AL51 - Cathode Design Effects on MHD Stability of Aluminium Reduction Cells

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Abstract

Magnetohyrodynamic (MHD) stability is known to limit aluminium reduction cell efficiency. Normally cell stability is achieved by designing the cell with an optimized magnetic field, while the electric current distribution in the liquid metal is an equally important requirement. Modelling of electric current distribution requires a detailed 3D representation of the cell cathode coupled to the liquid metal zone.

The modelling software known as MHD-VALDIS is an established tool for MHD stability investigation and cell design. The recent update described herein permits to account for current distribution in liquid metal and coupled cathode features including variable contact resistance along collector bar and carbon, temperature-dependent collector bar conductivity variation, carbon block length limitation, ledge profile along cell wall, etc.

In the present article, we demonstrate MHD stability improvement when these features are optimized along with the total cathode voltage drop (CVD) control. The software permits to recompute the full electric current distribution change in time with the continuous magnetic field update resulting in the velocities and metal/electrolyte wave development leading to damping in a stable state or growth in an unstable cell. Examples of commercial cell applications are presented.

Keywords: Aluminium reduction cells, MHD stability, Electric current distribution, Cell modelling.

1. Introduction

To be able to compute the Lorentz force field responsible for the bath-metal interface instability, it is first required to compute the current density field in the liquid zone. It is particularly important to compute accurately the horizontal current in the metal pad as this significantly contributes to the interface instability. Givry was the first to present mathematical models that could perform current distribution calculations [1].

Givry's models are based in the discretization of 3D conductors by a network of 1D conductors, as illustrated in Figure 1. MHD-VALDIS (Magnetohydrodynamic versatile aluminium pad instability solver) software uses that type of representation for the solid parts of the electrical network as it leads to extremely fast computing time which is required to solve the full non-linear dynamic evolution of the current redistribution initiated by the interface wave motion in the cell stability analysis. The complete cell electric current is obtained at each development time step combining the extensive 1D element network representing the 3D cell busbars and the high order Fourier representation in the liquid zone, see details in [2].

When the only purpose is to solve for the steady-state current density distribution in the metal pad, using a more detailed 3D Finite Element (FE) representation of the system leads to a more accurate solution. One of the earliest 3D FE-based full cell model was presented at the 1994 ANSYS conference [3], see Figure 2.

The solution of the metal pad current density is very sensitive to the model setup as the liquid metal electrical resistivity is very low. Any discrepancy between two given models will affect their respective solution of the metal pad current density.

A comparison between MHD-VALDIS and ANSYS-based 3D model was first published in 2003 [4] for a 500 kA demonstration cell. This paper revisits this comparison in more detail using the 180 kA TRIMET cell with the most recent version of the code MHD-VALDIS. The new version of MHD-VALDIS is used to study impact of some design changes of the cathode assembly on the horizontal current in the metal and consequently on the cell stability.

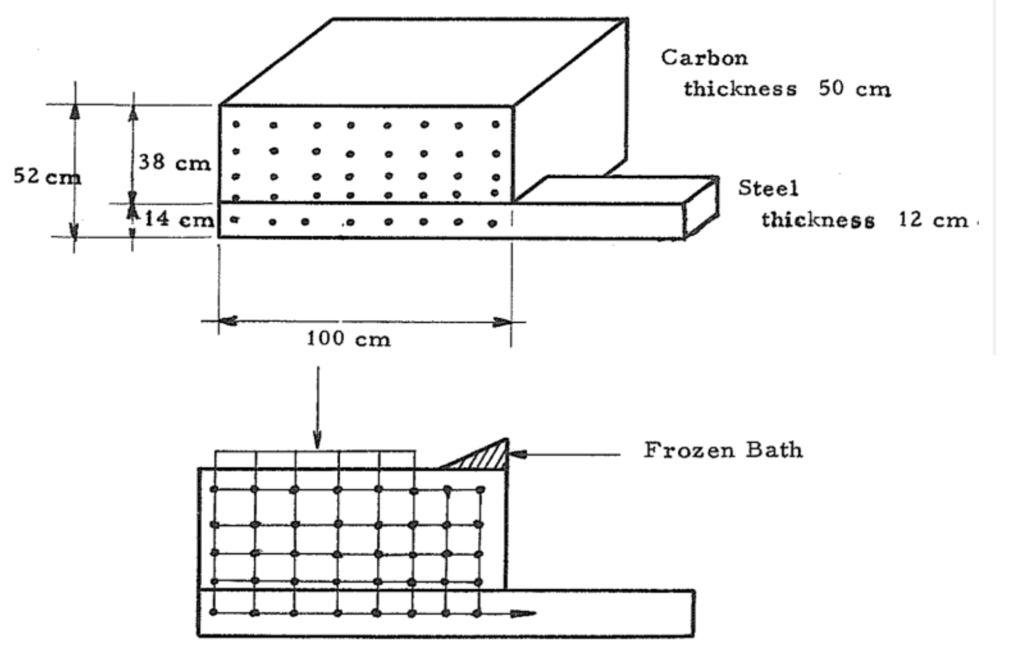

Figure 1. Representation of a cathode assembly by a network of 1D conductors, reproduced from Figure 14 in [1].

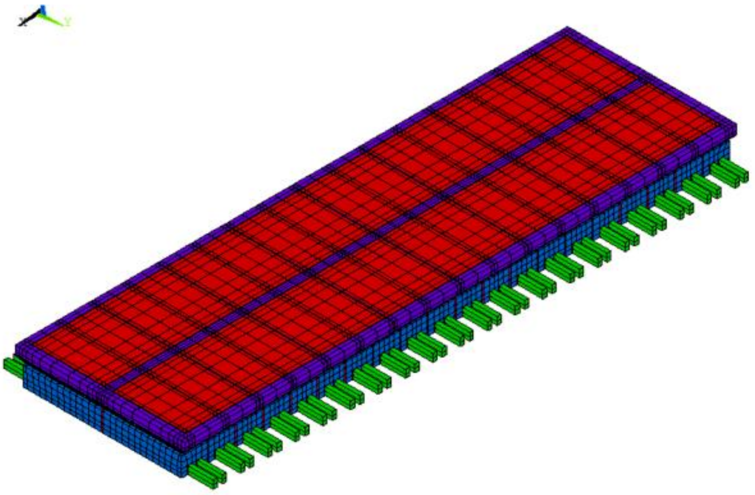

Figure 2. Representation of cathode assemblies, liquid phases and anode blocks by 3D finite elements, reproduced from Figure 4 in [3].

2. Comparison Between the Old and the New Code

The code MHD-VALDIS (or, simply, "code") is in continuous development. Recently, the part of the code computing the metal pad current density has been improved and is available in the latest release. This paper serves to illustrate the new options available within the updated code.

As the first example, the current density solution of the old and the new versions of the code for the 180 kA TRIMET cell model setup is presented. The MHD-VALDIS 180 kA TRIMET cell model was first used in a TMS 2015 paper [5]. The 180 kA TRIMET cell design is using a side-by-side configuration with a combination of 2 end risers and 2 side risers as illustrated in Figure 3 using 1D elements of various sizes and orientation generated by the MHD-VALDIS software.

The old version of the code was assuming that the cathode block length is as long as the specified cell liquid zone width (parallel to the cell short axis), regardless of the block's actual dimensions. This is corrected in the new version where the true cathode block length is specified. In the case of the 180 kA TRIMET cell, the width of the liquid zone is 3.6 m. The old version of the code also assumes that the rodding between the collector bar and the block is continuous over the entire length of the block (*i.e.*, up to both its extremities) and that the contact resistance is constant along that length. In other words, it was not possible to model either incomplete or selective rodding cathode assembly designs.

The new code version is computing the horizontal current in the carbon cathode block while the older code versions were not.

3. Comparing the Old and New Input Methods Using the New Code Version

The new code version still accepts the old input method when the new input file `CBARCONTR.txt` used to describe the cathode design details is not present. The old input method streamlines the way the collector bar to cathode block interface contact resistance is defined by using a single line in the `DATA.dat` input file [2]. The code is asking for the resistance, [Ω], of the single equivalent conductor representing the cathode block-to-collector bar interface contact. Since the contact surface area is not explicitly defined, the value can be estimated by the collector bar current and the expected voltage drop across the interface.

For the TRIMET model, a contact drop of 0.1 V was selected. Since there are 14 carbon blocks with 2 collector bars each, 28 collector bars carry the entire potline current with an average load of 180000/28 = 6428.6 A per a collector bar. To obtain this voltage drop, a resistance of 15.6 µΩ is required between each collector bar and its corresponding cathode block segment. Consequently, the resulting input line in the `DATA.dat` input file is:

```
0.0000156 |Cathode bar average contact Resistance, Ohm 0.1/180000/28)
```

As previously mentioned, cathode blocks are assumed to be as long as the full liquid cavity width, *i.e.*, 3.6 m long. Since there are two collector bars per block – one facing the upstream (US) and another, the downstream (DS) – the total contact length between a given collector bar and its respective block segment is assumed to be half the block length (1.8 m). Given that the collector bar cross-section is 0.20 m tall and 0.18 m wide, the actual value of the contact resistance, [µΩ·m^2], can be calculated as:

$$15.6 \times (2 \times 0.2 + 0.18) \times 1.8 = 16.28\ \mu\Omega\cdot\text{m}^2 \tag{1}$$

The new input method permits more refinement while using the file `CBARCONTR.txt`. First, the carbon cathode block length is input, so, for the comparison exercise, the value of 1.8 m per collector bar is given. The total liquid cavity width is discretized using 31 elements in total, then 3.6 m width divided by 31 gives the element length of 0.116 m. So, for each one of those 31 elements connecting a given cathode block to its respective collector bars, the corresponding contact area is:

$$(2\ \text{x}\ 0.2 + 0.18)\ \text{x}\ 0.116 = 0.0673\ \text{m}^2 \qquad (2)$$

Hence, the value of each equivalent resistance connecting the collector bars to their cathode block should be:

$$0.00001628/0.0673 = 0.00024\ \Omega \qquad (3)$$

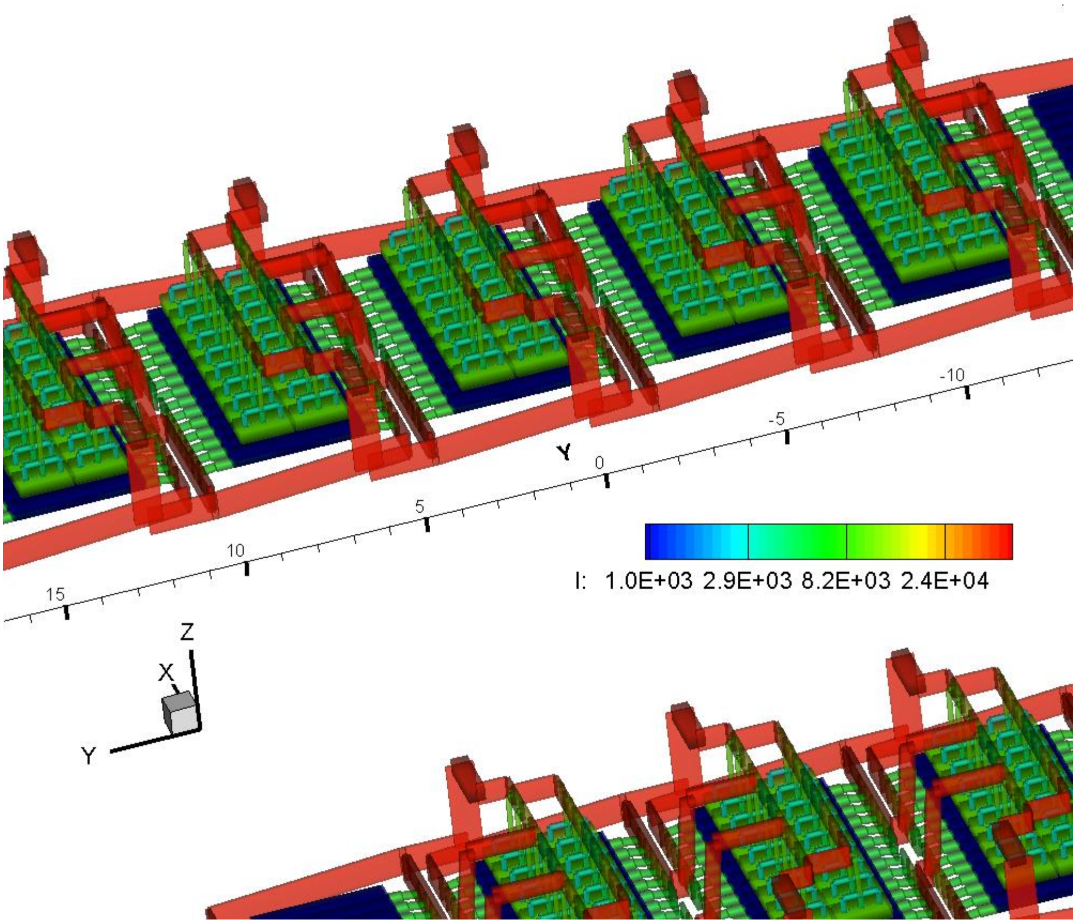

Figure 3. Revised side by side 180 kA TRIMET cell configuration when the pot-to-pot distance is reduced to 6.1 m from the previous 7.01 m used in [5]. Scale represents current magnitude, [A].

As a result, the new version code computes the average cathode voltage drop CVD = 317 mV when the old input method is used, and the new input method using 0.00020 Ω as uniform equivalent resistance value gives the CVD = 312 mV. The resulting horizontal current density is presented in Figure 4 for the old input method, and for the new one in Figure 5. Figure 6 presents the horizontal current in the carbon cathode block, where the 0.26 m ledge effect can be seen. The solution is very similar for both input methods, the small difference in both CVD and maximum horizontal current is due to the fact that 0.00020 Ω was used instead of 0.00024 Ω.

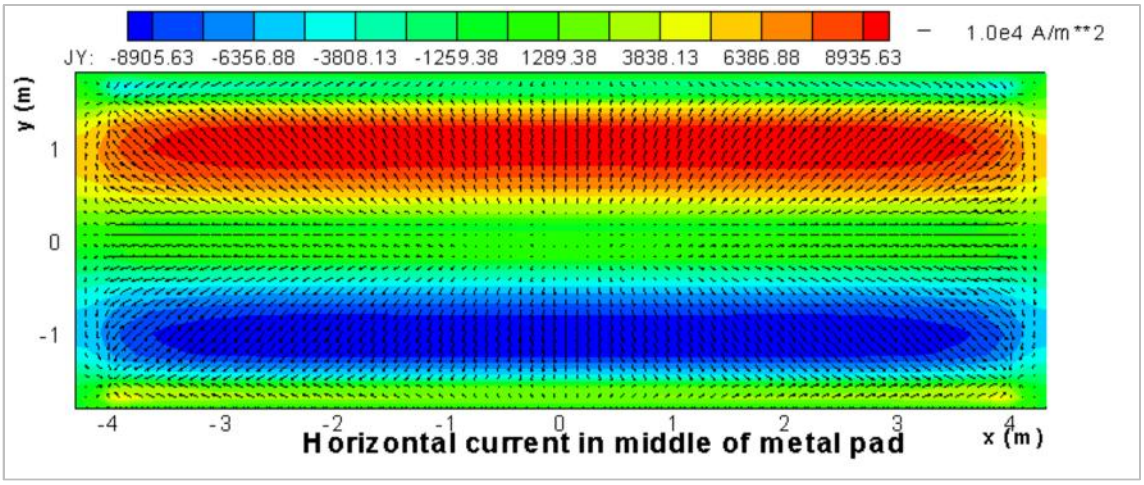

Figure 4. Horizontal current in the middle of the metal pad using the old input method.

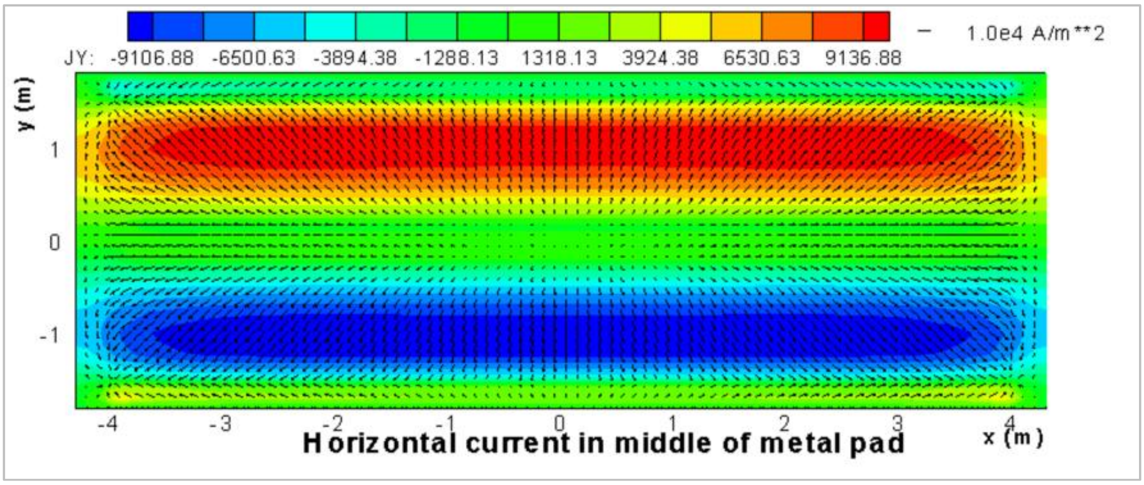

Figure 5. Horizontal current in the middle of the metal pad using the new input method version, using the same cathode length as assumed by the old input method.

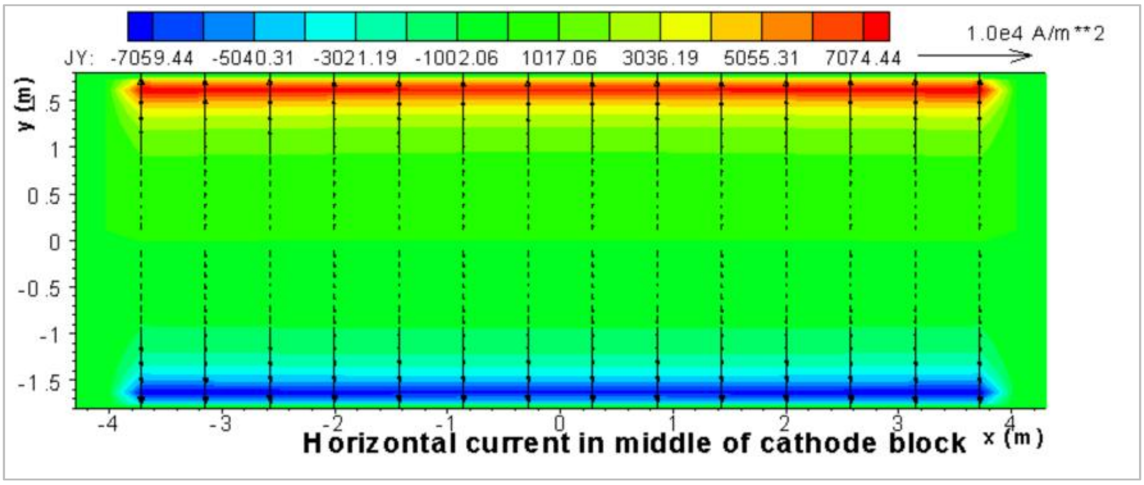

Figure 6. Horizontal current in the middle of the cathode block calculated using the old input method.

So far, we demonstrated that the new code version, using the old or new input methods to define the cathode block-to-collector bar contact resistance, produces essentially identical results if the same (incorrect) cathode block length of 3.6 m is used. However, this is not the correct solution as the new physics accounts for the horizontal current in the cathode carbon block in both cases.

4. Comparison Between ANSYS and the New MHD-VALDIS Code Using the Corrected Setup

As shown in the previous section, it is possible to obtain different horizontal current distributions depending on how they are calculated. The validation of these results is particularly problematic as, contrary to the magnetic field, it is not possible to measure the current density in the metal pad of a cell in operation. The only option available is to compare with another solution obtained by a different independent model, possibly using a different discretization method.

4.1 ANSYS Model Results for the TRIMET Cell Case

Figure 7 presents the ANSYS 3D model mesh for the TRIMET 180 kA cell case. In that model, the actual cathode block length, 3.2 m, is used. The ledge toe is covering 6 cm of the cathode top surface on both US and DS sides. Figure 8 presents the obtained CVD when the 10 µΩ·m^2 contact resistance value is used. Figure 9 presents the corresponding horizontal current in the middle of the metal pad.

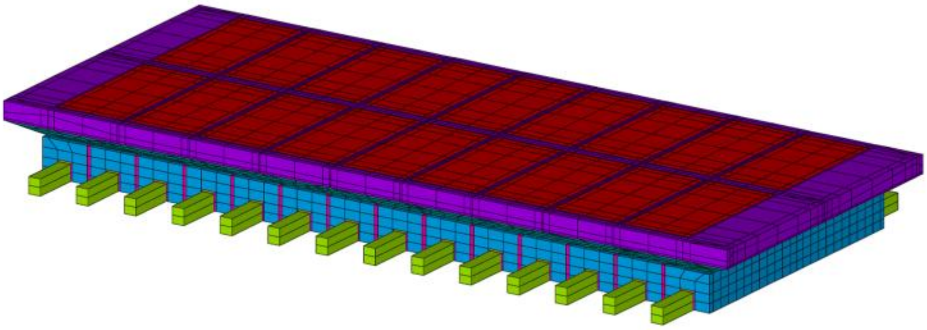

Figure 7. ANSYS 3D model mesh for the TRIMET 180 kA cell case.

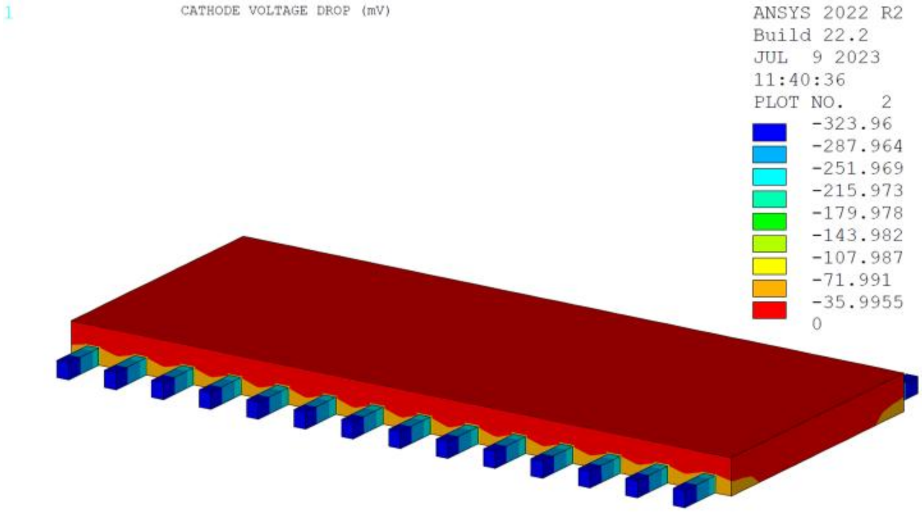

Figure 8. ANSYS 3D model CVD solution for the TRIMET 180 kA cell case.

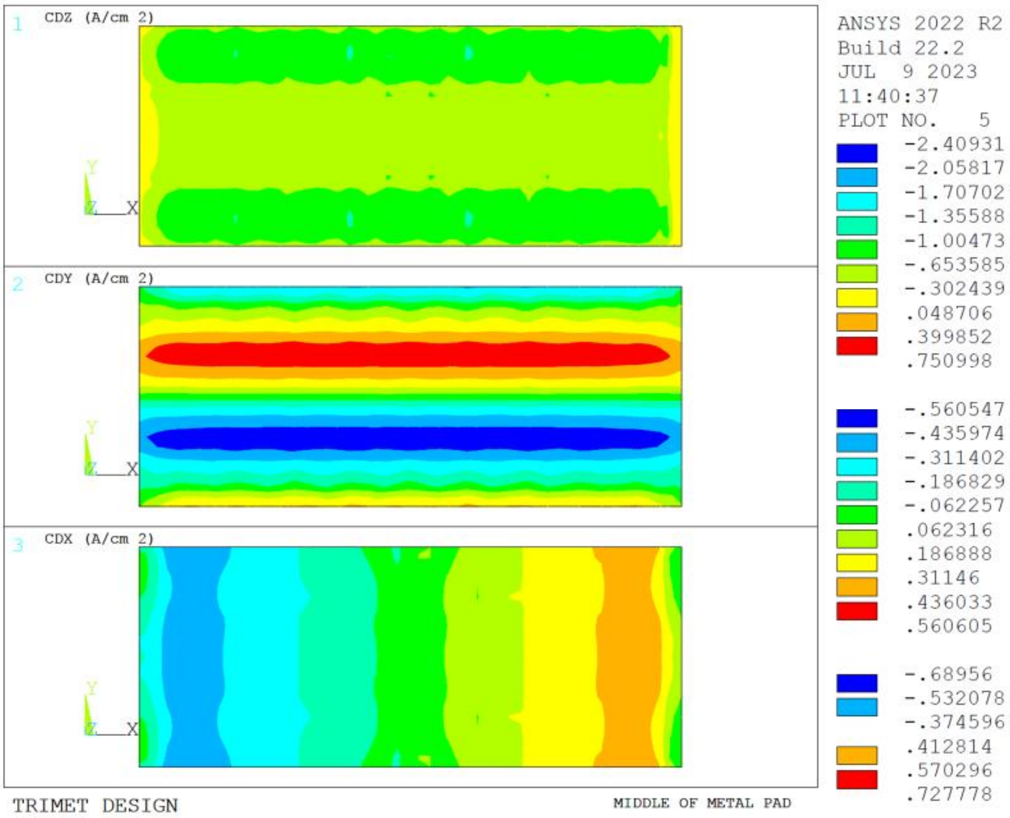

Figure 9. ANSYS 3D model current density solution for the TRIMET 180 kA cell.

4.2 New MHD-VALDIS Model Results for the TRIMET Cell

It is now time to update the MHD-VALDIS TRIMET model setup using the new `CBARCONTR.txt` file inputs. This permits to use the correct cathode block length of 3.2 m. The equivalent resistance of each one of the 31 elements connecting the collector bars to their cathode block is recalculated to correspond to the 10 μΩ·m^2 value used in ANSYS:

$$0.000010/0.0673 = 0.000148\ \Omega$$

When using the new model setup, the average CVD is calculated as 337 mV by MHD-VALDIS while ANSYS calculated 324 mV using the same cathode geometry and contact resistance value. MHD-VALDIS code accounts for the full busbar network between adjacent cells. Therefore, the local CVD varies between the collector bars connected to different pot-to-pot busbar branches. The program outputs only the average CVD value:

```
0.3371 = CVD = average cathode voltage drop (end of collectors)
```

The corresponding metal pad horizontal current is presented in Figure 10. The results are quite comparable to the 3D ANSYS results. Figure 11 presents the corresponding horizontal current at the middle of the cathode carbon block.

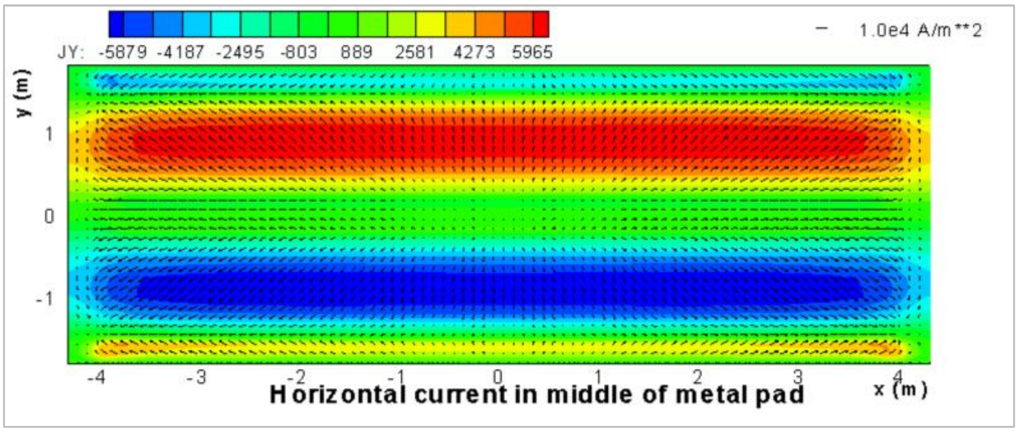

Figure 10. Horizontal current in the middle of the metal pad using the updated inputs with the new code version.

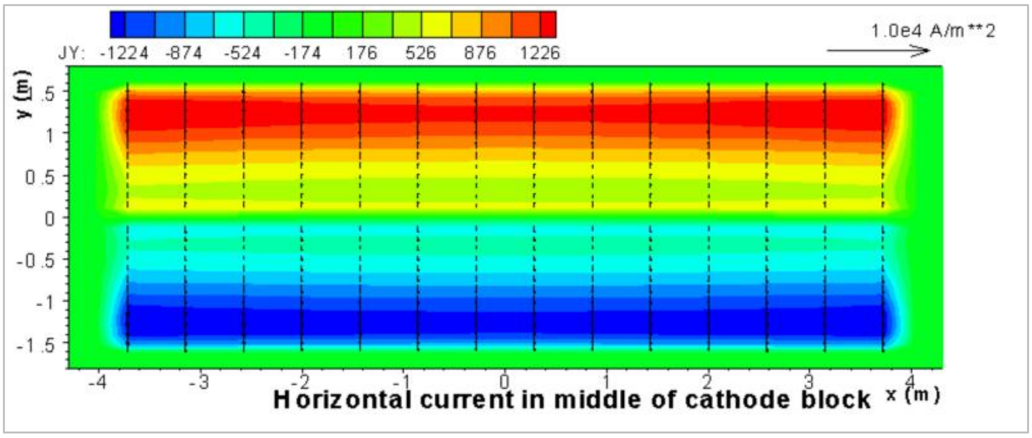

Figure 11. Horizontal current in the middle of the cathode block calculated by the new code version using the updated input.

5. Using the Input Features of the New Code Version to Analyse the Gain of Cell Stability by Using Incomplete Rodding and Selective Rodding Designs

The MHD-VALDIS code takes only a few seconds of CPU (Central Processing Unit) time to calculate the current density solution. From this point, the code continues to compute the magnetic field, the Lorentz force field, the steady state flows of both the bath and metal, and the steady state bath-metal pad interface deformation. Finally, the program computes a transient evolution of the bath-metal pad interface perturbation producing a rotating wave that will either increase or decrease (damped out) in magnitude depending on the stability of the system.

The code now permits to get the solution of metal pad horizontal current due to a change of cathode assembly design, making it possible to assess the impact of this change on the cell MHD stability. This is clearly a big advantage of using MHD-VALDIS as modeling tool for cathode assembly retrofit design studies.

5.1 Incomplete Collector Bar Rodding Case

Stopping the rodding of the bar about 10 cm short of both edges of the cathode block is a classic way to reduce the metal pad horizontal current. It was part of the AP18 design already 50 years ago. It is part of the TRIMET 180 kA cell cathode assembly design. But until the new version, this design feature could not be studied in an MHD-VALDIS cell stability analysis.

As already described, in MHD-VALDIS, the 3.6 m cell cavity width is divided in 31 mesh elements, each 0.116 m long. In `CBARCONTR.txt,` it is possible to independently define the local contact resistance of different sections along the cathode block length.

Since the block is defined in `CBARCONTR.txt` to be 3.2 m long (*i.e.*, shorter than the liquid cavity width), the last 2 sections on both sides of the cathode block are already deactivated, leading to an effective cathode block length of 3.136 m. So, the way to represent the absence of rodding of the bar at the edge of the block is to set high contact resistance value for the third element from the end of each collector bar. The total rodded length becomes 2.904 m, about 10 cm shorter than the actual cathode assembly design (3.0 m).

As a result, MHD-VALDIS predicts that CVD increases from 337 to 368 mV while the horizontal current in the metal pad decreases, as displayed in Figure 12:

```
 0.3680 = CVD = average cathode voltage drop (end of collectors)
```

It is possible to analyse the case of not rodding the last 10 cm of each collector bar in an ANSYS 3D model. As a result, the CVD is predicted to increase from 323 to 335 mV and the new horizontal current is presented in Figure 13. This shows again a good agreement between ANSYS and MHD-VALDIS of the impact of not rodding up to the edge of the block and the reduction of the metal pad horizontal current.

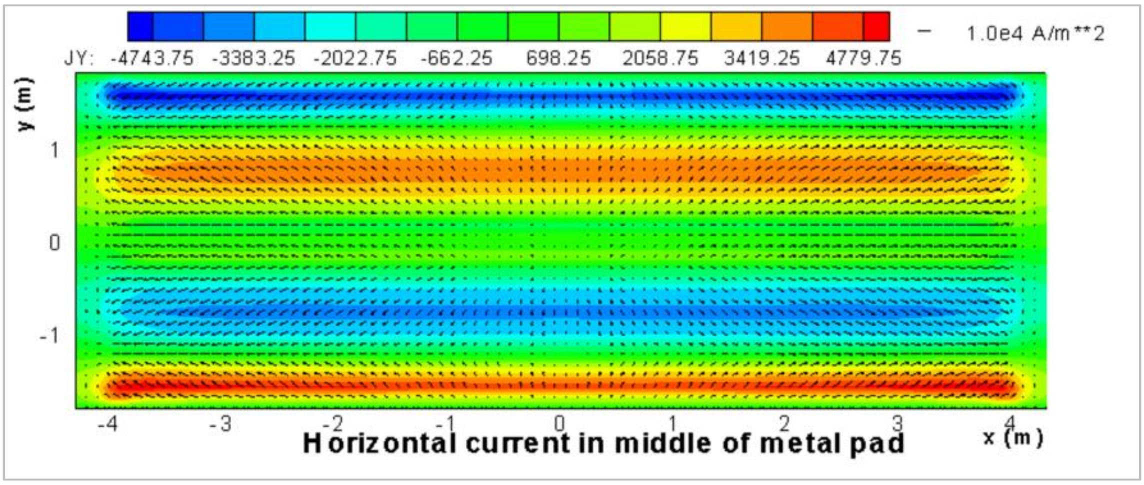

Figure12. Horizontal current in the middle of the metal pad for the incomplete bar rodding case.

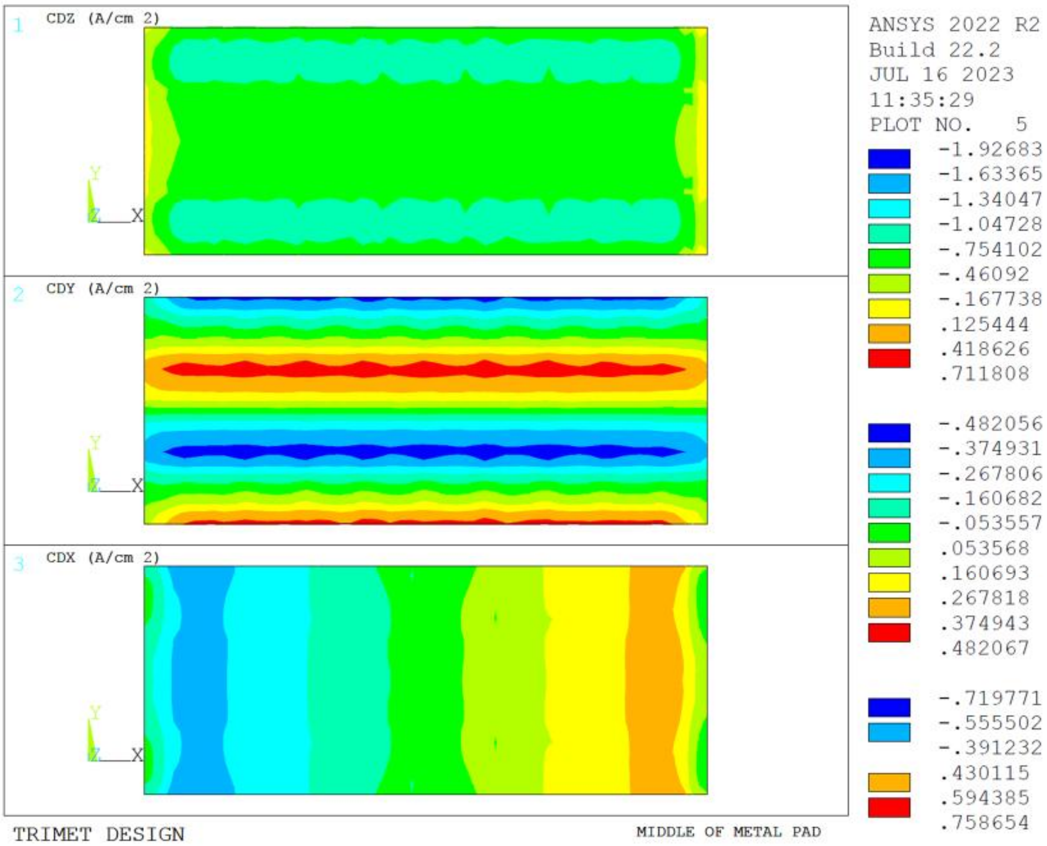

Figure 13. ANSYS 3D model current density solution for the TRIMET 180 kA with rodding stopped 10 cm short of both edges of the cathode block.

5.2 Collector Bar Selective Rodding Case

It was demonstrated in COM 2000 paper [6] that the usage of selective rodding can produce uniform current density at the surface of the cathode block which, in turn, produces a uniform erosion rate on the surface of the cathode, leading to extended pot life.

The selective rodding would also eliminate horizontal current in the metal pad. This was never specifically analysed for the MHD stability, but now it is quite straightforward to implement selective rodding with the `CBARCONTR.txt` file. The drawback of using selective rodding is the increase in CVD, therefore a bar of increased cross-section is used to test the selective rodding case. This requires the recalculation of the value of the contact resistance. The new value of the equivalent resistance to maintain the average figure of 10 µΩm^2 turns out to be 0.000134 Ω. The collector bar cross-section increased by 33 %, increasing the contact surface by about 10 % (a wider bar).

Figure 14 displays the concept of selective rodding: there are 3 zones of cast iron rodding in red around the bar of progressively decreasing length towards the block end, separated by some insulating material in green.

The predicted new CVD of the selective rodding design with a 33 % bigger bar is 336 mV, so the CVD value remains equivalent to the fully rodded case. Figure 15 presents the obtained horizontal current in the metal pad, while Figure 16 presents the horizontal current in the cathode block.

```
 0.3356 = CVD = average cathode voltage drop (end of collectors)
```

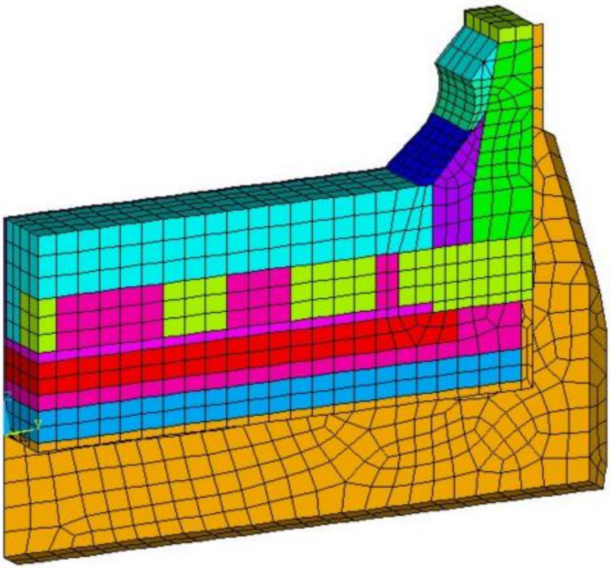

Figure 14. Model of the selective rodding concept as presented in 2000, reproduced from Figure 3 in [5].

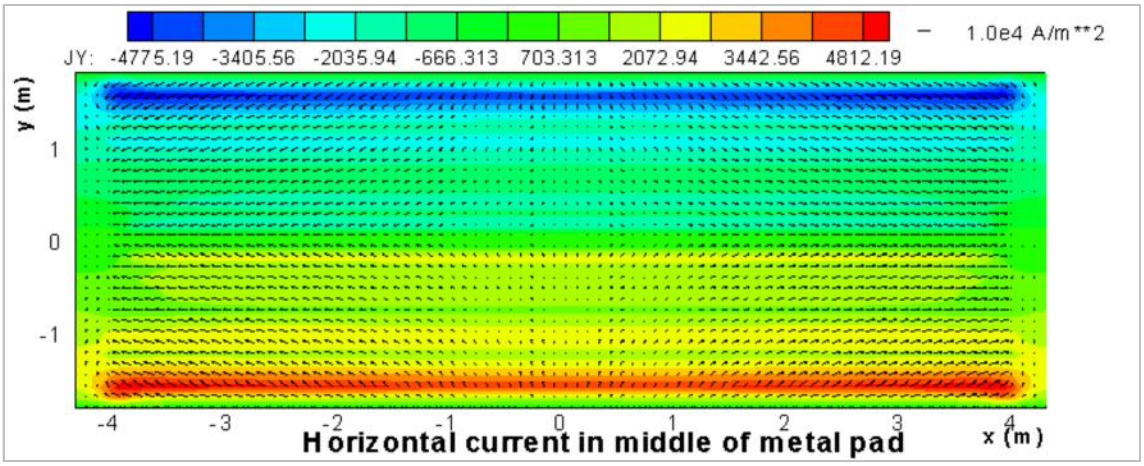

Figure15. Horizontal current in the middle of the metal pad for the selective rodding case.

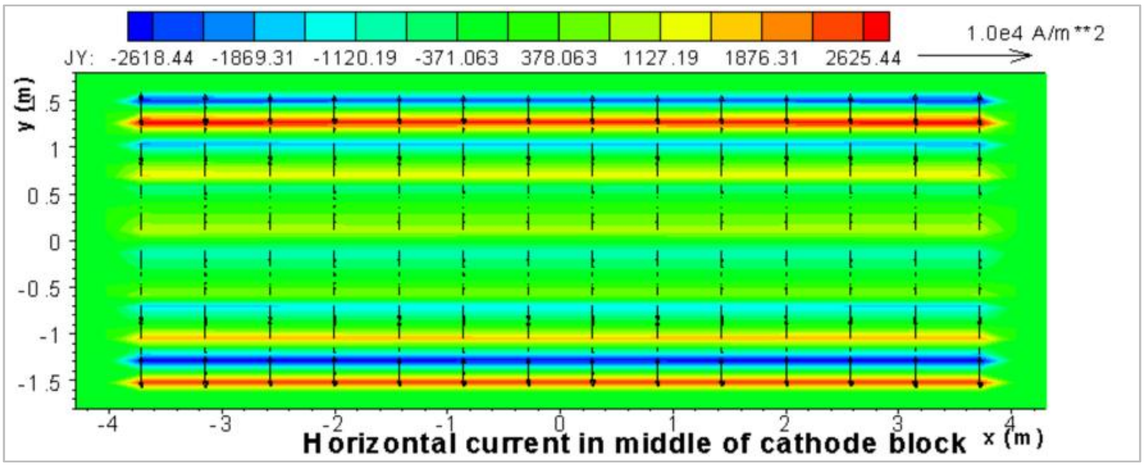

Figure 16. Horizontal current in the middle of the cathode block for the selective rodding.

5.3 Analysis of the Relative Cell Stability for the 3 Cases Investigated

As already discussed, quite advanced modeling tools like the 3D ANSYS model presented above have been around for at least the last 30 years, but the advantage of the MHD-VALDIS modelling tool is that the impact of a design change on the cell stability can be investigated immediately in the same analysis (run).

Figure 17 presents the evolution of the mid-point position on the bath-metal pad interface starting with the initial perturbation for the fully rodded case (full line) and the case where the rodding stopped about 10 cm from the edge of the block (dashed line). Clearly, there is a huge increase of cell stability: the cell was critically unstable at 43 mm anode-cathode distance (ACD) in the fully rodded case, and it is predicted to be more stable in the incomplete rodding case. Notice that it is important to compute a long-term interface development (10-20 periods of oscillation).

Figure 18 compares the stability of the incomplete rodding and the selective rodding cases, both at 43 mm ACD. The gain of stability is comparable despite the much greater reduction of the horizontal current Jy in the selective rodding case. This is counter intuitive and highlights the need to carry out the complete long-time analysis while accounting for the longitudinal horizontal current component Jx, as it was the case in the MHD-VALDIS code runs. Finally, Figure 19 compares the stability of the selective rodding case at 43 and 41 mm ACD. This demonstrates that the gain in cell stability is similar to the one obtained by increasing the ACD by 2 mm.

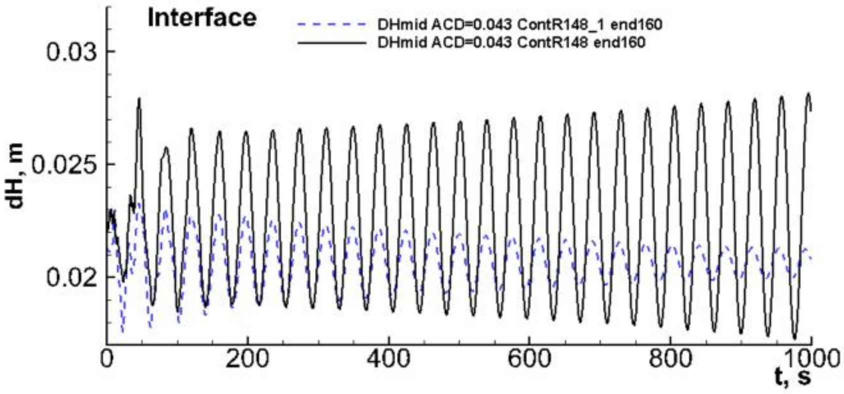

Figure17. Cell stability analysis for the fully rodded case (full line) and the incomplete rodding (dashed line).

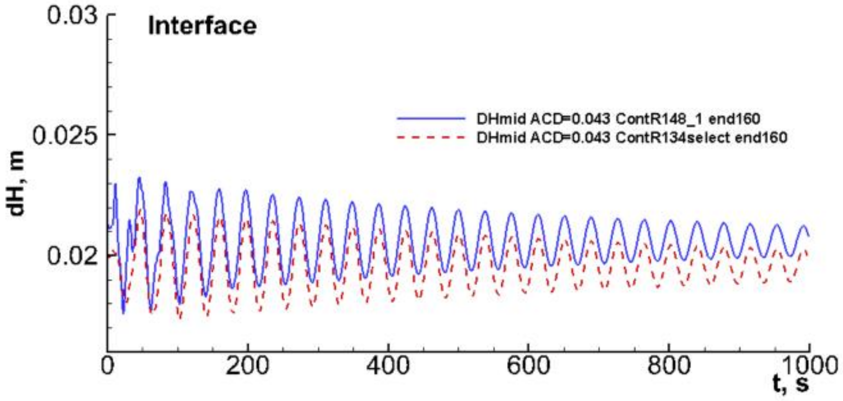

Figure 18. Comparison of the cell stability for the incomplete rodding case (full line) and the selective rodding case (dashed line).

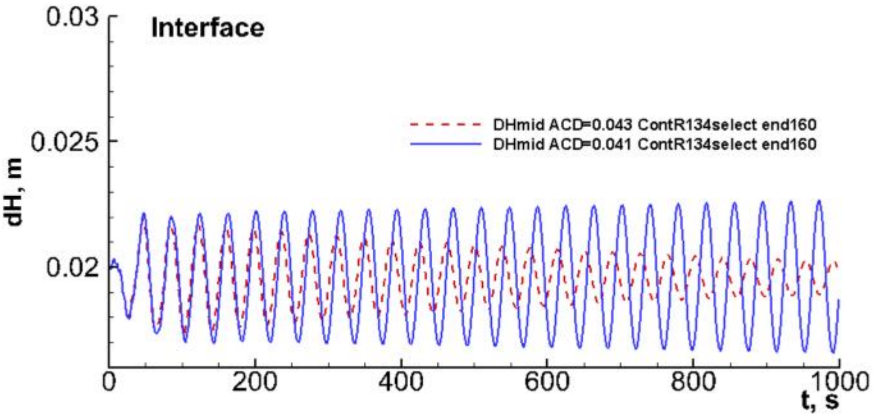

Figure 19. Comparison of the cell stability for the selective rodding case at 43 (dashed line) and 41 mm (solid line) ACD.

6. Conclusions

A more accurate method of computing the current density in the metal pad has been implemented in a new release of the code MHD-VALDIS using a new, more flexible way to define the contact resistance value(s) between the bar and the cathode block.

1. It was demonstrated that using the old contact resistance definition method with the new code version produced wrong results, so it is highly recommended to use the new code version with updated model setup for the contact resistance definition method based on the `CBARCONTR.txt` file;
2. The metal pad horizontal current obtained using the new MHD-VALDIS code version and the `CBARCONTR.txt` input file are very comparable with the solution produced by a 3D ANSYS model for the same TRIMET 180 kA cell case;
3. The gained input flexibility provided by the `CBARCONTR.txt` input file was used to test the impact of both stopping collector bar rodding short of both edges of the cathode block and selective rodding. The assessment was performed both in terms of metal pad horizontal current density and cell stability;
4. It was confirmed that both methods reduce the metal pad horizontal current and increase cell stability.

7. References

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