

Preliminary Development of a Transient 1D-Electrical Model of Hall-Héroult Electrolysis Cells

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Abstract

Alumina is transformed into aluminium through electrolysis in the Hall-Héroult process. An efficient production of primary aluminium requires precise control and optimization of electrolysis cell operations. However, the process is inherently complex, involving intricate interactions between physical and electrochemical phenomena. Key factors such as magnetohydrodynamic effects, uneven electric current distribution, variability in anode-cathode distance (ACD), changes in the anode structure, and bubble formation all contribute to the difficulty in achieving real-time monitoring and management of critical parameters. These challenges hinder the ability to predict and control the electrolysis process effectively. To overcome these hurdles, this study introduces a transient 1D-electrical model that analyses the temporal evolution of various parameters in the electrolysis cell. The model incorporates simplified physical laws, which provide valuable insights into the dynamic nature of the system. By analysing the temporal behaviour of key parameters, the model offers predictions on the operation of the cell, enabling more accurate monitoring of the anode and cathode performance. These insights facilitate improved management of anode consumption, better distribution of current, and the optimization of operational conditions, ultimately leading to enhanced Hall-Héroult process efficiency. This approach holds promise for advancing the production of primary aluminium by addressing critical challenges and optimizing the overall electrolysis process.

Keywords: Hall-Héroult process, Aluminium reduction, Electrical resistances, Anodes.

1. Introduction

Aluminium is an essential material in numerous industries thanks to its lightweight nature, excellent strength-to-weight ratio, and strong resistance to corrosion [1]. Aluminium is produced in several steps, beginning with the extraction of bauxite ore, followed by refining it into alumina (Al_2O_3) using the Bayer process [2]. The alumina is then reduced to pure aluminium metal through the Hall-Héroult process, an electrolytic method in which alumina is dissolved in molten cryolite, and electric current is passed through the solution to separate aluminium at the cathode and oxygen at the anode [2].

Achieving efficient and stable operation of Hall-Héroult electrolysis cells requires precise control of key parameters such as electric current distribution. However, in practice, these parameters fluctuate due to the complex interplay of electrochemical, thermal, hydrodynamic, and magnetohydrodynamic effects. Key challenges include, among others, uneven current distribution, dynamic variations in anode shape due to consumption, changes in anode-cathode distance (ACD), and gas bubble formation. These factors can lead to alumina dissolution inefficiencies, anode effects, anode incidents, disruptions in magnetohydrodynamic stability, and potential short circuits, all of which compromise process efficiency [3].

To effectively investigate the operation of electrolysis cells, several studies have been conducted, including models of anodic current distribution [3] and alumina distribution behaviour [4]. Several of these models require significant computational time, which makes them unsuitable for real-time control. Having an accurate model for real-time monitoring and predictive analysis of the electrolysis cells is essential.

Therefore, to address the limitations of previous models and provide a more precise representation, this study develops a transient one-dimensional (1D) electrical model that captures the temporal evolution of key electrolysis parameters. Using more accurate relationships and alternative methods to calculate the resistance of various parts of the electrolysis cell enhances the richness and reliability of this model. Therefore, this approach offers valuable insights that support improved process control, and enhanced overall efficiency in primary aluminium production.

2. Methodology

This study introduces a one-dimensional (1D) transient electrical model to simulate the behaviour of a Hall-Héroult electrolysis cell over time. Each cell has 40 prebaked anodes that are connected in the model to the electrolyte bath, the cathode, and various structural components, enabling continuous current flow and aluminium production. The modelling approach relies on an equivalent electrical circuit formed by a combination of resistances in series and in parallel. The resistance values vary over time as a function of physical parameters, including anode height, metal pad height fluctuation, material properties, and other influencing factors.

To accurately capture the time-dependent resistance of the anode, COMSOL Multiphysics is employed to model its complex geometry and pre-calculate its resistance at various heights, accounting for its gradual consumption throughout the operational cycle. These simulation results are then integrated into a Python-based computational framework, where the time-varying anode resistances are used to update the overall electrical network. This integration enables the calculation of the equivalent resistance of the cell at each time step and provides a transient view of the current distribution and electrolyte behaviour. The following section provides a detailed explanation of the electrical modelling of the electrolysis cell.

2.1 Electrical Modelling of the Electrolysis Cell

According to Figure 1, the electrolytic cell is modelled as a parallel network of 40 resistors, each representing a complete electrical path that includes one anode along with other connected components. This configuration reflects the irregularity of electric current distribution, with each electrical path carrying a different current due to the varying resistance associated with its physical state.

Each electrical path is modelled as a local sub-network of series and parallel resistors, representing its internal components such as the rod, carbon anode, bath, cathode, and collector bar (Figure 2). The resistance values are dynamically updated over time based on the evolution of physical parameters, such as anode height, material properties, and ACD. This detailed structure allows the model to accurately capture local electrical behaviour.

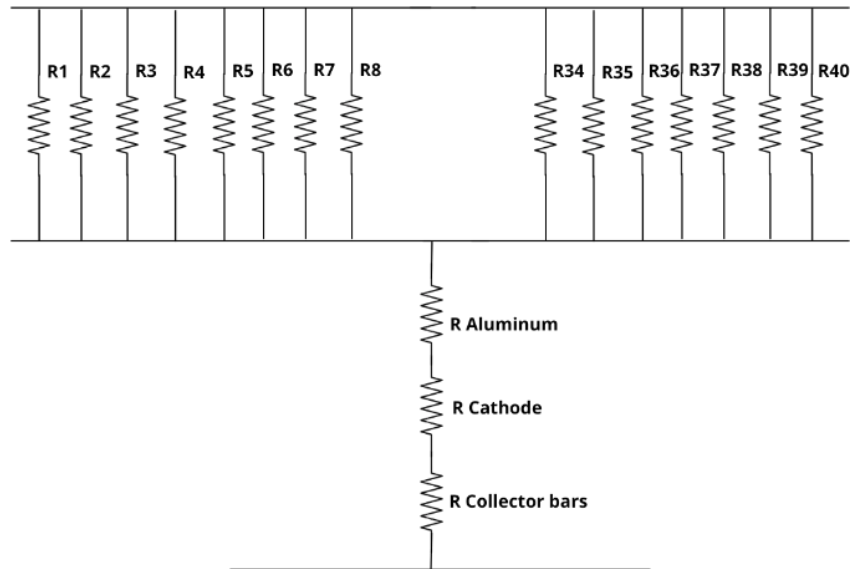


Figure 1. Electrical model of the electrolysis cell.

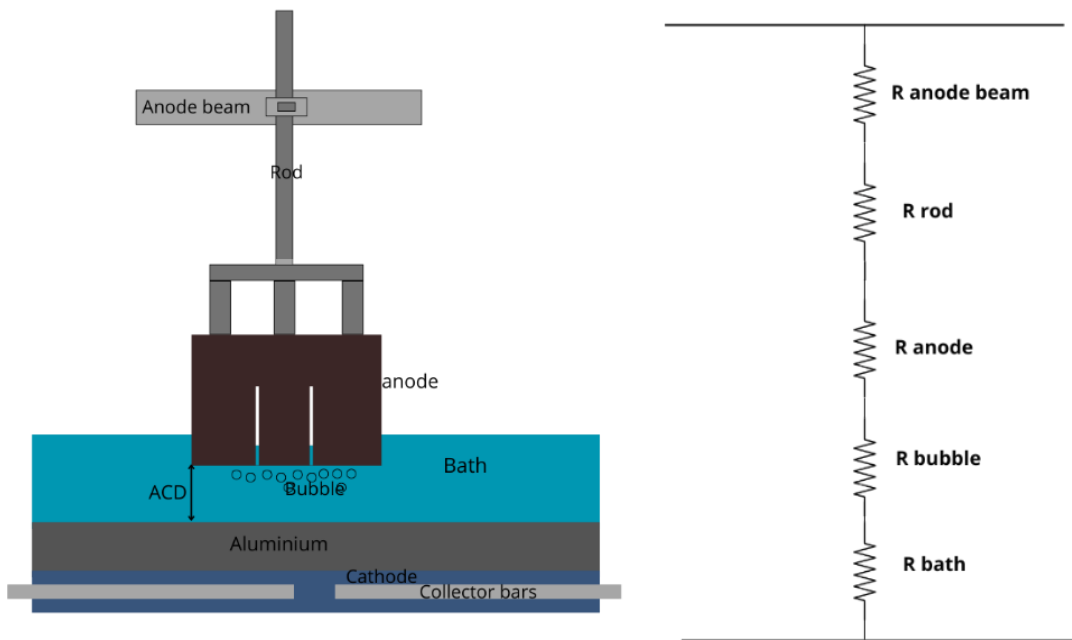


Figure 2. Electrical model of a single electrical path within the cell.

The Ohmic resistance of each component is calculated based on its material resistivity, length, and cross-sectional area, using the classical relation, Equation (1):

$$R = \rho \frac{L}{A} \quad (1)$$

where:

- ρ Material electrical resistivity, $\Omega \cdot m$
- L Length, m
- A Cross-section area, m^2

This approach is applied to all conductive components, including anode rods, the produced aluminium, the cathode, and collector bars, with resistivity values and geometries chosen based on industrial cells. For the resistance of an anode block, the L is represented by height, H , which is variable as specified in Equation (2). Moreover, the bath resistance is determined based on the mass fractions of the chemical species present in the bath, including Al_2O_3 , CaF_2 , AlF_3 , MgF_2 , LiF , as well as the bath temperature [4].

For the carbon anode, its height gradually decreases due to carbon consumption in the Hall-Héroult process, as illustrated in Figure 3. This consumption is accounted for in the electrolysis cell model by updating the anode height over time. The anode height at any given moment is calculated using Equation (2) [4]:

$$H_A = H_{Ini} - N C_{Con} \quad (2)$$

where:

- H_A Anode height at any given moment, m
- H_{Ini} Initial height of the anode, m
- N Total time since the anode was installed in the cell, s
- C_{Con} Carbon consumption per second, m/s.

When an anode becomes too short at a given time, it is replaced in the model by a new one and the current stops to pass in the anode for a fixed duration. In practice, the anode volume decreases over time, which affects the performance of the electrolysis cell. Therefore, to maintain the operation of the electrolysis cell under desired conditions, the rod length must be increased. While in reality the rod length remains fixed and increases only at discrete intervals, the developed model assumes that the length changes continuously according to Equation (3).

$$L_{Rod} = L_{Total} - H_A - L_{fix} \quad (3)$$

where:

- L_{Total} Fixed total distance between the anode beam and the bottom of the anode, m
- L_{fix} Constant length of the non-consumable three-branch structure part, m

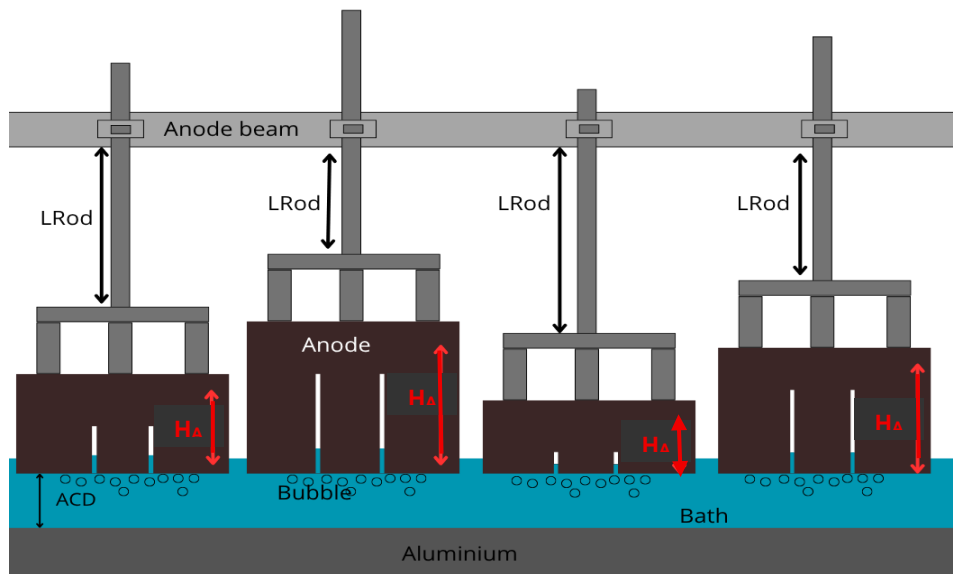


Figure 3. Illustration of different stages of anode consumption in an electrolysis cell.

The current distribution within the anode assembly is complex due to the geometry, contact resistance, and interactions between multiple conductive paths. As a result, determining the electrical resistances of its individual components using basic analytical Equation (1) is not always sufficient. To address this, the anode assembly was modelled and simulated using COMSOL Multiphysics. A sample of the generated geometry and mesh is shown in Figure 4. To determine the resistance of the anode from the finite element simulation, a current is imposed at the top domain and a fixed potential at the bottom of the domain. The calculated voltage drop can then be divided by the imposed current to obtain the resistance.

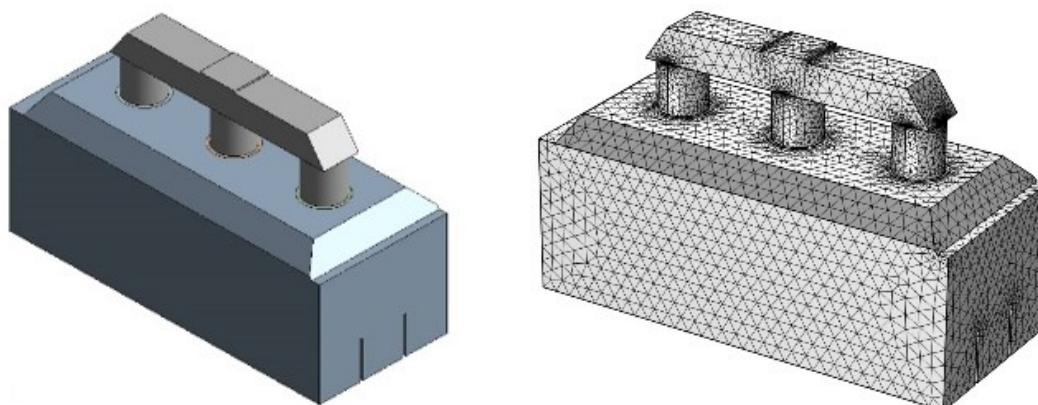


Figure 4. Geometry and meshing of the anode assembly in the COMSOL model.

Ten cases were simulated, each corresponding to a different anode height, ranging from the initial carbon anode height to the point at which the anode is replaced, representing successive stages of carbon consumption over time. The consumable height of the anode is presented in Table 1 corresponding to different anode heights. These cases were used to calculate anode resistance at different heights. Then, by knowing the anode resistance at various heights and determining its height using Equation (2), the anode resistance at any moment in the simulation is computed.

Table 1. Anode consumable heights for 10 simulated configurations.

Case	1	2	3	4	5	6	7	8	9	10
Height (mm)	450	400	350	300	250	200	150	100	50	10

2.2 Numerical Network Model

In this study, a time step of 15 minutes is used for simulating the electrolysis cell. Therefore, at each time step, the properties and dimensions of the components are recalculated, and the resistance at that moment is determined. Then, by computing the resistance of each component, the equivalent resistance of each electrical path is obtained. Subsequently, the total equivalent resistance of the electrolysis cell, which includes 40 electrical paths with a total of 40 anodes, is calculated. With the total input current to the electrolysis cell known, the total voltage is then determined. Finally, using this voltage and the equivalent resistance of each of the 40 electrical paths, the current flowing through each anode is computed.

To simplify the modelling process and focus on the key phenomena, several assumptions were made as follows:

- Anode consumption occurs uniformly throughout the cycle, with each anode being consumed up to 70 % of its initial volume during its lifecycle [5].
- The initial anode heights are assigned based on their installation sequence in the plant.
- The anode-cathode distance (ACD) remains constant.

- All electrical resistivities are considered constant, derived from fixed temperature values for each component.

3. Validation

To validate the model, data provided by Alcoa Corporation was used. The dataset includes the equivalent resistance of one electrolytic cell over time (Figure 5). The measured data (orange curve) show continuous fluctuations around the mean, reflecting real physical phenomena such as periodic alumina feeding, which is not yet included in the current model. As a result, the simulated resistance (blue curve) appears smoother. As observed, the developed model accurately predicts the sudden changes in resistance caused by anode replacement. Additionally, the drop in resistance following the replacement is due to the consumption of the anodes over time, which reduces the anode resistance and consequently the total resistance. However, due to the assumptions made in the modelling, the current model is unable to capture the fluctuations that occur in practice. Nevertheless, the order of the calculated resistance and the model prediction of the main phenomena are well aligned.

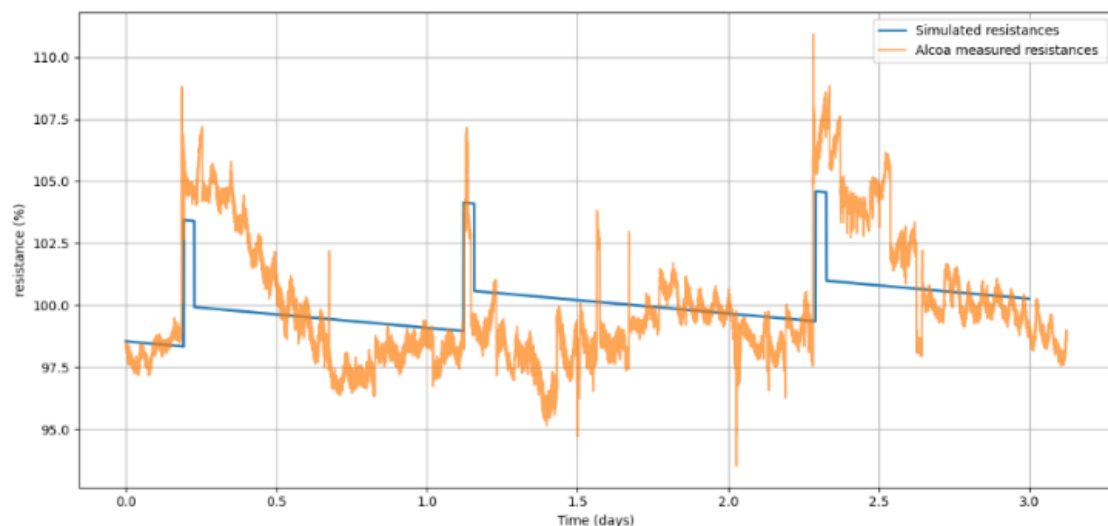


Figure 5. Evolution of simulated and measured nominal resistances in the electrolysis cell.

4. Results

In this section, the results of the performed modeling are presented. First, the results of anode modeling using COMSOL are discussed, followed by the integrated electrolysis cell modeling results obtained using Python.

4.1 Anode Resistance

An example of results obtained from a generic anode modelling in COMSOL is shown in Figure 6. By passing current through the anode and calculating the voltage distribution inside it, the anode resistance is determined. As observed, due to the complex geometry of the anode, the voltage distribution inside it is not uniform. Therefore, considering the anode as a one-dimensional body in the modelling does not yield accurate results. Consequently, using COMSOL and performing a three-dimensional modelling of the anode has significantly improved the accuracy of the results.

This process was repeated for ten anodes with varying heights, as listed in Table 1, with their respective resistances being calculated. Finally, based on the derived resistances, a correlation was formulated to express the relationship between anode resistance and its height.

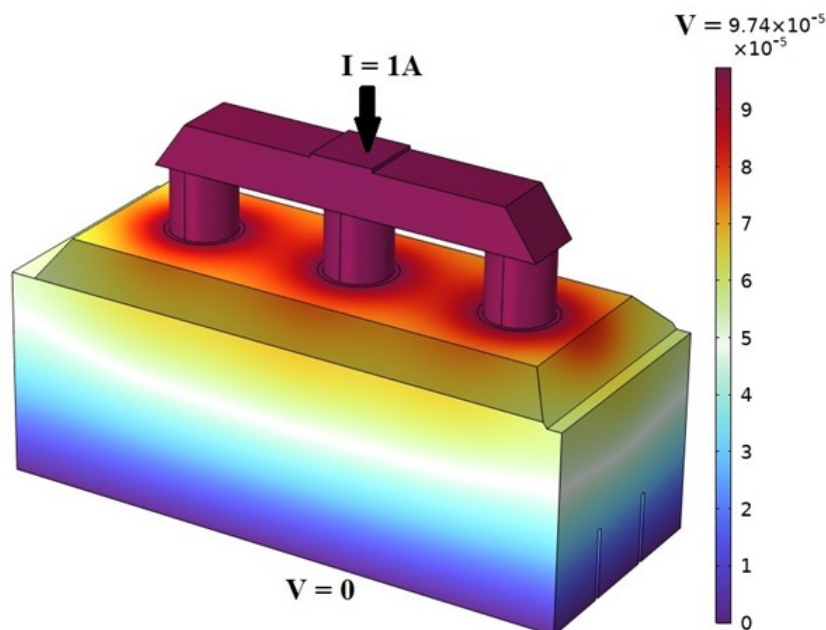


Figure 6. Voltage drop in a generic anode at the beginning of its cycle with the initial anode height.

4.2 Electrical Modelling of the Electrolysis Cell

In this model, 40 anodes with different initial heights were simulated within the electrolysis cell. The time evolution of the nominal electrical current, determined in reference to the average current in the cell, in three selected electrical paths during a full anode lifecycle in the electrolysis cell is shown in Figure 7. The electrical behaviour of the anodes changes progressively over time due to the gradual consumption of the anode material during the electrolysis process. As each anode height decreases through consumption, its electrical resistance also decreases. This relationship between height and resistance results in a gradual increase in the current flowing through the anode, since lower resistance allows more current to pass.

Among the three analysed anodes, anode 16 initially had the shortest height, followed by anode 36 and then anode 22. Due to its shorter initial size, anode 16 reached its critical minimum height earlier than the others, making it the first to be replaced. Anode 36 and anode 22 followed in sequence as they reached their respective minimum heights.

When an anode reaches its minimum operational height, it is removed from service and physically replaced with a new one. During this transitional period, the replaced anode temporarily goes out of operation, meaning that no electrical current flows through it. This sudden absence of current in the replaced anode causes a redistribution of the electrical load. The current that was previously shared by all anodes is now redistributed among the remaining active ones. As a result, these remaining anodes experience a temporary current increase, which appears as a noticeable jump in the current curves during the replacement phase. This increase continues until the replacement anode is fully integrated into the system and begins to conduct current again.

Furthermore, once a new anode is installed, it has a greater height than the one it replaced, resulting in a higher electrical resistance. Consequently, the newly installed anode initially

conducts less current than the older, consumed anodes. Over time, as the new anode is gradually consumed and its height decreases, its resistance also drops, allowing more current to flow through it. This cyclical process continues throughout the life cycle of each anode and is clearly reflected in the time evolution of current observed Figure 7.

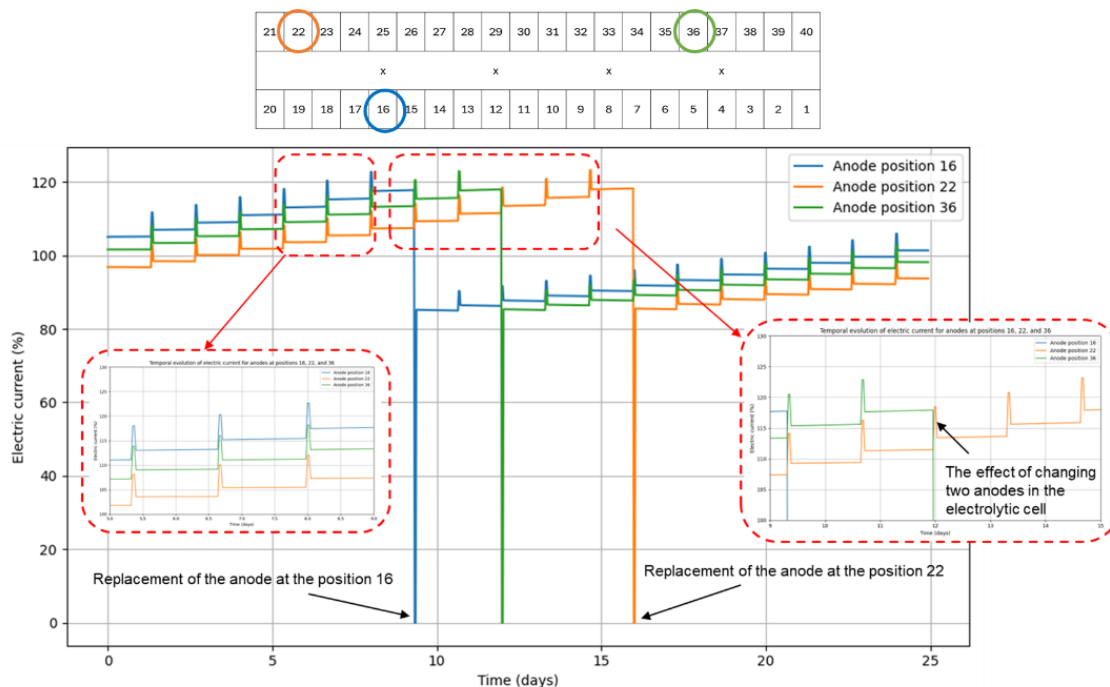


Figure 7. Numerical modelling results showing the temporal evolution of nominal electric current over an anode lifecycle.

5. Conclusions

The Hall-Héroult process is the primary industrial method for aluminium production. Understanding and predicting electrical behaviour during transient events such as anode effects is essential for improving energy efficiency, reducing emissions, and enhancing process control.

To address this need, a transient one-dimensional electrical model of a Hall-Héroult cell was developed in this study. The model aims to simulate the time-dependent current distribution during dynamic operating conditions. An electrical network composed of series and parallel resistances was implemented in Python to represent the evolving internal structure of the cell. Given the three-dimensional geometry of the anode, COMSOL Multiphysics was used to calculate its electrical resistance for various anode heights.

The model was validated against operational data provided by Alcoa Corporation, demonstrating acceptable with the measured equivalent resistance of the electrolysis cell. Furthermore, the time evolution of nominal current for a hypothetical scenario was analysed, providing valuable insights into the transient electrical behaviour of the system. This modelling approach supports real-time monitoring, predictive analysis, and the development of digital twins for advanced control of aluminium electrolysis cells.

In the next stage of the project, the time-dependent evolution of alumina concentration and other relevant species will be included to better reflect the dynamic behaviour of the bath during electrolysis.

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