An Improved Finite-Element Model for Electromagnetic Analysis in Aluminum Cells

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This article presents the use of an improved finite-element model to calculate the static electromagnetic field for an aluminum reduction cell. Consisting of three solid cells and their surrounding bus bars, the model can evaluate the non-uniformity of the current distribution in the inside conductors and bus bar system and couple the current into the sequential magnetic analysis through a conversion routine. Voltage potential distribution in the molten aluminum was investigated based on one industrial 320 kA aluminum cell with two designed bus bar arrangements. Characteristics of magnetic components' distributions were also given.

INTRODUCTION

High-amperage aluminum reduction cells with capacity over 300 kA have been used widely not only in new aluminum plants, but also in retrofitting old plants. Worldwide, extremely large commercial electrolysis cells are being developed with capacities of 400 kA, 500 kA, and even more. As is well known, AP 50 prototype pots were set up to test the structure design, control system, and economic performance of these cells.[1]

Magnetic compensation is an important factor to be considered in the design of high-amperage cells in order to stabilize the shape of the bath-metal interface and control the velocity of the molten liquids. Numerical calculations such as with the finite-element method (FEM)[2,3] or boundary element method[4] are performed to solve the Maxwell equations with the presence of ferromagnetic material. Study of the electromagnetic field to date has included building a complete and complex electromagnetic mathematic model,[5] designing new bus bar arrangements especially for very large electrolysis cells,[6] and performing measurements of newly used industrial cells for validation purposes.[7]

How would you...

...describe the overall significance of this paper?

We proposed a finite-element model that consists of three solid cells and their surrounding bus bars. The model can be used to calculate non-uniform current distribution in the whole electric circuit. Then the current is coupled into the sequential magnetic analysis through a fast conversion routine.

...describe this work to a materials science and engineering professional with no experience in your technical specialty?

This work is related to the Hall–Héroult aluminum reduction cell for commercial production of primary aluminum. Because more than 300 kA direct current passes through and around the cell, its electric and magnetic distribution are difficult to predict. We proposed a finite-element model that takes into account more factors than ever that may influence the accuracy of numerical calculation. Based on this model one can know more about how to design optimal bus bar networks of the large cell.

...describe this work to a layperson?

This work is related to the aluminum electrowinning process, namely the Hall–Héroult process. The aluminum reduction cell used in this process has more than 300 kA current passing through it to reduce alumina in a bath of molten electrolyte to molten aluminum. The electric circuits inside and outside the cell occur so complexly that it is hard to calculate the magnetic fields conveniently. Therefore, a simulation model was proposed to enable the design of more stable and efficient cells.

Currently, high-amperage cells are arranged side by side in the potline, which allows current to come into anodes through side risers. To reduce the magnetic field, the current out from the upstream side of the cell can be directed to the next anode risers under the bottom or can be passed around the end of the cell. The current out from the downstream can be connected to the next anode risers as closely as possible. The bus bar sizes have to be adjusted to achieve resistivity balance in the whole circuit and make sure that current flowing out in the collector bars can be evenly distributed.

Realistically, all conductors inside and outside the cell should be connected with demonstrated electric integrity to get the current and voltage distribution. Meanwhile it is necessary to consider how the change occurring in the electric field will affect the magnetic field. The magnetic distribution is caused by both the inside conductors and bus circuit, but it is essential to determine how much each one will contribute to the magnetic field alone. With that information one can find the most effective bus bar arrangement for magnetic compensation. If the static Maxwell equations are solved numerically by FEM, the problem of building the continual meshes remains, where solid conductors, lining, steel shell, and open-air domain are involved. Fortunately, bus bars can be represented by source elements to supply current and modeled separately. In this study, three cells and their surrounding bus bars will be investigated using FEM.

FINITE-ELEMENT MODEL DEVELOPMENT

The fundamental physical laws applicable to the electric field are the Ohm's

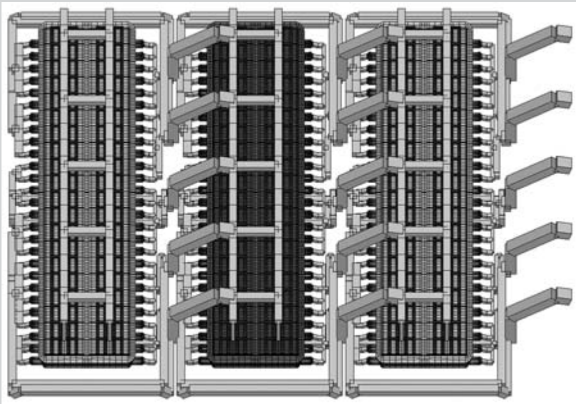

Figure 1. A schematic of the electric model with three solid cells and the bus bar circuit and with the middle cell as the target cell.

and Coulomb's Laws, which govern electric current distribution. Ampere's Law and the magnetic permeability definition govern the magnetic field distribution. In the authors' electric model, the inside conductors and bus circuits are connected by electrically constrained boundary conditions, with contact between the carbon block and the steel bar defined as the electric contact and magnetic contact for the electromagnetic solution. The solution procedure is seen as time independent or static.

To simplify the development of the computer model, certain assumptions were made. The complex shell and cradles were replaced by a simple rectangular box. The superstructure did not contribute to the magnetic field and therefore was omitted from the model. Infinite boundary was defined at the open boundary of air. A given ledge profile existed surrounding the liquids and the interface between the bath and metal was flat.

The ANSYS code is employed to build the geometric model, assign material properties, mesh the model with all hexahedrons, and to determine electric and magnetic finite-element models. Five anode risers on the positive side are given a value of potline current, and five on the negative side are given zero electric potential. Magnetic scalar potential is applied on nodes at surrounding surfaces of air.

The flow procedure of the electromagnetic sequential coupled simulation is as follows. First the electric model is built and solved by the electric scalar potential to get the current distribution. Then this model is converted to the corresponding magnetic model by changing element types, materials, and boundary conditions, which is solved by the magnetic scalar potential. Current of the conductive parts in the cell can be stored in the result file and shared by the magnetic solution procedure. The bus bars are simply treated as conductive two-dimensional (2-D) wire-bars in the electric model. For the magnetic field they must be precisely transferred to current source elements according to the carrying current, the flowing direction, and the cross sections of every bus bar. Figure 1 is the electric model with three solid cells and the bus bar circuits.

The origin of the coordinate system is shown near the bottom of Figure 1, located at the bottom of the cathode lining and in the center of the target cell, with the upward direction as x axis, the direction to the upstream cell as y axis, and the outward direction as z axis.

LOCAL BUS BAR DESIGNS FOR COMPARATIVE ANALYSIS

Commercial aluminum cells are running at 320 kA with one set of designed bus bars. In the authors' computer model the bus bar arrangements were designed quite differently than in the original. One bus bar configuration is the basic setting. Two local bus adjustments differ near one corner at the upstream side (Figure 2). They are ready for a detailed analysis of the impact of the bus bar change on the electric and magnetic field. The solid structure and dimensions of the model cell are the same as the commercial 320 kA electrolysis cell.

ANALYSIS OF THE ELECTROMAGNETIC FIELD

The static electromagnetic field of the target cell was calculated according to the steps mentioned previously. The voltage solution in the cathode and the

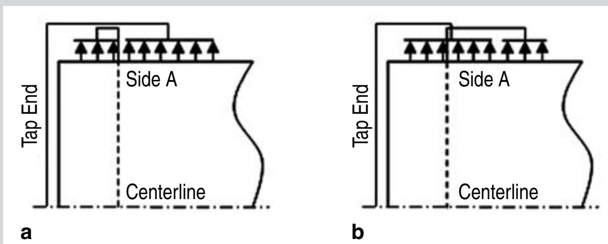

Figure 2. Two local bus bar configurations (a and b) near the corner at the upstream side.

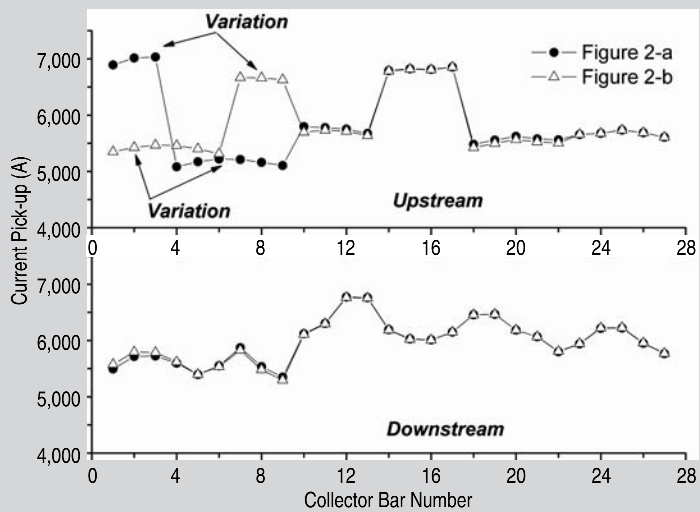

Figure 3. Current distributions in the steel bars.

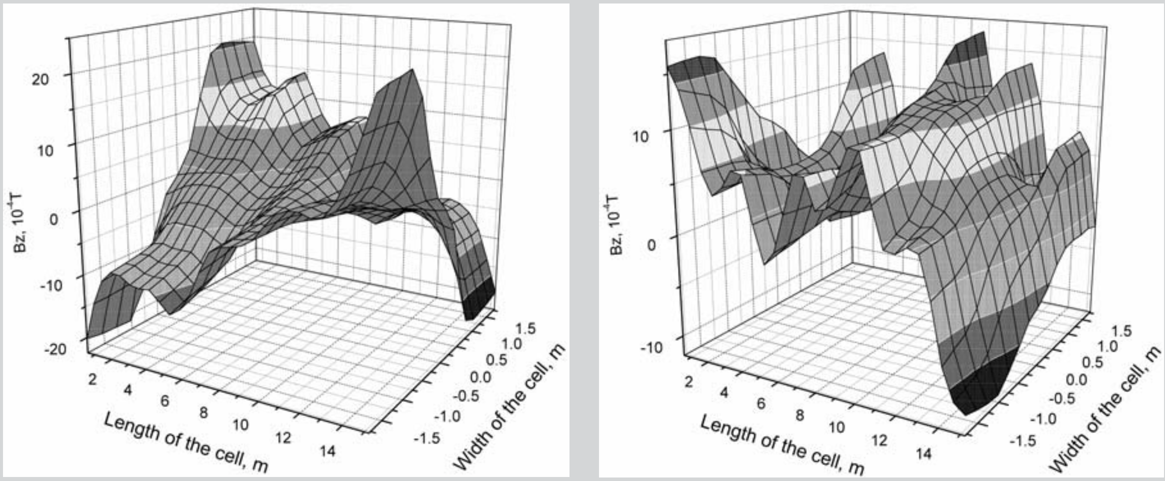

Figure 4. Vertical magnetic components induced by (a) inside currents and (b) bus circuits.

metal, current distribution in the steel bars, and magnetic flux in the middle of the metal were of interest.

Voltage Distribution

Cathode voltage drop (CVD) was calculated by the electric contact model. The CVD was about 0.290 V with semi-graphitic blocks used in this case. Contact phenomenon can be responsible for an ohmic drop of about 100 mV. Predicted iso-potential curves concentrate near the bar outlet and this kind of distribution agrees well with Reference 8.

Molten aluminum has a very large electric conductance but it still goes through about ten milli-voltage drops, which means existence of horizontal current flow in the metal. Examples of two local bus bar configurations show that changing the bus bars' grouping and location caused different voltage distributions in the metal. The voltage potential was higher where steel bars were connected by six flexes to direct current passing around the end side of the cell than where steel bars were connected by three flexes to carry current under the bottom of the cell. The redistribution of voltage is influenced by the bus bars' equivalent resistivity, which is dependant on its paths and cross sections. An ideally optimized bus bar configuration will make voltage potential nearly even in the sides of the metal, but the voltage is higher in the middle than in the side. To direct current effectively from the metal vertically into the block, the cathode structure with full-length collector bars is preferred.

Current Distribution

Figure 3 shows how much current steel bars could take out in two local bus bar configurations. Variations of current were seen at the upstream side, which correspond to the change of the local bus bars' grouping and localization.

Also found in Figure 3 are seven cathode bars collecting current over 6,500 A at the positive side, which are wired to the circuit going beneath the cell. The current was more smoothly and uniformly distributed in the negative side than in the positive side, suggesting that the cathode bus should be positioned under the cell to get the current uniformity. In two examples a 50:50 split for the two sides was not reached but the currents flowing out of the negative side were only about 1% more than the positive side.

Magnetic Flux Distribution

Magnetic flux dependent on the non-uniformity of the current distribution was calculated. In both examples, distribution of the horizontal magnetic component Bx in the middle of the metal was antisymmetric along the longitudinal direction of the centerline of the cell, with a value ranging from –138 Gauss to 169 Gauss. And that of By was also antisymmetric along the transversal direction with a value ranging from –23 Gauss to 23 Gauss. It is seen that local bus bars' adjustments have little effect on the horizontal magnetic field.

However, the vertical component was influenced indeed. In the Figure 2a bus pattern, the maximum and minimum values of Bz were 30 Gauss and –25 Gauss, respectively, with the average being 7 Gauss. In the Figure 2b bus pattern, the maximum and minimum values of Bz were 28 Gauss and –24 Gauss, respectively, with the average being 8 Gauss. In both patterns, max./min. values of Bz were localized at two corners of the metal near the upstream side. Bz was relatively large in the area between the first and second risers (from the coordinate origin toward the x axis) for the latter bus pattern, which was caused by current increasing in the grouped collector bars and decreasing in the second risers. This fact indicates that the adjusted bus circuit can cause current redistribution in the risers and that risers are important contributors to the magnetic field.

Characteristic of the Magnetic Field

Generally, discussion of the magnetic field is based on the final calculated results without dealing with inside conductors and outside bus circuits. It is necessary to know the influence of the bus bar network on the magnetic field and how it will compensate the magnetic pattern introduced by the inside currents passing in the anodes, bath, aluminum, cathode, and steel bars. The second bus configuration is for this purpose.

The horizontal component Bx induced by the inside currents was antisymmetric along the length and ranged from –65 Gauss to 67 Gauss. That caused by the bus network had a similar distribution with min./max. values being –75 Gauss to 117 Gauss. Concerning By, the distributions were much different. The perfect antisymmetric pattern occurred in the former case with max./min. values existing at the end compared to the latter case where max./min. values appear at the sides. Two horizontal parts of the magnetic field would finally seem to superimpose to strengthen themselves.

Inside conductors caused the vertical component Bz to form two diagonal peaks and troughs at four corners (Figure 4a). This was due mainly to horizontal current out of collector bars, which also determined the basic distribution pattern for the whole magnetic field. Bz by the bus network is shown in Figure 4b. This kind of distribution would assist in strengthening the basic pattern at the upstream side while compensating it at the downstream side. It is suggested that some amount of current should be arranged to go around the end side of the cell to reduce the magnetic field.

DISCUSSION

The upstream and downstream solid cells were considered in this model, therefore, designed tests were computed to confirm that they were actually involved in the magnetic solution procedure. Since these computations were performed on desktop workstations, more neighboring solid cells can be involved in the model if powerful computers are available. To design large aluminum cells, the length/width ratio, confining the number of collector bars and their interval spaces, is important to the MHD stability since currents in bars can induce the basic magnetic field. Another worry is that assumptions and applied boundary conditions on the model might cause effects on the solution precision, but these effects could be very limited.

CONCLUSIONS

The finite element model of the electromagnetic field is improved by building the contact mechanisms between steel bars and cathode blocks to make sure that voltage drops are properly distributed in the metal and the cathode. The model including three solid cells and the bus circuits is used to take into account impacts of bus bar adjustments on the electric and magnetic distribution. It is concluded that it is important to balance resistivity of bus bars in the whole circuit by means of directing current under the bottom of the cell and also directing some amount of current around the end side of the cell for the magnetic compensation.

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