Electro-Mechanical Synergy in the Design of Hybrid Busbar Distribution Systems

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Abstract. This paper focuses on electric energy distribution and utilizes injection lap riveting to assemble two different configurations of copper-aluminum (hybrid) busbar distribution systems with geometric variations. A combined experimental-numerical methodology is employed to investigate the influence of the different configurations and geometries on current crowding and electrical resistance of the joints. The study reveals that prioritizing the reduction of manufacturing costs through the use of simple and easier-to-fabricate geometries results in poorer electrical performance and increased operational costs of the energy distribution systems in service. The work represents a key step towards achieving electro-mechanical synergy in the design of hybrid busbar distribution systems.

1 Introduction

Busbars are essential components to transfer and distribute mid-to-high amounts of current in power stations, electric vehicles, industrial facilities, commercial spaces, institutional buildings, and various other applications. They are typically made from copper in a diverse range of shapes, such as flat sheets, solid bars, or rods, and provide practical and functional advantages over traditional cables, offering easier installation, compactness, flexibility, and the elimination of wiring defects [1].

The use of copper in electric power distribution systems results from its high electrical conductivity, low thermal expansion, good corrosion resistance, and mechanical strength. However, the increase in copper prices [2], driven by the central role of this material in the ongoing green energy transition, has led to the search for alternative materials such as aluminum for the fabrication of busbars.

Shifting towards aluminum comes at the price of aluminum being only about 61% as electrically conductive as copper. Very often, it requires assembly with copper in specific regions of the energy distribution systems, giving rise to what will hereafter be referred to as 'hybrid busbar distribution systems'. The fabrication of these systems presents several challenges, particularly regarding the geometry of the connections between copper and aluminum flat sheet conductors. Differences in the electrical, thermal, and mechanical properties of the two materials further compound these challenges.

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Starting with the challenges related to the use of copper and aluminum, it is important to mention the difficulties in connecting dissimilar materials using joining technologies built upon heating-cooling cycles, such as welding, due to the formation of brittle intermetallic compounds [3]. Welding copper and aluminum sheets also creates problems related to the varying levels of distortion and residual stress resulting from the heating-cooling cycles.

The above-mentioned limitations justify why fastening with bolts has been favored in this type of application, despite the electrical performance of the resulting joints being significantly influenced by the size and surface conditions of the contact areas, as well as the applied pressure. These factors are dependent on the number of bolts and the effectiveness of tightening [4]. Self-loosening of bolts in service also necessitates regular maintenance of the joints, as it can significantly increase electrical resistance and diminish the overall performance of the energy distribution systems.

In recent years, efforts have been made to develop alternative solutions based on joining by forming technology. Several innovative joining processes have been specifically developed and applied in the connection of hybrid busbar distribution systems with the aim of eliminating thermal cycles, improving the contact conditions between the overlapped sheets, and preventing material protrusions caused by bolt heads and nuts above and below the sheet surfaces [5]. This last issue is particularly relevant in applications facing challenges with space or physical access during assembly and maintenance.

The use of joining by forming leads to the second challenge related to the geometry of connections between copper and aluminum sheet conductors, which can be analyzed from two different perspectives. The first perspective, unavoidable, necessitates the thickness of the aluminum busbar sheets to be approximately 2.3 times greater than that of the copper busbar sheets to ensure the same conductance [5]. The second perspective requires focusing on the electro-mechanical synergies of the joints to emphasize the importance of not prioritizing ease and cost of manufacturing over electrical performance. In other words, it is crucial not to view the design of hybrid busbar distribution systems solely with the goal of replacing fastening through joining by forming to reduce the number of parts, eliminate material protrusions and diminish maintenance costs.

This paper is aimed at addressing both challenges which play a key role in the design of hybrid busbar distribution systems. The work uses injection lap riveting, a joining by forming process recently developed by the authors [6], to assemble the different parts of the hybrid busbar distribution systems and to study the influence of their configuration and geometry on current crowding, and electrical resistance of the joints. The investigation is supported by experimental testing on two different types of electrical current distribution systems, and numerical simulation using an in-house finite element software developed by the authors.

2 Materials and methods

2.1 Materials and fabrication methods

The hybrid busbar distribution systems were fabricated from aluminum AA6082-T6 sheets with $t_{Al} = 5$ mm thickness and electrolytic copper C11000 sheets with $t_{Cu} = 2$ mm thickness, to obtain a cross section ratio $S_{Al}/S_{Cu} = 2.5$. This value closely approximates the theoretical cross-section ratio of 2.3, which ensures equal electrical conductance in both aluminum and copper conductors [5].

Two different configurations for the hybrid busbar distribution systems were chosen: (i) a radial configuration, in which one feeder (F) supplies two distribution points (DPs) placed along the main busbar, and (ii) a divided configuration, in which one feeder (F) supplies two distribution points (DPs) placed in independent branches of the main busbar. The main busbars, feeders, and distribution points used in each configuration of the electric distribution systems were fabricated from the aluminum and copper sheets by water jet cutting, according to the various geometries illustrated in Fig. 1. These geometries encompass sharp and rounded corners, as well as sharp and smooth transitions, to investigate their influence on current crowding and electrical resistance.

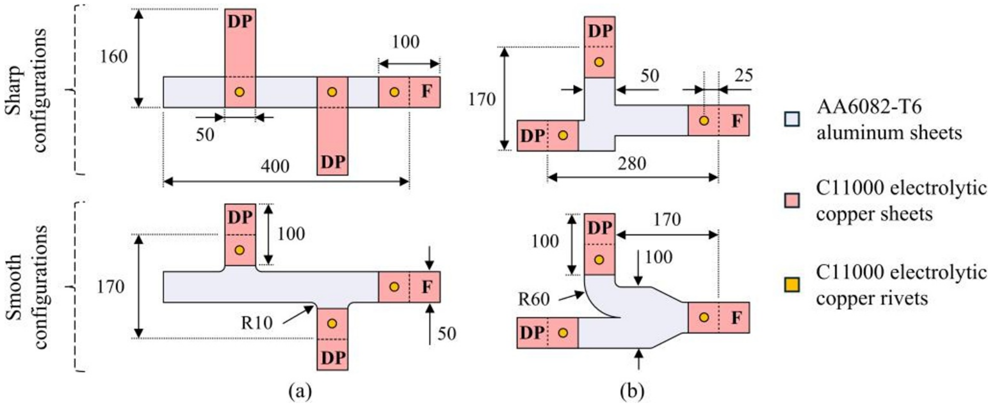

Fig. 1. Geometry and main dimensions of the (a) radial and (b) divided hybrid busbar distribution systems.

The assembly of the copper feeders and distribution points to the main aluminum busbar was performed using injection lap riveting (ILR), as illustrated in Fig. 2. The ILR process is carried out in two steps. Firstly, countersunk and dovetail ring holes are drilled in the copper and aluminum sheets using a countersunk drill bit and a special cutting tool developed by the authors [7], respectively. Then, each copper-aluminum joint is formed by forcibly inserting a semi-tubular rivet made from electrolytic copper C11000 through the countersunk hole of the copper sheet into the dovetail ring hole of the aluminum sheet using compression with a punch. The assembly by ILR was conducted at ambient temperature using a hydraulic testing machine (Instron SATEC 1200 kN).

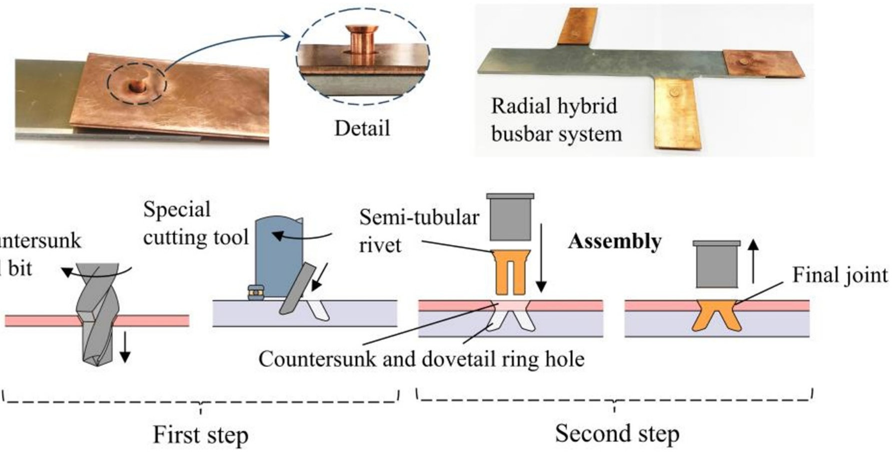

Fig. 2. Schematic representation of the injection lap riveting (ILR) process utilized for assembling the different parts of the hybrid busbar distribution systems. A photograph detail shows one of these joints before and after assembly.

2.2 Electrical characterization

The electrical resistance of the hybrid busbar distribution systems between the feeder and the distribution points was measured in an experimental setup developed by the authors.

The measurement was performed with a four-point probe technique [8] using a KoCos PROMET R600 micro-ohmmeter. The micro-ohmmeter supplied a 600 A current for approximately 2 seconds, while the voltage probes measured the drop in voltage that was necessary to determine the electrical resistance of the joints by Ohm's Law. Fig. 3 shows a photograph of the experimental setup.

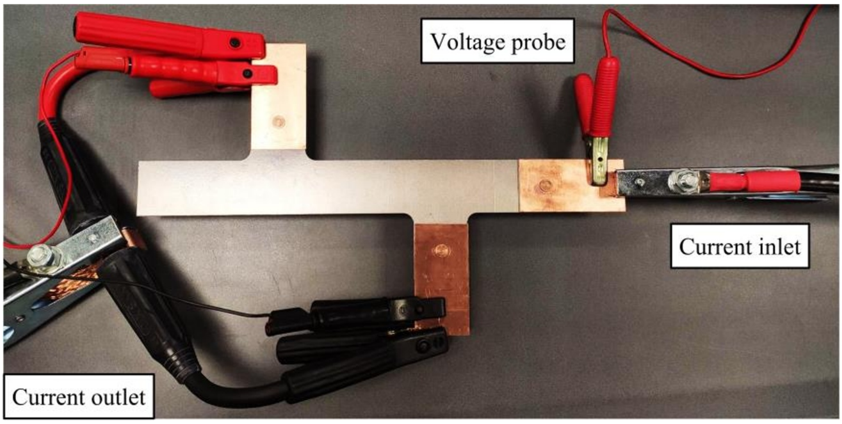

Fig. 3. Photograph of the experimental setup developed by the authors during the electrical characterization of a hybrid busbar distribution system with a divided configuration.

The same experimental setup was utilized to determine the electrical resistivity at ambient temperature of the aluminum ($\rho_{Al} = 40.6\ \mu\Omega \cdot \mathrm{mm}$) and copper ($\rho_{Cu} = 17.6\ \mu\Omega \cdot \mathrm{mm}$) sheets for subsequent use in numerical modelling.

2.3 Numerical modelling

Numerical modelling of the transmission and distribution of electric energy was conducted in the electric module of the in-house finite-element software i-form [5]. The different configurations with geometric variations (refer to Fig. 1) were discretized by approximately 50,000 hexahedral elements, while the grippers that are used to apply the electric current of 600 A were approximated by a rigid, non-conductor, object that was discretized by means of spatial triangular surface elements (Fig. 4).

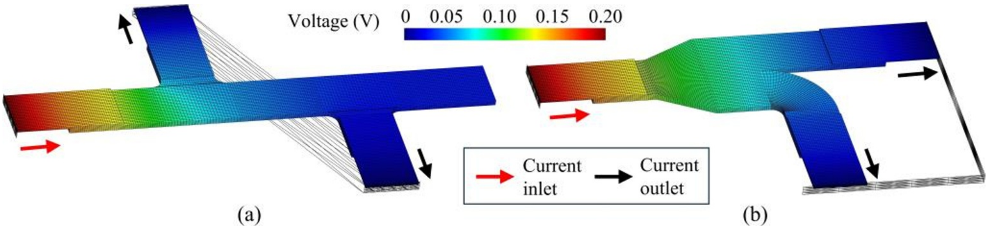

Fig. 4. Three-dimensional finite element models utilized in the (a) a radial and (b) a divided hybrid busbar distribution system.

The models did not account for the influence of temperature because the electric characterization of the hybrid busbar distribution systems was carried out at ambient temperature and because the temperature rise during the very short time duration of each measurement performed with the micro-ohmmeter was negligible (below 1℃). Electrical finite element simulations were carried out for ideal configurations without rivets, in which all the adjacent sheets are in perfect contact and without contaminant or oxide films along their contacting interfaces.

The simulations performed under these modelling conditions provided the minimum electrical resistance values that will be used in the following sections of the paper for comparison and normalization purposes. A simple ideal busbar consisting of a feeder and a distribution point was also simulated for comparison purposes.

3 Results and Discussion

Fig. 5 shows the finite element predicted distribution of electric current density for the two different configurations and geometric variations of the hybrid busbar distribution systems that are shown in Fig. 1.

As seen, current density is uniform through the cross-sectional surfaces of the feeder and distribution points, where the current enters and exits the distribution system. Current density builds up and redistributes non-uniformly around sharp corners and geometric discontinuities. This is because electric current can take a shorter path between the feeder and the distribution points in sharp corners and geometric discontinuities, rather than traveling along longer paths, which inherently possess higher resistance.

However, despite the reduction in path length, the electrical resistance increases due to current crowding at the corners and sharp transitions, as seen in Fig. 6.

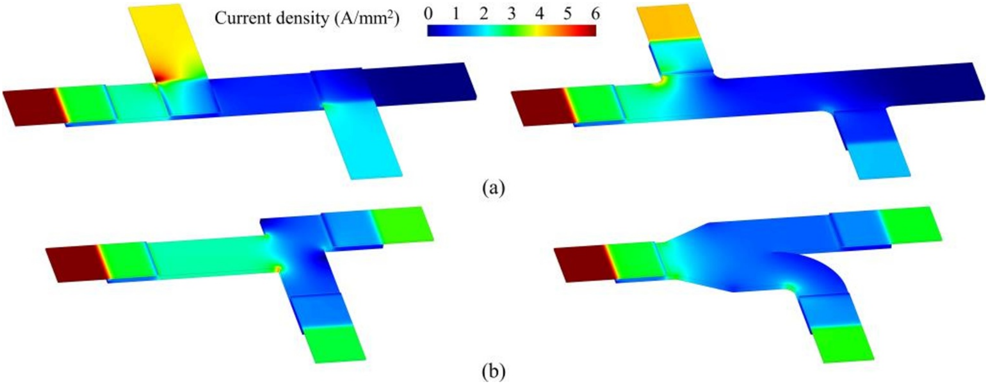

Fig. 5. Finite element predicted distribution for two different geometries of the (a) radial and (b) divided configurations of the hybrid busbar distribution systems.

In addition to the increase in electrical resistance observed in the easier-to-manufacture geometries with sharp corners and transitions, results also indicate appreciable differences between the values obtained for the ideal joints with perfect contact and no contaminants or oxide films between the two overlapped sheets, and those obtained for the real joints fabricated by ILR.

Still, the ratios between the electrical resistances of the injected lap riveted joints featuring smooth corners and transitions and the ideal joints for the two types of configurations (1.62 – radial, and 1.41 - divided) are close to the ratio of 1.39 obtained for the hybrid busbar with one feeder and one distribution point, which is included for reference purposes in Fig. 6. This confirms the good electrical performance of the newly proposed joints.

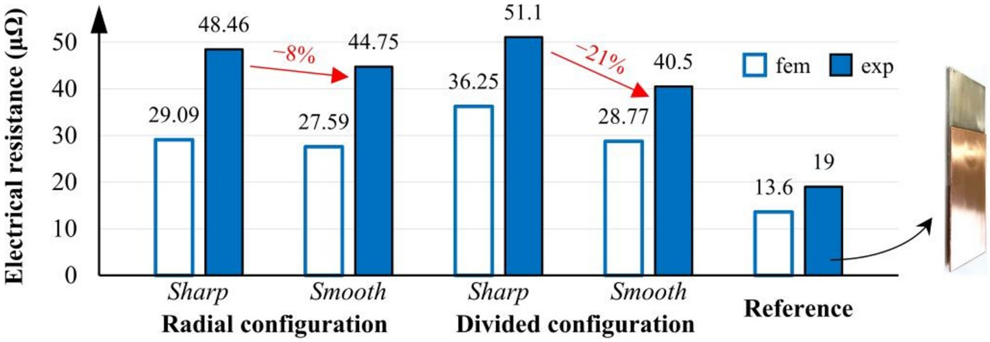

Fig. 6. Experimental and finite element predicted values of electric resistance for the configurations and geometric variants of the hybrid busbar distribution systems that are shown in Fig. 1. The reference case is a simple hybrid busbar consisting of a feeder and a distribution point.

4 Conclusions

The design of copper-aluminum (hybrid) busbar distribution systems must prioritize both ease of fabrication and assembly as well as electrical performance. Electric finite element analysis should thus play a role similar to finite element analysis of the assembly processes.

Configurations with rounded corners and smooth transitions exhibit lower electrical resistance compared to simpler and easier-to-fabricate geometries with sharp corners and sharp transitions, due to current crowding. Differences account for 8% in the case of radial configurations and 21% in the case of divided configurations.

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