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A Thermal-Mechanical Approach for the Design of Busbars Details

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Abstract

The mechanical behavior of busbars is a complex, displacement-controlled problem intimately linked to the conductors' temperature. Thermal stresses are generated between two bodies submitted to differential thermal expansion, such as a pair of busbars at different temperatures that are mechanically connected at multiple locations. It can also occur to a single busbar circuit if the system lacks the required flexibility to accommodate the hot conductors-to-cold supports differential thermal expansion.

An approach for the thermal-mechanical design of busbars was developed using ANSYS™-based numerical simulation. Special attention is given to specific design features such as weld plates, flexible joints, sliding supports and fixed points positioning for they play a major role on both the thermal expansion's preferential direction and system's ability to accommodate it.

A test case based on a demonstration busbar system is presented and the impact of geometry and temperature on the thermal-mechanical performance of those specific features is discussed.

Introduction

Busbars are an integral part of the aluminum reduction technology and their design has a profound impact on the stability and performance of cells, notably through magneto-hydro-dynamics (MHD) effects. However, on the most basic level, their purpose is to collect current from the cathodic part of a cell and feed it to the anodic part of the next. Busbars are also needed to connect groups of cells, for example at passageways and between potrooms, and to carry the electrical current to and from the rectifiers.

The reliable operation of these conductors is therefore of capital importance to sustaining smelter operations. The mechanical performance of the system is intimately linked to the thermal expansion and its ability to accommodate it.

Thermal stresses are generated when a body has its thermal expansion restrained somehow. The positioning of sliding supports and fixed points is of key importance for they provide a preferential direction for the thermal expansion and, consequently, the means to obtain the required flexibility by allowing the design of suitable flexible joints as well as gaps between conductors and guides/stoppers.

This article discusses the thermo-mechanical performance of specific design features such as weld plates and flexible joints. It also introduces a methodology to access the behavior of long conductor arrangements such as liaison busbars (input/output circuits, crossovers), compensation loops and booster circuits.

Long Busbars Thermal-Mechanical Behavior

The thermal-mechanical (TM) behavior of structures is a complex, displacement-controlled problem. If a given body is submitted to a condition that differs from its expansion-free temperature, it will experience a change on its dimensions – the linear thermal expansion can be calculated by Equation (1).

$$\Delta L_{th} = L_0 \cdot \alpha_{th} \cdot (T_{bus} - T_0) \quad (1)$$

Where: ΔL_{th} is the thermal expansion, [m]; L_0 is the body length measured at a reference temperature, [m]; α_{th} is the temperature-dependant material's thermal expansion coefficient, [°C^{-1}]; T_{bus} is the equivalent body temperature, [°C]; and T_0 is the reference temperature, [°C]. T_0=20°C is assumed in this work.

If said component has its volume change restrained somehow, thermal-mechanical stresses will develop, typically due to the differential expansion between two different bodies (or even regions within the same body). This phenomenon is easily recognizable on the thermal expansion ΔL_{th} vs. gap δ problem (Figure 1), where compressive stresses necessarily develop when the thermal expansion ΔL_{th} is larger than the gap δ.

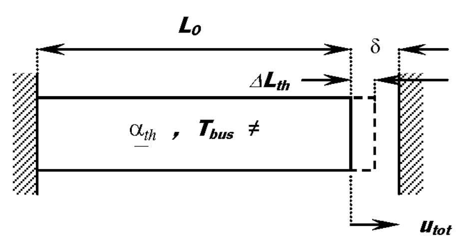


Figure 1 – Thermal expansion vs. gap problem.

The mechanical strain ε_{mech}, *i.e.*, the one that generates stresses, equals to the difference between the total ε_{tot} and thermal ε_{th} strains:

$$\varepsilon_{mech} = \varepsilon_{tot} - \varepsilon_{th}$$
$$\varepsilon_{mech} = \left(\frac{u_{tot}}{L_0}\right) - \alpha_{th} \cdot (T_{bus} - T_0) \quad (2)$$

Where: ε_{mech} is the mechanical strain, [-];ε_{tot} is the total strain, [-]; ε_{th} is the thermal strain, [-]; and u_{tot} is the total displacement, [m].

Equation (2) clearly shows that the existence of mechanical strains (and stresses) is governed by the total displacement-to-free thermal expansion ratio $u_{tot}/\Delta L_{th}$:

- No stresses are generated as long as $u_{tot} = \Delta L_{th}$;
- Tensile stresses are generated when $u_{tot} > \Delta L_{th}$;

- Compressive stresses develop when $u_{tot} < \Delta L_{th}$.

The typical function of long conductors (*i.e.*, transport of electrical current over considerable lengths) and the consequent overall slender geometry lead to some remarkable differences with respect to the thermo-electro-mechanical behavior of pot-to-pot busbars:

- <u>Geometry and interaction between conductors</u>: pot-to-pot busbars are usually connected together by means of tie rods at the shunting clamping stations and their mechanical behavior depends on the interaction between the different pot-to-pot circuits [1] while long busbars can be mostly treated as beams that are connected at certain locations by means of weld plates and flexible joints;
- <u>Current density and temperature</u>: while loading of pot-to-pot busbars is strongly dependent on process conditions (lining design and potshell temperature, normal operation/bypass mode and contact resistances, as discussed in [2]), the main parameter that impacts the internal heat generation of long conductors is the amount power provided by the rectifiers. Furthermore, the temperatures of these circuits can be estimated by a simplified bidimensional (2D) thermo-electrical approach, whereas pot-to-pot busbars are inherently tridimensional (3D) problems;
- <u>Thermal expansion and stresses</u>: the geometry of the conductors may inherently lead to thermal stresses. In the case of pot-to-pot circuits, two parallel busbars with different temperature distributions may be welded together at two different locations thus generating thermal stresses. Long conductors, on the other hand, may develop thermal stresses if the circuit lacks flexibility to accommodate its own thermal expansion. Note that special attention should be given to potential direction changes in order to avoid the generation of bending moments.

The calculation of the displacement and consequent stress and strain fields of long busbars is a complex, non-linear problem. In order to assist smelters to evaluate the performances of busbars systems under realistic operating conditions, a mixed analytical and Finite Element-based analysis methodology was developed.

Long Busbars Modeling Approach Description

There are three distinct body forces that can act on long busbars: temperature distributions, gravity and Lorentz forces.

<u>Busbar Temperatures</u>

As mentioned earlier, the rather slender shape of long conductors allows for the usage of a previously published [3] simplified 2D thermo-electrical (TE) approach with the following characteristics (see Figure 2):

- Volumetric heat generation;
- Cross-sectional heat conduction;
- Material properties for both aluminum busbars and air as functions of temperature;
- Radiation to ambient: if a pack of identical parallel busbars with the same current load is considered, the vertical surfaces-to-ambient view factor is calculated by means of analytical expressions. If, on the other hand, a single conductor is considered, the view factor equals to unity;
- Convection to ambient: convenient convection heat transfer coefficients applied to the busbar perimeter. Note that the air velocity due to the potroom's draft can be either measured in existing plants or accessed by means of detailed potroom ventilation models [4]. Furthermore, natural convection can be considered as a worst-case scenario.

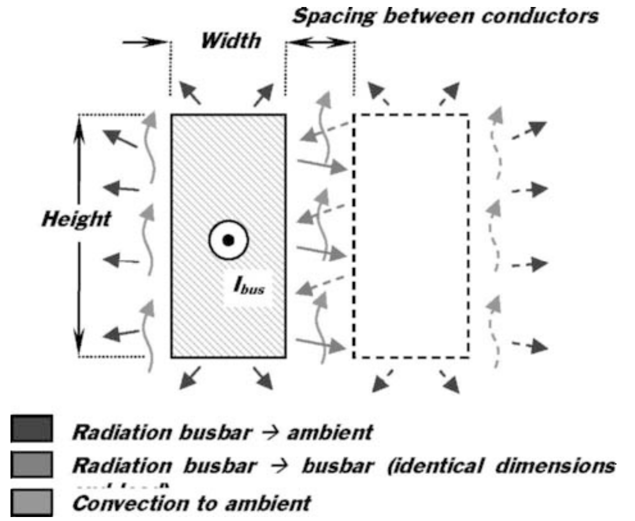


Figure 2 – Heating and cooling mechanisms acting on long conductors.

Note that the TE analysis output not only provides the driving force for thermal expansion but also allows the evaluation of temperature-dependent aluminum mechanical and physical properties show in [1].

<u>Lorentz Forces</u>

The interaction between the busbar current and the magnetic field surrounding it generates Lorentz forces, Figure 3. These ever present electromagnetic forces, which are particularly intense during a short circuit situation, may largely increase the reactions on the civil structure and should be taken into account during the circuit design.

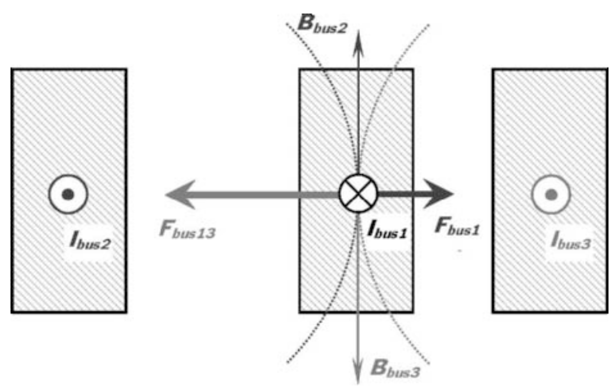


Figure 3 – Electromagnetic forces acting on long conductors.

Lorentz forces between parallel conductors can be estimated according to Equation (3). Note that complex busbar arrangements (and the eventual presence of ferromagnetic materials) can be studied in greater depth by the usage of numerical methods, such as Finite Element Analysis (FEA).

$$F_{pq} = \left(\frac{\mu_0}{2\pi}\right) \cdot I_p \cdot I_q \cdot \left(\frac{L_{pq}}{d_{pq}}\right) \cdot k \qquad (3)$$

Where: F is magnitude of the total force between the considered conductors, [N]; μ_0 is the magnetic permeability of vacuum, [H/m]; I is the busbar current, [A]; L is the length of the parallel conductors, [m]; d is the distance between the parallel conductors, [m]; k is the effective spacing correction factor, [-]; and the indexes p and q relate to conductors p and q, respectively.

Global Unidimensional Thermo-mechanical Model

Once again, the typical elongated shape of the conductors at hand allows one to describe the circuit's overall behavior by means of a unidimensional (1D) TM model[1], Figure 4, which takes the following characteristics into account:

- Busbars geometry, including the location of flexible joints. Presence of spacers between busbars is also taken into consideration;
- Positioning and type – simple, sliding or fixed – of considered supports. Impact of the gap δ (or lack of it) between the civil structures and the conductors is accounted for;
- Busbars thermal expansion, based on the temperatures calculated by the above mentioned 2D TE approach;
- Inclusion of Lorentz forces for both normal operation and short-circuit situations, based on either analytical or numerical assessment.

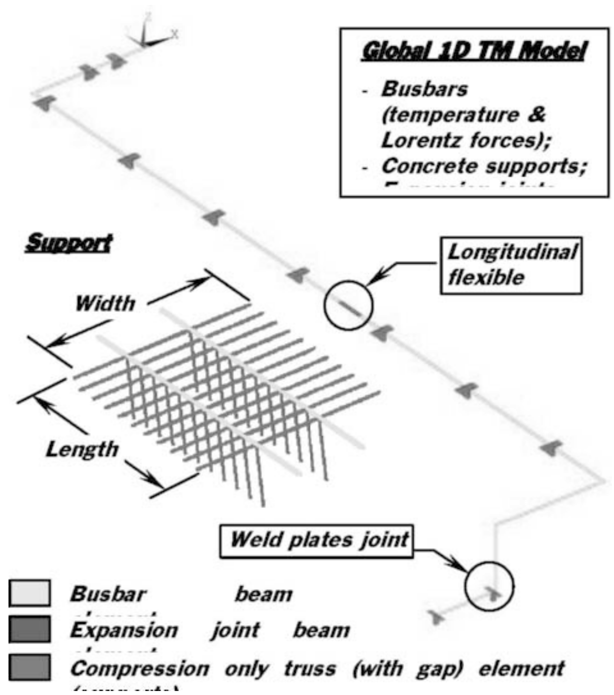
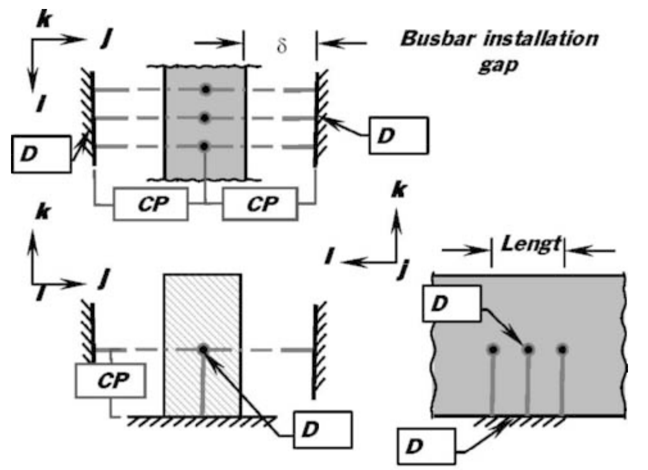


Figure 4 – Global 1D TM model.

[1] Considered material properties can be found in [1].

The interaction between the conductors and their supports is represented by means of compressive only truss elements (Figure 5), where no loads are transferred to a given surface of the civil works if the busbar moves away from it. Furthermore, convenient degrees of freedom (DOF) are coupled (CP) between the two defining nodes of the compression only link element in order to avoid spurious traction and, consequently, unrealistic loss of contact between the busbar and the civil structure. The loads acting on a busbar support can be seen in Figure 6.



Type	Name	DOF	Comment
Simple	D #2	Uk	= 0
	D #3	Roti	= 0
	CP #2	Ui, Uj	Coupled DOF
Sliding	All the above and		
	CP #1	Ui, Uk	Coupled DOF
	D #1	Uj	= 0
Fixed	All the above and		

Figure 5 – Interaction between busbars and the civil works, represented by means of compression only truss elements.

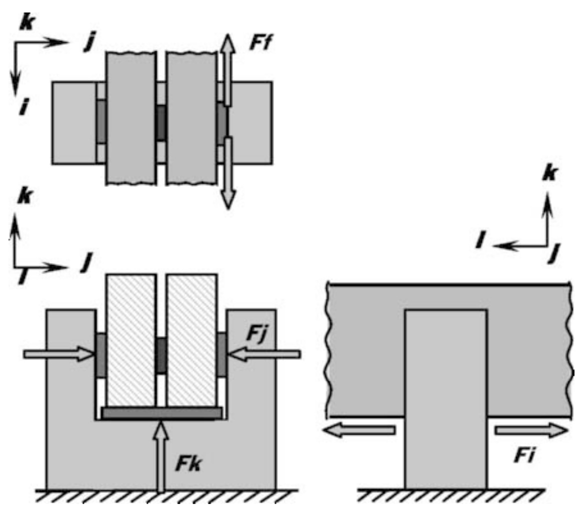


Figure 6 – Loads acting on busbars supports.

Specialized Submodels

Specific design features, such as flexible joints and weld plates, can de studied in greater depth by the usage of specialized submodels, which include frictional contact-target element pairs between each and every flexible sheet (or weld plate).

The traditional flexible joint is made of several sheets stacked together which bend in-plane in order to accommodate differential displacements between its two extremities thus allowing one to represent it as a 2D problem. The first step of analysis consists in creating the spacing between the flexible sheets by taking the joint from forming to installation position, Figure 7, which is then defined as the stress-free geometry. Prescribed displacements, representing the total thermal expansion to be absorbed by the component, are then applied at the submodel's cut boundaries. Furthermore, it is worth mentioning that the previously calculated busbar temperatures are only used to estimate the material properties, making it a pure mechanical (M) analysis.

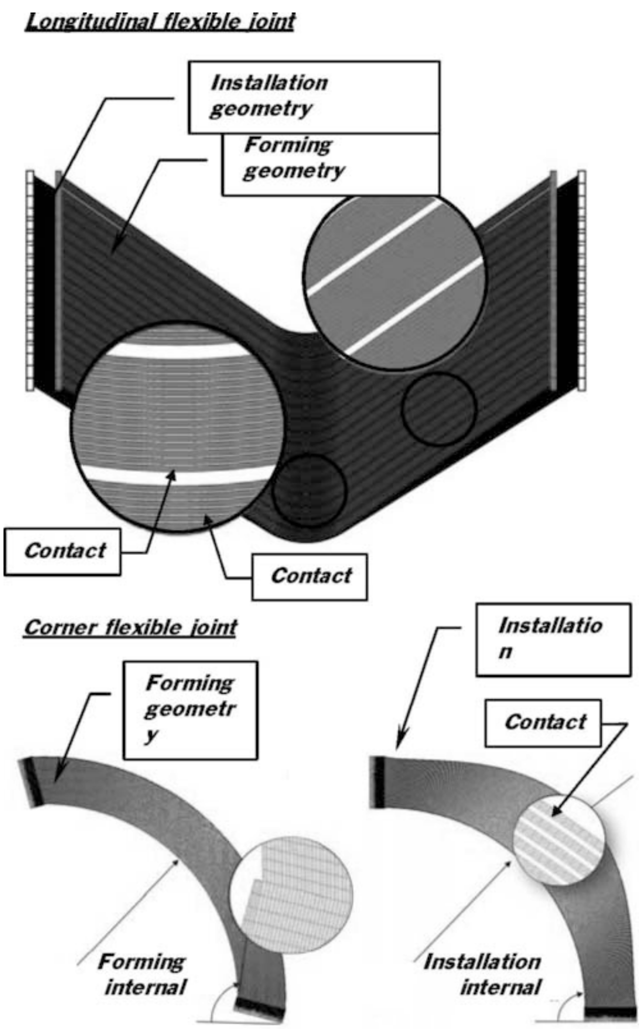


Figure 7 – Flexible joint 2D M submodel.

A weld plate joint, on the other hand, must be treated as 3D problem, given that its limit case would be that of a solid busbars assembly, which is potentially submitted to differential displacements and rotations on all three directions (evidently, depending on geometry and constraints).

The specialized 3D weld plate submodel – see Figure 8 – takes all the aforementioned body loads into account: gravity, thermal expansion (temperatures obtained from the 2D TE analysis) and Lorentz forces (which is included as equivalent accelerations). The Global 1D TM model provides the mechanical boundary conditions to be prescribed at the submodel extremities.

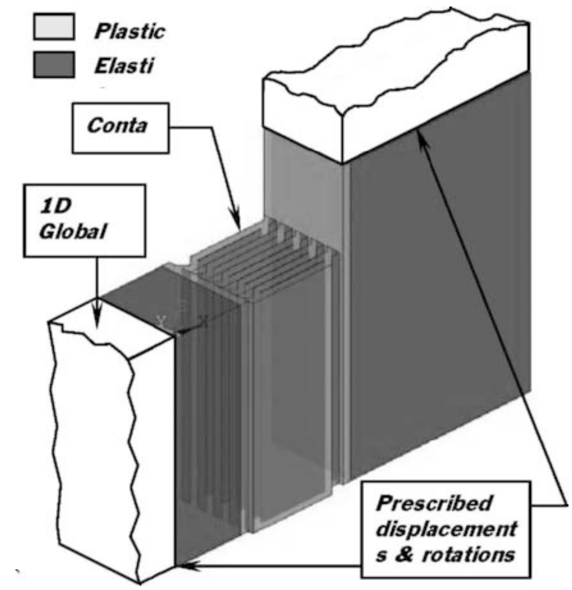


Figure 8 – Weld plates joint 3D TM submodel.

Typical Analysis Workflow

Figure 9 shows the typical analyses involved on the assessment of the long busbars performance.

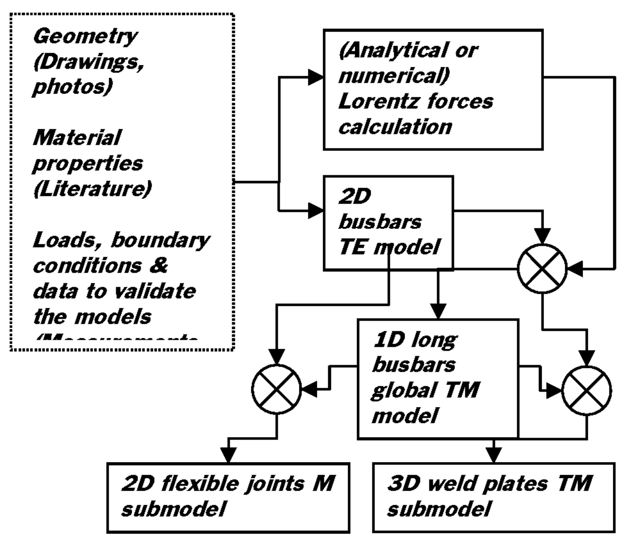


Figure 9 – Typical workflow for the assessment of long busbars performance.

Test Case Model

In order to illustrate the proposed approach's capabilities, a fictitious busbar arrangement will have its TM performance assessed. This circuit is used to boost 10 fictitious cells[2] by 50 kA, see Figure 10. Note that only the positive circuit will be studied.

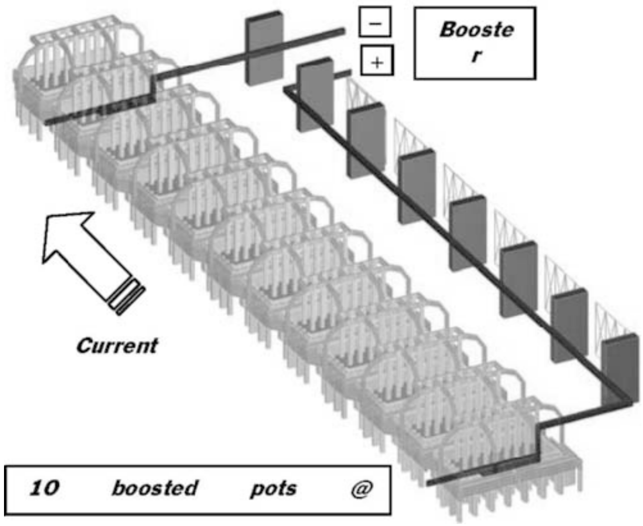


Figure 10 – Fictitious booster test section at 200 kA.

The *original* concept[3] consists of two parallel busbars of 300 mm X 125 mm (spacing between conductors = 25 mm), supported by 11 concrete supports and having one longitudinal flexible joint, as previously shown in Figure 4.

The 2D TE calculations show that the conductors' temperature would be 136°C when running at 50 kA, summer conditions (30°C), natural convection and aluminum's emissivity = 0.2. Lorentz forces representing the booster short-circuit case[4] ($I_{booster}$ = 200 kA, I_{line} = 150 kA) are considered. The Global 1D TM model provides the circuit's overall behavior – see Figure 11.

The civil works loading is quite dependent on the spacing between conductors and their lateral guides, as per Table 1. It can be clearly seen in that the lack of a proper gap δ – *i.e.*, lack of flexibility in the system to accommodate displacements – would considerably increase the horizontal loads *Fj* on the supports, as expected.

Table 1 – Impact of δ in civil works loading, [kN].

	Fl	*Fj*	*Fk*	*Ff = 0.3*Fj*
δ = 0 mm	3.3	5.0	6.5	1.5
δ = 10 mm	3.1	0.9	6.5	0.3

The combined action of thermal expansion, Lorentz forces, busbars supports and flexible joint positioning on the *original* concept causes the weld plate joint at the base of the vertical segment – refer to Figure 4 and Figure 8 – to experience a complex combination of loads in all 3 directions which leads several weld fillets to yield, as per Figure 12.

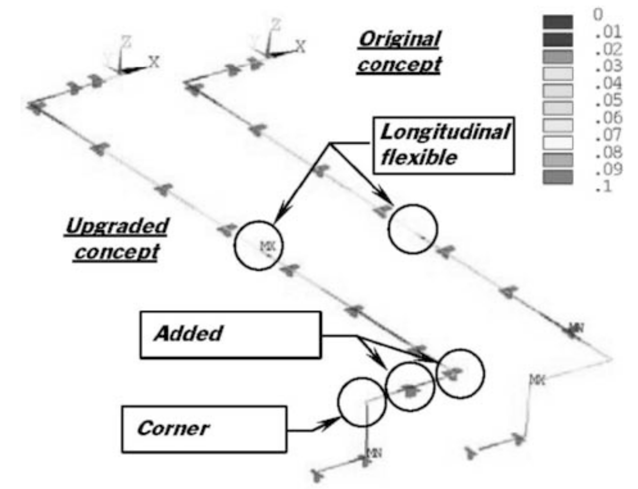


Figure 11 – Displacements for both *original* and *upgraded* concepts, [m].

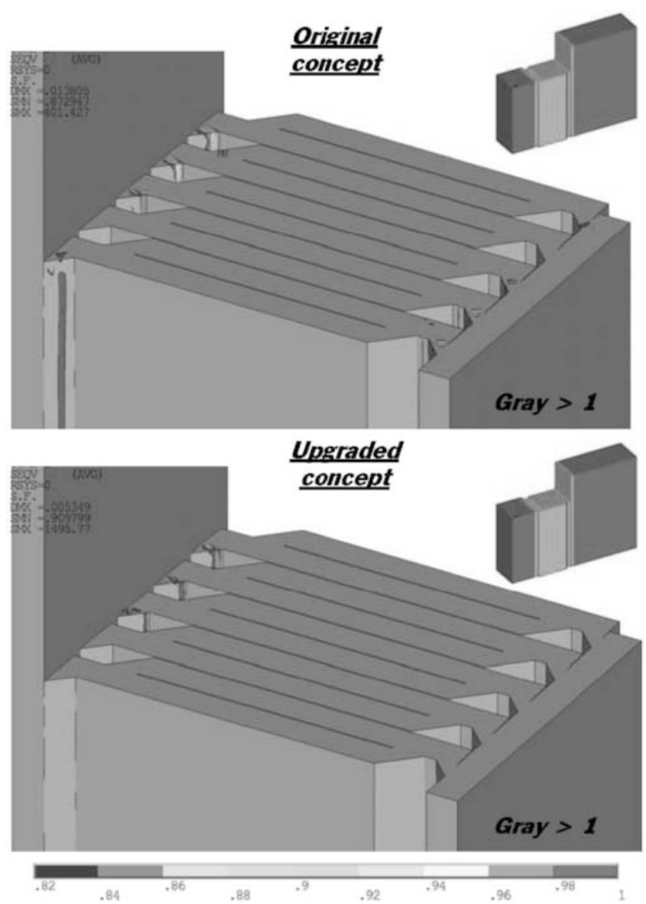


Figure 12 – Vertical weld plates joint: safety factor with respect to yield SF_Y, [-], for both *original* and *upgraded* concepts.

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[2] Previously introduced in [2].

[3] Note that potential impact of the booster circuit in the MHD behavior of the cells is beyond the scope of this work. In a real-life case, its layout is determined by process requirements.

[4] Note that these forces are ~ 17 times larger than those under normal operation conditions ($I_{booster}$ = 50 kA, I_{line} = 150 kA).

These results motivated the development of an *upgraded* concept featuring 2 additional supports and a corner flexible joint – see Figure 11, in order to avoid the transfer of loads between the vertical and overhead conductors. It can be seen in Figure 12 that the added flexibility effectively reduced the efforts over the weld plates joint thus substantially reducing the plasticized zone. Further improvement might be obtained by stacking the plates *horizontally* in order increase the assembly's rigidity parallel to the busbars thickness (Figure 13). Finally, reductions in both the conductors' temperatures (by modifying the surface emissivity or the ventilation conditions, for instance) and the Lorentz forces (normal operation instead of short-circuit case) are likely to enhance the system's mechanical performance.

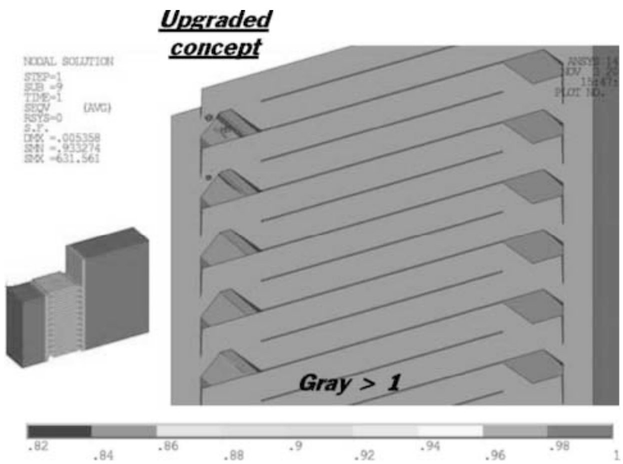

Figure 13 – Horizontal weld plates joint: safety factor with respect to yield SF_Y, [-], for the *upgraded* concept.

Both the corner and the longitudinal flexible joints were designed to accommodate the total displacement imposed by the solid conductors for the *upgraded* concept (see Figure 11) without causing plastic deformations to the sheets-to-busbar weld fillets – see Figure 14 and Figure 15, respectively.

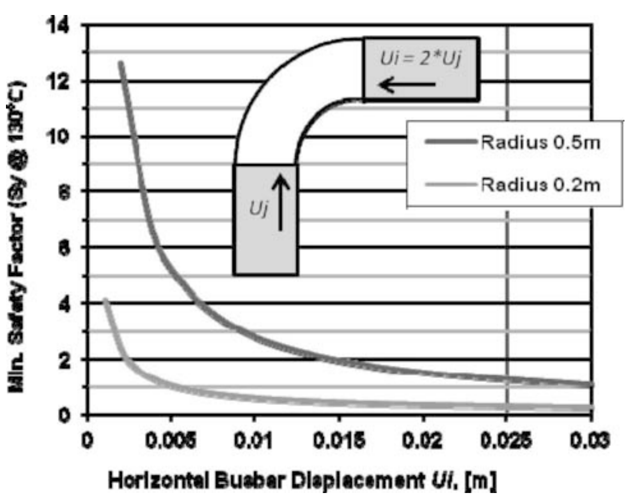

Figure 14 – Corner flexible joint: evolution of the safety factor with respect to yield SF_Y, [-], at the sheets-to-busbar weld fillets for the *upgraded* concept as a function of imposed displacement and forming internal radius.

Note that the safety factor with respect to yield decreases with increasing prescribed displacement. It is also noteworthy to mention that, for any given displacement *Ui* (and *Uj*), SF_Y increases with increasing forming dimensions, *i.e.*, that the joint becomes less rigid thus generating less mechanical stresses.

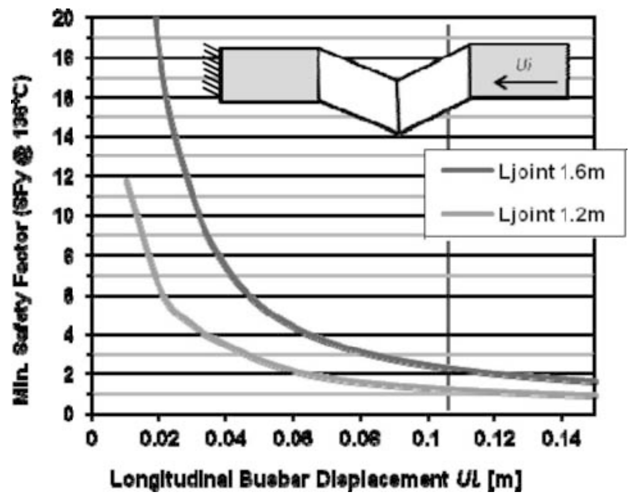

Figure 15 – Longitudinal flexible joint: evolution of the safety factor with respect to yield SF_Y, [-], at the sheets-to-busbar weld fillets for the *upgraded* concept as a function of imposed displacement and forming overall length.

It is important to note, however, that yield is virtually unavoidable at the most external fibers of each sheet as a consequence from the extreme flexion to which these components are submitted once in operation.

Conclusions

A numerical simulation methodology was proposed for the assessment of the thermal-mechanical performance of long busbars systems and specific design features such as flexibles and weld plates joints. Said approach takes gravity, conductors' thermal expansion, and Lorentz forces into account. It is important to note that the circuit's flexibility has a remarkable impact on every aspect of the system's behavior, from supports sizing to reliability of weld plate joints. It was shown that special attention must be given to both rigid and flexible joints for they can be seen as the system's weak links, where mechanical stress concentrations might occur. Furthermore, it was shown that both the orientation of weld plates and the forming dimensions of flexible joints impact the performance of said components.

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