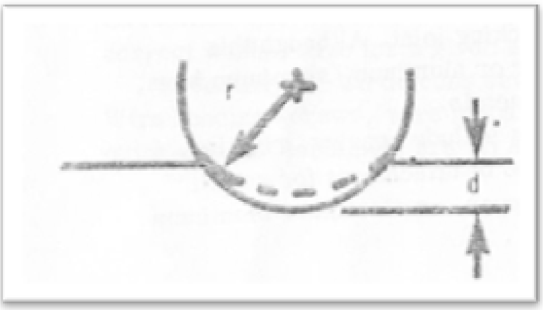

Fig-1: Determination of contact hardness. [1]

ii)Amount of contact force:

Contact resistance is dependent more on the total applied pressure than on the area of contact. If the total applied pressure remains constant and the contact area is varied, the total contact resistance remains practically constant. This can be expressed by the following equation:

$Ri = \frac{C}{p \quad n}$

Where

Ri = resistance of the contact.

P= total contact pressure.
n=exponent between 0.4 and 1.
C= a constant.

The greater the applied total pressure the lower will be the joint resistance and therefore for high efficiency joints high pressure is usually necessary. The Fig-5 shows the effect of pressure on joint resistance.

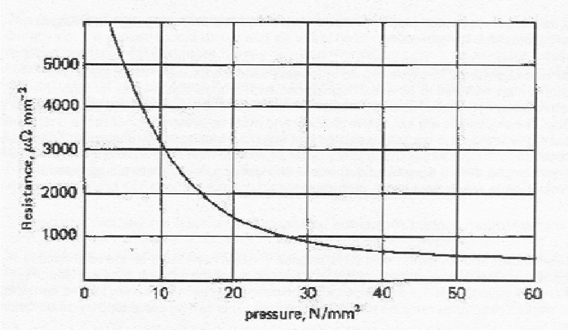

Fig-2: Effect of pressure on contact resistance of a joint between two copper conductors

The joint resistance falls rapidly with increasing pressure, but above a pressure of about 15N/mm2 there is little further improvement. These busbar joint may heat up under load as the contact pressure applied with steel bolts tends to increase because of the difference in expansion coefficient between two dissimilar metals, copper and aluminum. The thermal expansion coefficient of aluminum is 1.36 times that of copper.

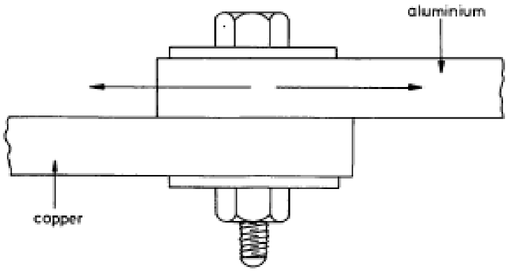

Fig-3 The aluminum / copper bolted joint [10]

Thus, when an assembly such as that shown in Fig. 3 is clamped at ambient temperature and then heated by the passage of current, there will be a tendency for the aluminium to expand relative to the copper causing movement at the interface (as shown by the arrows). If the friction resisting force at the interface is sufficiently high this movement will be slight. This movement will cause significant numbers of contact spot ruptures which will lead to temperature rise of the joint and increased wattage loss. Such repeated thermal expansions and contractions of dissimilar metals will vary the contact force and eventually will cause loose joints. To compensate for these changes, spring pressure should be added to this joint. Belleville washers are frequently used to compensate for thermal expansion and contraction in clamped joints. It is important that these washers are not over stressed.

Fig-4 shows a bolted joint with Belleville washer

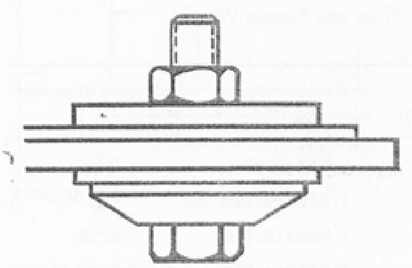

Fig-4 Belleville washer in a bolted joint [1]

The following method can be used to calculate the size and material properties of Belleville washers (Refer Fig-07 & Fig-08)). Load and stress are calculated according to the following equations:

$$\mathrm{F(load)} = \frac{\mathrm{E_f}}{(1-\sigma^2)\mathrm{M}(\mathrm{D_2}/\mathrm{D_1})^2}\left[(\mathrm{h}-\frac{\mathrm{f}}{2})(\mathrm{h - f})(\mathrm{t}+\mathrm{t}^3)\right]$$

$$\mathrm{h} = \frac{\mathrm{MS}(\mathrm{D_2}/\mathrm{D_1})^2(1-\sigma^2)}{\mathrm{EfC_1}} + \frac{\mathrm{f}}{2} + \frac{\mathrm{C_2}}{\mathrm{C_1}}\mathrm{t}$$

Where
F = load, lb
S = stress, psi at the inside diameter.
f = deflection, in.
t = thickness, in.
E = modulus of elasticity of material, 30x 10^6 psi
σ = Poissons ratio for material (0.3 value for steel)
h = height, in.
D1 = inner diameter, in.
D2 = outer diameter, in.
Washer dimensions are shown schematically in fig-8. The constants C1,C2 and M can be taken from fig-7.

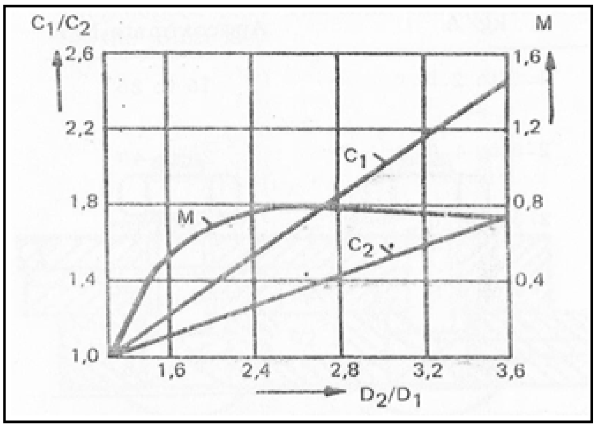

Fig-5 Constants for equation related to Belleville washer [1]

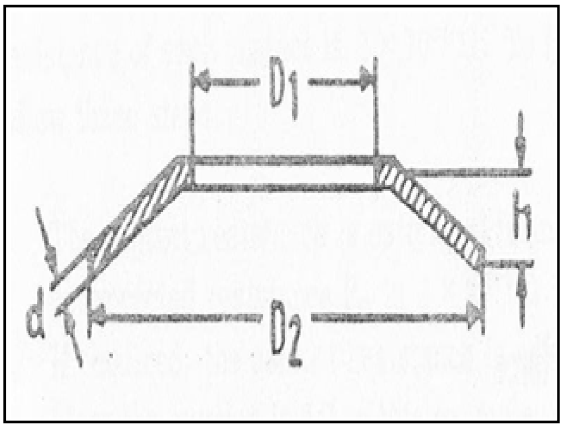

Fig-6 Dimensions Of Belleville Washers [1]

3. RESULTS BASED ON PRACTICAL EXPERIMENTS:

In the figures and the charts given below we are trying to compare results of the following busbar combinations at different loads varying from 100 Ampere to 603 Ampere. Here we are measuring voltage drop across the contacts. Lower the voltage drop lower will be the contact resistance.
a. Buffed Aluminum busbar and Buffed Copper busbar (D-D)
b. Aluminum busbar and Copper busbar, both without buffing (C-C).
c. Buffed Aluminum busbar and Silver plated Copper busbar (F-F)
d. Without buffed Aluminum busbar and Silver plated Copper busbar (E-E)
Size of the bus bar in all the cases:
Length: 100 mm, Width: 30 mm, Thickness: 5 mm
Overlap between two connecting busbars in all the cases:
Length: 30 mm, Width: 30 mm
Bolts used for jointing busbars:
Size : M10 , MOC: MS with zink plated
Torque applied while connecting busbars in all the cases:12 nM

Chart-1

Al - Cu (Both with Buffing)		*Al - Cu (Both without Buffing)*	
Current	***mv Drop***	***Current***	***mv Drop***
106	11.0	104	11.1
203	11.4	207	12.6
301	12.1	306	14.3
404	12.6	404	16.6
503	13.3	501	19.0
604	14.0	606	21.9

Chart-2

Al (With Buffing)- Cu Silver coated		*Al(without Buffing)– Cu Silver coated*	
Current	***mv Drop***	***Current***	***mv Drop***
100	11.0	106	10.5
205	11.2	200	11.0
302	11.4	300	11.5
406	11.6	402	12.1
503	11.8	509	12.7
602	12.1	600	13.4

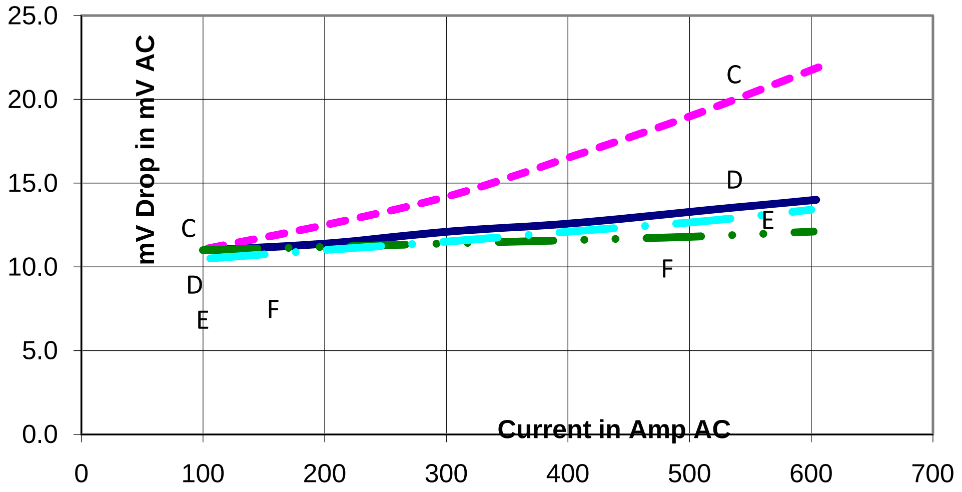

Fig-7

Thus in all these cases we have kept same overlap between the bus bars, applied optimum pressure and used Belleville washers. A thin film of petroleum coating was applied on each contact surfaces to avoid formation of oxide layer.

In figs 7, X axis of the curve is showing current flowing through the bus bar joints and Y axis is showing milli-volt drop taking place in the joints. Lesser the milli-volt drop across a joint better will be the joint, as there will be lesser contact resistance, lower temperature rise and lesser power loss.

From the results shown in chart-1 we can see that joints between aluminum busbars and copper busbars are better when mating surfaces are buffed.

In chart-2 we can see that joints between Aluminum busbars and silvercoated copper bus bars are better when the mating surface of aluminum busbar is buffed

Fig-7 shows overall comparison of the all four cases considered in the experiment which clearly shows supremacy of joints between Buffed copper busbar and Silver plated Copper busbar above the other three combinations.

CONCLUSION:

The 1350 aluminium/copper bolted joint is fundamentally less secure than the all-aluminum or all cooper connection. Differential expansion shearing force at the interface is considered to be a significant degrading influence. Substantial clamping pressures are required in addition to having regard to surface preparation and bolting torques. Inert greases are used at the interface to restrict corrosion. Stable and minimum contact resistance of joints will reduce the need for frequent maintenance, decrease overall downtime of equipment and maintenance costs and greatly reduce the risk of catastrophic failures.

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