Impact of Amperage Creep on Potroom Busbars and Electrical Insulation: Thermal-Electrical Aspects

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Abstract

Busbars electrical insulation is a critical aspect of aluminium smelters potrooms electrical safety. With amperage creep, busbars are typically running hotter than they were at start-up. The long-term reliability of busbars and the integrity of insulating materials is therefore of concern.

To assist smelters evaluate the performance of the busbars systems under realistic operating conditions, a methodology was developed using ANSYS™-based numerical simulation, laboratory testing and *in situ* measurements. This approach has been validated on different pot technologies and smelters.

A realistic test case based on a demonstration busbar system is presented and the typical impact of line current, ambient temperature and selected operational procedures on thermal-electrical performance and reliability is discussed.

Introduction

Busbars are an integral part of the aluminium 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 and their insulating materials is therefore of capital importance to sustaining smelter operations and workers safety.

Typically, busbars design will be dictated by a target electrical current distribution mostly based on MHD considerations and acceptable collector bar current unbalance (bar-to-bar, upstream/downstream, tapping end/duct end). To reduce cost, sizing of the bars is often based on the minimum bar cross-section at the maximum allowable temperature. Insulators are also selected based on that allowable temperature.

Past experience has shown that the window for a trouble-free operation of these components tends to reduce with increasing ambient temperature, pot line current and contact resistance between non-welded assemblies, such as in bolted connections and short-circuiting stations. In particular, excessive heat generation due to increased current or poor contact resistance has led to busbars systems damage and, in extreme cases, to catastrophic failure of both conductors and insulators. Poor cooling conditions, for example due to excessive covering material in the potroom basement, can also contribute to busbars overheating. Amperage creep and operational procedures therefore play an important role in the performance of busbars.

Pot-to-pot Busbars Heating & Cooling Mechanisms

In a continuous busbar, heat is internally generated by the passage of electrical current through it, as per Equation (1).

$$q'''_{gen,busbar} = \rho \cdot J^2 \qquad (1)$$

where: $q'''_{gen,busbar}$ is the volumetric heat generation in a continuous busbar, [W/m^3]; $\rho = f(T)$ is the temperature-dependant material's electrical resistivity, [Ω.m]; and J is the conductor's current density, [A/m^2].

On the other hand, when surfaces from different bodies are in contact, a localized heat generation occurs at the interface due to the imperfect contact, represented by a contact resistance, shown in Equation (2).

$$q''_{gen,contact} = R_{ctc} \cdot J^2 \qquad (2)$$

where: $q''_{gen,contact}$ is the interfacial heat generation at the contact between different conductors, [W/m^2]; R_{ctc} is the contact resistance between neighbor conductors, [Ω.m^2].

By inspecting these equations it is obvious that increasing current density J (through amperage creeps for instance) or increasing contact resistance R_{ctc} (for example on risers bolted connections, bypass wedges and start-up shunts) leads to increased Joule Heat generation and, consequently, leads to increased busbars and insulators temperatures.

Heat can also be conducted from the hotter cathode block/collector bar assemblies to the colder pot-to-pot busbars through the flexibles linking them. Furthermore, conductor surfaces facing the potshell will be exposed to radiant heat loads.

Busbars are mainly cooled by means of convection and radiation to the ambient. Potroom building ventilation will generally determine the air flow around the conductors.

Heat is also redistributed in the busbars through conduction. For example, a large section busbar with a low current density can act as a heat sink for a conductor with higher current density. Heat is also transferred between neighboring busbars by means of bus-to-bus radiation.

Note that all these heat generation and transfer mechanisms (depicted in Figure 1) are dependent on the potline current, busbar system, pot room ventilation and cell designs, and operational procedures.

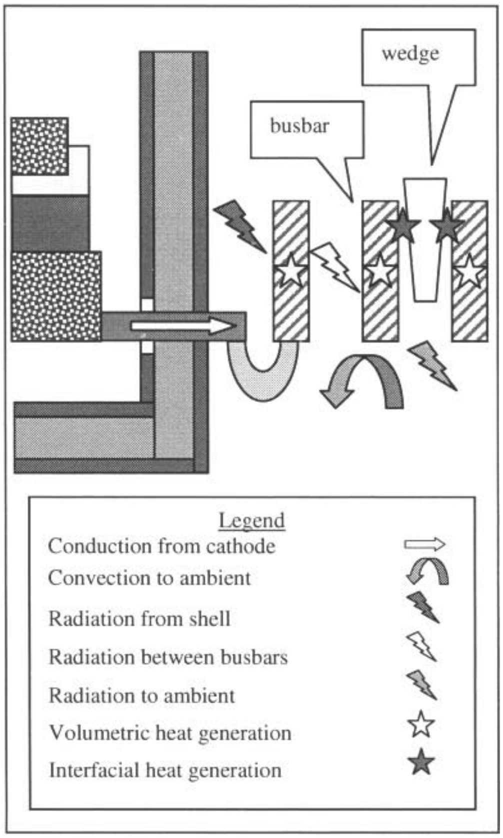

Figure 1 – Heating and cooling mechanisms acting on pot-to-pot busbars.

Cell-to-Cell Busbars Thermo-Electrical Problem Modeling

The calculation of the temperature and voltage distributions in the busbars is a non-linear coupled problem through Joule heating and the temperature-dependent nature of aluminium electrical resistivity. To solve this thermo-electrical (TE) problem and assess the operational performance of busbars systems, a methodology was developed using ANSYS™-based numerical simulation, laboratory testing and *in situ* measurements.

The proposed approach, which has been validated on different pot technologies and smelters, can be used to assess the performance of busbar systems and their insulators regarding the impacts of potline current intensities, contact resistances and ambient conditions.

Finite Element TE Model Assumptions and Characteristics

The fully parametric pot-to-pot busbars TE Finite Element (FE) model spans two consecutive metal pads (*i.e.*, two consecutive equipotentials) allowing the electrical current to redistribute itself according to the equivalent resistance of each circuit. The pot shell, busbars supports and insulators are included in the thermal calculation. Normal operation (Figure 2), single (Figure 3) and multiple bypass conditions can be analyzed. The system is assumed to be in thermal equilibrium (*i.e.*, steady-state) and the temperature-dependent thermal conductivity and electrical resistivity of aluminum are considered to be those of the pure element.

During bypass analyses, short-circuiting wedges and equalizer components (*e.g.*, wedges or flexibles) can be included while the pot shell and collector bars flexibles can be removed. Note that the worst condition is when the hot pot shell is still in place (thus transferring heat through radiation to the busbars), the collector bar flexibles are cut and the extra equalizer components (if any) are not included (which forces the whole potline current to flow through a selected group of busbars, leading to increased current densities). Contact resistances at the risers bolted connections and between the wedges and shunting-clamping stations are also considered.

Reference voltage is applied at the bath/metal pad interface of the cell of interest and uniform anode current is prescribed at the next considered downstream interface, which is modeled by equivalent resistors representing the anode, rod, yoke and bath. Pot-to-pot, cathode assembly, busbars external and equivalent anode resistances are calibrated based on measured voltage break downs.

Temperatures are typically prescribed at the following locations:

- Busbars supports bottom (basement's ambient temperature);
- Cell of interest's bath/metal pad interface (~960°C);
- Cell of interest's cathode assembly's bottom (~900°C);
- Next downstream riser flexibles/anode bridge interface (measured or estimated anode bridge temperature).

The following heat generation and transfer mechanisms are considered (as per Figure 1):

- Volumetric and interfacial heat generation – see Equations (1) and (2), respectively;
- Busbars-to-busbars and cathode-to-busbars conduction;
- Shell-to-busbars, busbars-to-busbars, busbars-to-ambient and collector bars-to-ambient radiation – note that the sum of all view factors for any given surface necessarily equals to 1;
- Busbars-to-ambient and collector bars-to-ambient convection.

In Situ Measurements

For existing potlines, an extensive *in situ* measurements campaign is carried out in order to determine suitable boundary conditions for the pot-to-pot busbars TE model. A non-exhaustive list of the measurements typically performed includes:

- Air velocities and free-stream temperatures on the vicinity of cathode and anode busbars. Used on the determination of the temperature/velocity-dependent convection film coefficient $h_c=f(T,V)$ to be applied on busbars surfaces, which are calculated using well-known semi-empirical correlations [1];
- Thermographic survey of the pot shell's temperature distribution. The measured data is mapped onto the shell surface by using in-house Visual Basic and APDL macros, thus establishing the temperature profile to be considered in the shell-to-busbars heat exchange;

- Pot-to-pot, cathode, busbars external and equivalent anode voltage drop (for model calibration purposes);
- Risers bolted connection and wedge-to-shunting clamping stations equivalent contact resistances R_{ctc} (model calibration);
- Collector bars, risers and main cathode busbars current distributions (model validation);
- Cathode and anode busbars temperatures at several locations (model validation).

Laboratory Testing

Ideally, the data sheet of an electrical insulator should specify the maximum allowable temperature (temperature rating) that this component can be submitted to without degrading its insulating and mechanical properties. However, different suppliers may provide different temperature ratings for the same class of material or this data may even not be provided at all. In order to assess the operational limit of electrical insulators when available information is either contradictory or incomplete, laboratory testing under realistic operation conditions (regarding service temperatures and pressures) can be performed following well-established testing standards (*e.g.*, ASTM D3755).

Coupling with Cell Heat Balance and Potroom Ventilation Models

The pot-to-pot busbars TE model can be further coupled with external cell heat balance and potroom ventilation analyses. Two kinds of coupling can be considered:

- One-Way Coupling: both the cell heat balance and the potroom ventilation analyses are performed considering loads and boundary conditions obtained independently from the pot-to-pot busbars model. Their outputs (pot shell and cathode assembly temperatures; air velocities and temperatures, and convective heat transfer coefficient distributions at the vicinity of cathode and anode busbars) are then used as boundary conditions for the busbars TE analysis. This is generally what has been done;
- Two-Way Coupling: while the cell heat balance and the potroom ventilation analyses provide the required boundary conditions for the busbars TE model, they would in turn have some of their loads and boundary conditions defined by pot-to-pot busbars model's outputs. Potroom ventilation models can be fed with proper busbars heat generation rates. Cell heat balance models can use the predicted collector bars current distribution and busbars surface temperatures to fine tune the cathode heat generation rates and the pot shell's radiant heat losses. This is an iterative procedure that repeats itself until convergence is achieved. This would be an improvement on the approach used so far.

Test Case Model

In order to illustrate the proposed approach's capabilities, a fictitious pot-to-pot busbars circuit will have its performance assessed when running under different amperage, ambient and operational conditions. The considered system was designed to operate at 150 kA and originally consisted of side-by-side cells with a symmetric design and 4 identical end-risers – a typical 1970s topology, according to [2].

After continuous potline current increases, a major busbar retrofit transformed the downstream (DS) end risers into quarter side risers in order to reduce the magnitudes of both transversal and vertical magnetic flux density components. Note, however, the shunting-clamping stations, located close to the head walls upstream (US) corners, were kept untouched.

This modification brought the busbar design a step closer to typical 1980s concepts [2] and enabled, along with other important modifications, to operate the cells at 200 kA. Figure 2 and Figure 3 show the modified busbars and supports arrangement in normal operation and single bypass modes.

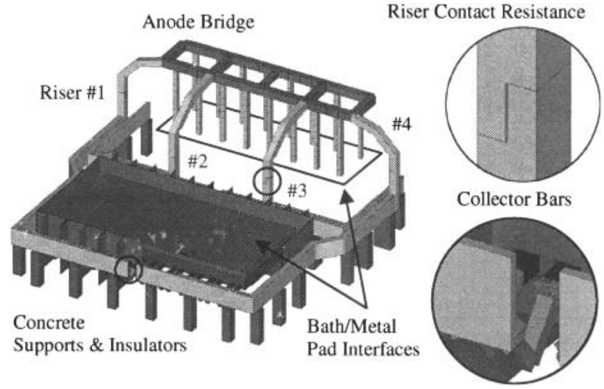

Figure 2 – Fictitious side-by-side busbars system with quarter and end risers in normal operation

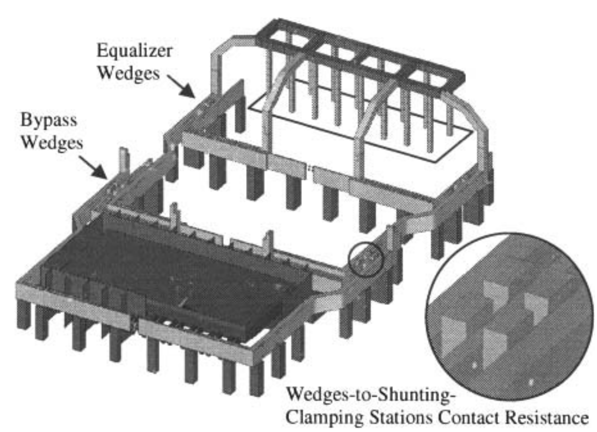

Figure 3 – Single cell bypass condition

Long-term operation at 200 kA led, however, to systematic failure of busbars and insulators in our fictitious smelter. A project was then carried out to investigate the damages probable causes and propose a viable, cost-effective mitigation strategy to avoid further damage. Upon the completion of the numerical tools, an *in situ* measurements campaign was performed during summer time to allow for model calibration and validation under worst-case ambient conditions[1]. Laboratory testing showed that electrical insulators start to degrade at 215°C and catastrophic failure occurs at 250°C.

[1] Minimum and maximum historical ambient temperatures are, respectively, 0°C and 30°C.

Normal Operation

Figure 4 shows the predicted busbars and supports temperatures for normal operation at 150 kA, 30°C. Note that even though the current is evenly distributed (~25%), the quarter risers (#2 & #3) are considerably hotter than the end ones (#1 & #4) due to increased radiant heat received from the pot shell's side walls.

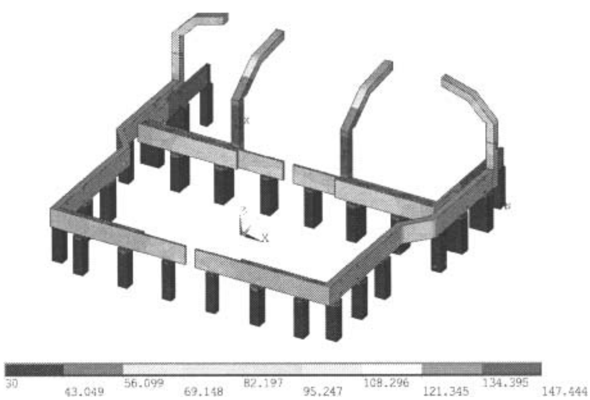

Figure 4 – Normal operation at 150 kA, 30°C: temperature distribution [°C].

Table 1 summarizes the predicted temperatures for normal operation under design and actual potline currents. It can be seen that the components temperature increases with both potline current and ambient temperature. Note that electrical insulators maximum numerical results are well within the maximum acceptable temperature (215°C) for all cases.

Table 1 – Normal operation: busbars and insulators maximum predicted temperatures [°C].

	150 kA, 30°C	200 kA	
		0°C	30°C
End Risers #1, #4	117	142	161
Quarter Risers #2, #3	148	179	203
Shunting-Clamping Stations Insulators	72	75	106
Supports Insulators	115	134	161

Single Bypass Condition at 150 kA

Figure 5 shows the predicted temperatures when bypassing one cell at 150 kA, 30°C, according to the standard operational procedures (use of equalizer wedges and typical shunting-clamping stations-to-wedges contact resistance $R_{ctc,wdg}$=0.080 μΩ.m^2). Maximum global temperatures occur at the end risers (#1 & #4) due to increased loading (32% of potline current each while each of the quarter risers #2 & #3 carry 18%). The bypassed cell's upstream head busbars evidently show increased temperatures for the same reason (50% of potline current each). Maximum electrical insulators temperatures at the shunting-clamping stations and supports are, respectively, 114°C and 125°C.

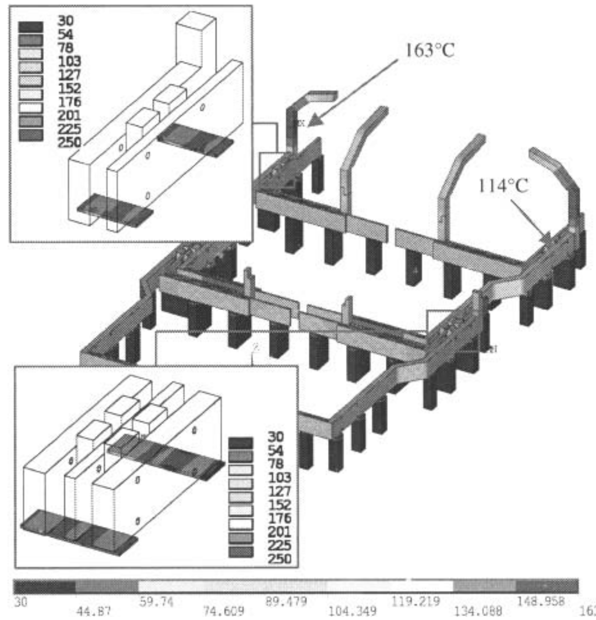

Figure 5 – Single bypass at 150 kA, 30°C: temperature distribution [°C] when following standard bypass procedures.

Practice in our fictitious smelter has shown, however, that the integrity of the electrical insulators could be maintained even when the pots were short-circuited without the systematic usage of the equalizer wedges at 150 kA, as shown in Figure 6. This resulted in a decrease of the labor involved on the bypass/pre-heating procedures and became the smelter's *modus operandi*. Furthermore, note that when the equalizer wedges are not in place, the quarter risers #2 & #3 are disconnected.

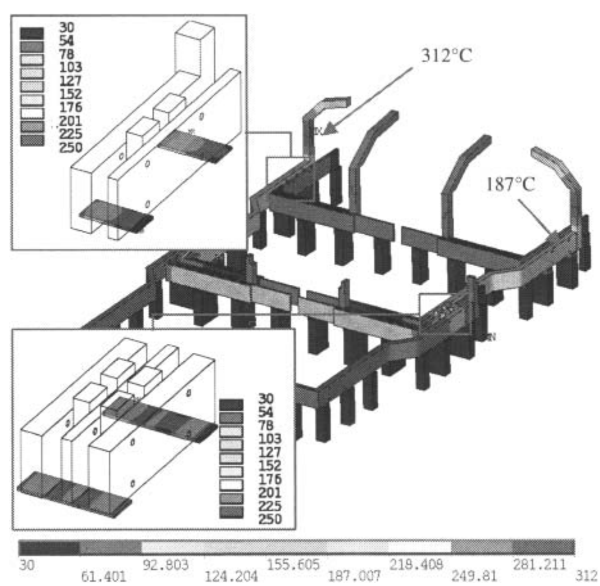

Figure 6 – Single bypass at 150 kA, 30°C: temperature distribution [°C] without equalizer wedges.

Single Bypass Condition at 200 kA

The fictitious plant's established practice of not installing the equalizer wedges led to severe degradation of the insulating materials when operating at higher amperages, as can be seen in Figure 7. End risers #1 & #4 temperatures can be as high as 490°C when bypassing the cells at 200 kA, 30°C without the equalizing wedges. The temperatures of the electrical insulators supporting the bypassed US head busbars can be higher than 250°C, as shown in the detail. The maximum predicted temperature of the shunting-clamping stations insulators is 290°C. As previously mentioned, the system's insulting materials experience catastrophic failure at 250°C.

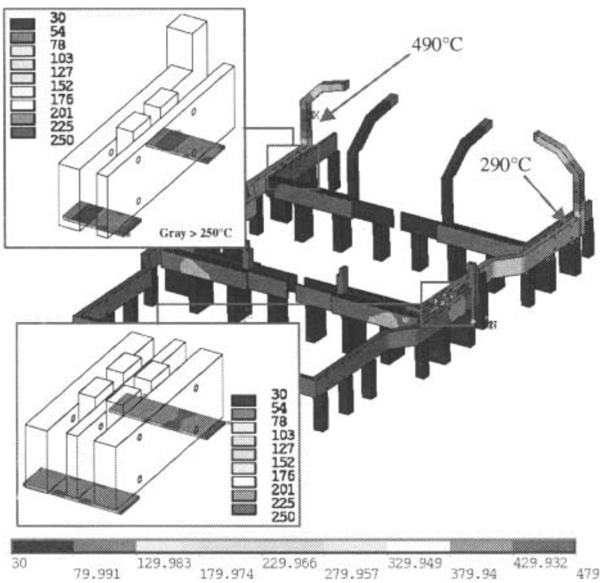

Figure 7 – Single bypass at 200 kA, 30°C: temperature distribution [°C] without equalizer wedges.

To illustrate the real-life implications of this, Figure 8 shows a busbar-to-support electrical insulator that has experienced severe damage under similar conditions.

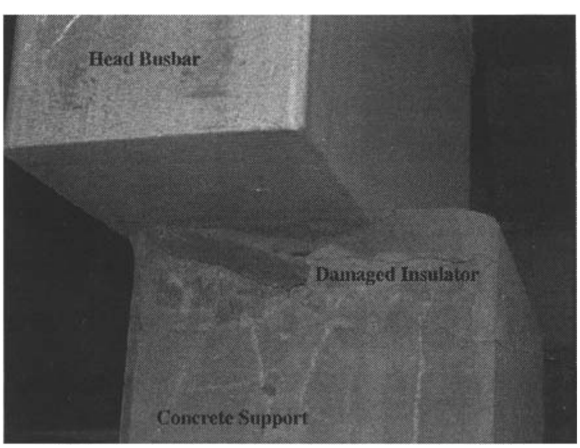

Figure 8 – Example of damaged electrical insulator.

Coming back to our fictitious potline, one also notes that the insulating materials of the shunting-clamping stations were also damaged. If enough electric potential difference between the cathode rings of two adjacent pots is experienced (*e.g.*, a severe anode effect), the current may flow through the steel spacers and/or tie rods. Again, Figure 9 shows a real-life severely damaged shunting-clamping station that conducted part of the potline current through its steel spacers under similar conditions. Part of the aluminium busbar melted while the steel spacer and the bottom tie-rod and insulating tube assembly fell in the basement.

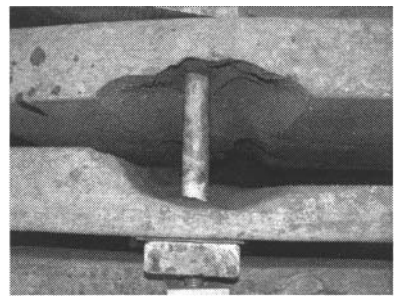

Figure 9 – Example of damaged shunting-clamping station.

It's obvious that this shunting-clamping station is not able to provide an adequate electrical contact with the wedges anymore. Data gathered during a real-life *in* situ measurements campaign showed that the contact resistance at damaged shunting-clamping stations can be an order of magnitude larger then the typical value.

Figure 10 shows the predicted temperatures for a cell with poor electrical contact at the right-side shunting-clamping station being bypassed at 200 kA, 30°C without equalizer wedges. Note that end riser #1's temperature increased to 513°C due to current re-routing.

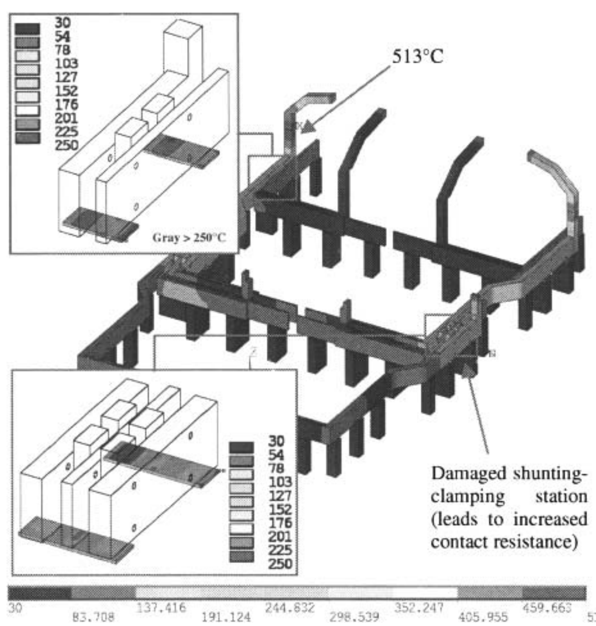

Figure 10 – Single bypass at 200 kA, 30°C: temperature distribution [°C] without equalizer wedges and with a damaged shunting-clamping station.

There is a critical riser contact resistance that would lead to a riser failure. Figure 11 shows the predicted temperatures for the single bypass at 200 kA, 30°C for the same cell if end riser #1 has a contact resistance ~6 times larger than the average value. Note that the end riser #1 reached the aluminum's melting point.

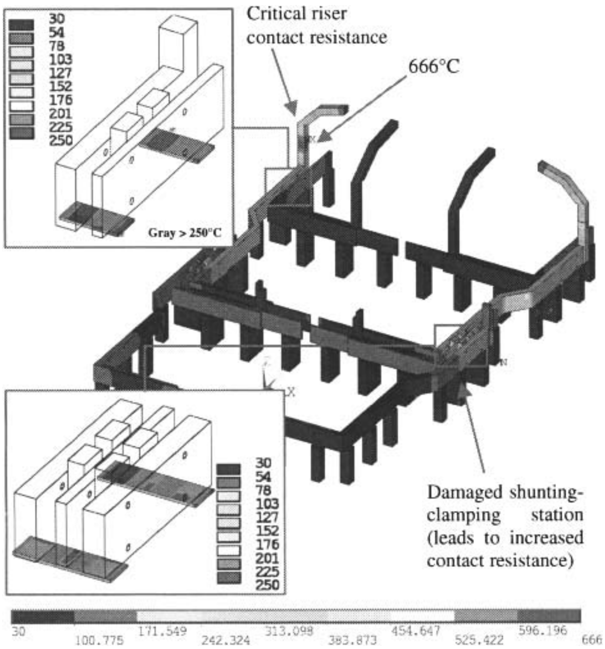

Figure 11 – Single bypass at 200 kA, 30°C: temperature distribution [°C] without equalizer wedges, with a damaged shunting-clamping station and critical riser contact resistance.

A real-life damaged end riser under similar circumstances can be seen in Figure 12.

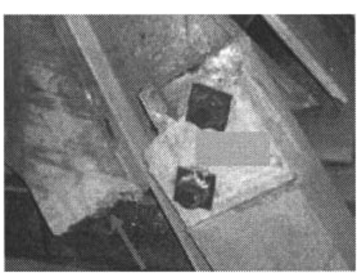

Figure 12 – Example of damaged end riser.

Proposed Mitigation Strategy

Initially, in our fictitious smelter the damaged busbars have been repaired either by reconstructing the original conductor's cross-section with aluminum weld plates or by replacing the damaged part. The damaged insulators were replaced by materials with higher temperature rating and new tie rods and spacers were installed wherever required. An additional bypass analysis showed that all electrical insulators should operate within the allowable range (maximum predicted temperature=193°C) if the standard bypass procedure is followed, even at 200 kA, 30°C – see Figure 13.

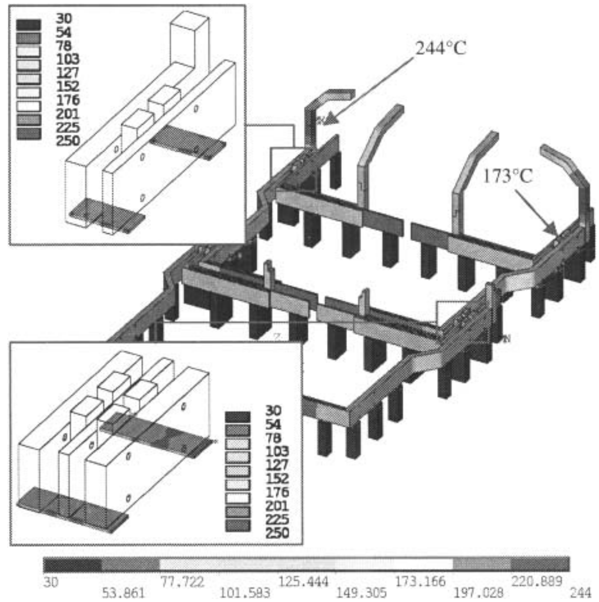

Figure 13 – Single bypass at 200 kA, 30°C: temperature distribution [°C] when following standard bypass procedures.

Finally, the fictitious smelter's bypass/pre-heating procedures were reviewed and a rigorous voltage drop and temperature follow-up routine was established to control the shunting-clamping stations and risers contact resistances.

Conclusions

A methodology based on numerical simulation, laboratory testing and *in situ* measurements was presented for the assessment of the thermal-electrical performance of busbars systems. It was shown that busbar design, insulating materials selection, amperage creep, operational procedures and potline conditions have important effects on the reliability of these systems.

Evidence was shown that busbars systems should not be ignored when planning amperage creep or when setting operational control procedures. Although not presented here, experience has also shown that liaison busbars between pot groups, between substation and potline and between potrooms, need to be included in the planning of amperage creep.

Future work includes the evaluation of the thermal-mechanical performance of the busbars systems, including expansion joints.

References

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