Magnetohydrodynamic Analysis of Load Shifting in Hall-Héroult Cells

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Abstract

The research project SynErgie aims to adapt large scale industrial processes to a volatile supply of renewable energy which is expected for the future. The aluminium electrolysis process is one of the biggest consumers of electric energy in Germany. The aim is to vary its nominal process power by ± 25 %. This numerical study focuses on the magnetohydrodynamic (MHD) behaviour of the electrolysis cells of Trimet Aluminium SE in Essen. To capture the MHD driven flow and electrodynamics inside the electrolysis cells a computational fluid dynamics (CFD) model is developed in the OpenFOAM® framework. This accounts for the influence of neighbouring electrolysis cells, the magnetization of ferromagnetic materials, a static ledge profile and the dynamic changes of anode shape caused by the carbon consumption. The simulation predictions show the heave of the aluminium cryolite interface for different line currents. To analyze the behaviour of flexible process operation, shifts of the line currents are studied in detail. After shifting the line current, the interface heave changes directly whereas the shape of the anode bottom reacts with a delay in time. This leads to a locally uneven anode cathode distance (ACD) followed by a disturbed current distribution inside the electrolysis cell after shifting the line current. The anodic current distribution is quantified by the model, which can help process operators to identify whether increased anode currents are caused by the line current shift or potential abnormalities like spikes.

Keywords: Magnetohydrodynamics, Hall-Héroult, Aluminium electrolysis, Current modulation, Metal pad heave.

1. Introduction

As the number of renewable electricity sources is increasing, the volatility of electric energy in the grid raises. This trend also affects large scale industrial processes, as the availability and the price of electric energy become more relevant. Trimet Aluminium SE aims to design the aluminium electrolysis pot lines flexible in terms of current input. To adapt the technology of the electrolysis cells, magnetic compensation of the cells has been installed by means of a modification to the pot busbars, which allows higher line currents and reduces problems related to cell control. Moreover, to maintain the thermal balance of the electrolysis cells, shell heat exchangers have been installed [1].

Despite of these actions, shifts of the line current still impact the process operation. These impacts and its consequences are the subject of the current study. It focuses on the operating condition after shifting the line current by ± 25 %. The results help process operators to understand the dynamics of the electrolysis cells and to adapt their actions regarding process operation accordingly.

2. Physical Background

In this section, the relevant equations to describe electrodynamics, magnetic fields and the resulting fluid mechanics are described. These are the basis of the implemented solvers, which were employed to execute the current study.

The electric potential of a system without free charges can be described by:

$$\nabla \cdot (\sigma \nabla \Phi) = \nabla \cdot (\sigma(\boldsymbol{u} \times \boldsymbol{B})) \tag{1}$$

where:

σ	Electric conductivity, S/m
Φ	Electric potential, V
u	Velocity, m/s
B	Magnetic flux density, T.

This equation implies that the current density must be divergence free. The current density can be expressed by:

$$\boldsymbol{J} = \sigma\,(-\nabla \Phi + \boldsymbol{u} \times \boldsymbol{B}) \tag{2}$$

where:

J	Current density, A/m^2.

Both the electric potential Φ and the current density J can be divided into a velocity dependent and a velocity independent part. Ampere's Circuit Law, which denotes the relationship between current density and the magnetic flux density induced by it, can be expressed as:

$$\nabla \times \boldsymbol{B} = \mu_0 \boldsymbol{J} \tag{3}$$

where:

μ_0	Magnetic permeability of free space, H/(m).

In this study, **B** is determined from the current density with the help of Biot-Savart Law, given by Equation (4). Note that subscripts $_r$ and $_{r'}$ indicate that a given parameter is evaluated at that particular spatial location (e.g., $\mathbf{B}_r$).

$$\boldsymbol{B_r} = \frac{\mu_0}{4\pi} \int_V \frac{\boldsymbol{J_{r'}} \times (\boldsymbol{r}-\boldsymbol{r'})}{|\boldsymbol{r}-\boldsymbol{r'}|^3} dV_{r'} \tag{4}$$

where:

V	Volume, m^3
r'	Location of current source, m
r	Location of evaluation point, m.

B is related to magnetic vector potential by:

$$\boldsymbol{B} = \nabla \times \boldsymbol{A} \tag{5}$$

where:

A	Magnetic vector potential, V s/m.

Combining Equations (4) and (5), the magnetic vector potential can be written as:

due to the flattening of the interface. All in all, the situation at 124 kA is by tendency the opposite to the situation of 206 kA.

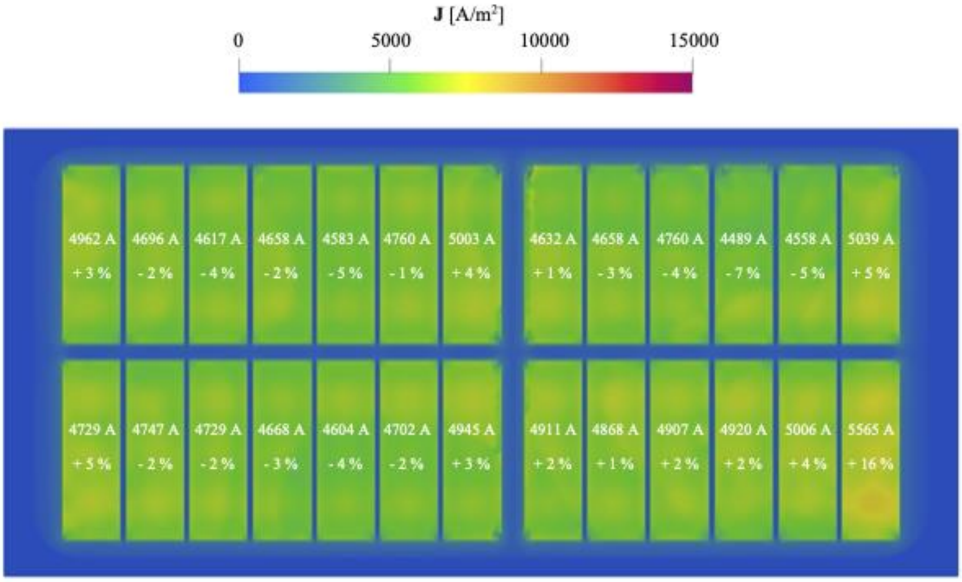

Figure 8. Current distribution in the anodes after shifting the line current from 165 kA to 124 kA. The percentages show the deviation from the average (nominal) anode current.

5. Conclusion

In the present numerical study, our MHD model for the simulation of Hall-Héroult cells is presented and applied to industrial EPT14 cells used at Trimet in Essen. The focus of the study is to analyze load shifting scenarios occurring at flexible operating conditions of aluminium electrolysis. The motivation for current modulation is to adapt industrial processes to a volatile supply of renewable electricity sources. The numerical model is able to consider the influence of neighbouring electrolysis cells, the magnetization of ferromagnetic materials, a static ledge profile and the dynamic changes of anode shape caused by the carbon consumption. Two load shifting scenarios are studied in detail. The standard line current of 165 kA is shifted to 124 kA and 206 kA which corresponds to a 25 % decrease or increase. The model predicts a flatter aluminium cryolite interface during the decreased line current situation. Combined with the anode bottom shape which was formed at the standard operation of 165 kA, this situation leads to relatively increased anode current at the corner anodes of up to 16 %. After increasing the line current to 206 kA, the interface deformation is reinforced, which leads to an increase of local current density maxima. Certain anodes have up to 10 % higher currents compared to the average anode current.

Acknowledgements

This research is financed by the *Bundesministerium für Bildung und Forschung* under the project SynErgie II (03SFK3B1-2), whose support is gratefully acknowledged by the authors.

6. References

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