Light Metals 2014
Edited by: John Grandfield
TMS (The Minerals, Metals & Materials Society), 2014

DYNAMIC SIMULATION OF CELL VOLTAGE RESONANCE EFFECT IN ALUMINUM ELECTROLYSIS CELL

Yongliang Wang [1], Jun Tie [2], Ganfeng Tu[1], Shuchen Sun [1], Rentao Zhao[2], Zhifang Zhang[2]
[1]School of Materials and Metallurgy, Northeastern University, Shenyang 110004,China
[2]North China University of Technology, Beijing 100144,China

Keywords: Aluminum Electrolysis Cell, Equivalent circuit, Resonance effect, Dispersion

Abstract

An equivalent circuit of aluminum electrolysis cell has been implemented to model the current distribution and cell voltage fluctuation using the Matlab/Simulink simulation software. Given disparity of liquid aluminum fluctuation frequency under each anode carbon block, the datum of these frequencies constitute a set of series. The current distribution and cell voltage fluctuation were investigated when the series is an ordered sequence and a random sequence. Then the dispersion of current distribution was calculated, of which the trend line was applied to determine the resonance effect. The simulation results show that cell voltage resonance effect is caused, with great cell voltage enlargement and anode current redistribution. Furthermore, the span and cycle of the resonance are closely associated with the vibration frequency.

Introduction

Cell voltage, a principal technical parameter in aluminum electrolysis production, contains significant information of the cell production, and is also the basis of cell production control and manufacturing management. Normally, cell voltage fluctuates in a small range, usually between 15-30mV [1-2]. When voltage exceeds this range and this phenomenon continues in the production, it is called cell noise [3], indicating that the cell may be out of order. Cell voltage fluctuation range is often used to judge the cell's operation status. Continuous high-frequency fluctuation of the cell voltage is called voltage vibration, and the low-frequency fluctuation is called voltage swing. In the process of aluminum electrolysis production, lots of factors may cause cell noise, such as the fluctuation of potline current, anode change, liquid aluminum fluctuation, the concentration of alumina, anode gas emission, and so on [4-5]. The voltage noise, as an important sign of deterioration of cell operation [6], reduces current efficiency and increases energy consumption. The aluminum reduction cell is a highly corrosive closed system with high temperature, so it is difficult to find the cause of noise through direct observing and determining. The cause can only be speculated by production experience and other abnormal phenomena in the cell, so there are still many problems that need further study.

The production process of pre-baked aluminum electrolysis cell is essentially a single cathode and multi-anode electrolysis process, which can be equivalent to a resistance circuit [7]. The Matlab/Simulink simulation software has been chosen for the task of constructing and simulating the equivalent circuit of the cell. Simulink is a visual simulation tool of the MATLAB, which is the software package used for dynamic system modeling, simulation and analysis, supporting linear and nonlinear systems which are continuous, discrete, and both at the same time, and a variety of sampling frequency systems. In the production of aluminum electrolysis, because of the electromagnetic force, gravity and the disturbance of anode gas escape [8-12], the liquid aluminum covering the surface of cathode constantly fluctuates, leading to the liquid surface instability. The distance between anode and liquid aluminum interface will change with the interface fluctuation, so the anode-cathode distance (ACD) changes. As a result of the constant change in ACD, the resistance between anode and cathode changes, causing the continuous change in the current distribution and cell voltage [13]. Therefore, this paper makes a preliminary study of the change in cell voltage and anode current distribution by changing the ACD under the anode carbon block and tries to explore the feature of cell voltage fluctuation.

Cell equivalent circuit simulation system

Model description

In the production of aluminum, constant current DC feeds the anode rod from the busbar, flowing through the anode carbon block, electrolyte, liquid aluminum, cathode block, and finally outflows from the cathode bars, as shown in Figure 1.

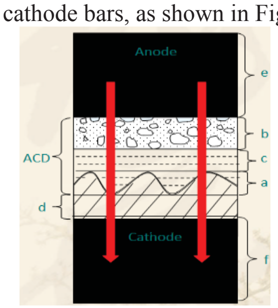

Figure 1 Schematic diagram of the DC through the cell

In this schematic diagram, area a represents the liquid aluminum fluctuation layer, area b shows the electrolyte and the air bubble mixing zone, area c indicates the electrolyte, area d shows the liquid aluminum, area e represents an anode block, area f shows the cathode block. Typically, the ACD is made up of area a, b and c; the cathode is made up of area d and f [14]. In the cell resistance circuit, the resistance of anode block (R_{anode}), resistance of electrolyte (R_{ACD}), resistance of liquid aluminum and cathode block ($R_{cathode}$) can be regarded as pure resistance; in the cell, the following main reaction occurs at the anode carbon block immersed in the electrolyte:

$$2Al_2O_3 + 3C(s) = 4Al(l) + 3CO_2(g) \quad (1)$$

The decomposition of alumina will produce a reaction resistance ($R_{reaction}$), and the overpotential at each electrode will cause a resistance (R_{over}); the anode reaction will produce carbon dioxide, a gas layer that will partly cover the surface of anode carbon block and will also mix with the electrolyte, which will increase the resistance of the electrolyte, and this resistance is called bubble resistance (R_{bubble}); in addition, the cell also includes anode rod, cathode steel bar, and some other resistors, all of which are called R_{other}, so the total resistance of the whole cell can be expressed as [7, 15]:

$$R_{total} = R_{anode} + R_{cathode} + R_{ACD} + R_{reaction} + R_{over} + R_{bubble} + R_{other} \quad (2)$$

According to the Nernst's equation, the reaction electromotive force E_{re} of the reaction (1) can be given as:

$$E_{re} = E^0 - \frac{RT}{zF}\ln\left(\frac{P_{co_2}^3 \times \alpha_{Al}^4}{\alpha_{Al_2O_3}^2 \times \alpha_C^3}\right) \quad (3)$$

Where α_{Al} is the activity of Al, α_C is the activity of C, P_{CO_2} partial pressure of CO_2.

In equation (3), E^0 is the standard potential and a function of temperature. In this reaction, E^0 is [16] :

$$E^0 = -1.8984 + 5.725 \cdot 10^{-4} \cdot T \quad (4)$$

Assuming that P_{CO_2} =1, α_{Al} =1, α_C =1, then:

$$E_{re} = E^0 + \frac{2RT}{zF}\ln \alpha_{Al_2O_3} \quad (5)$$

In the bath, the activity of Al_2O_3 can be expressed as [7]:

$$\alpha_{Al_2O_3} = \left[\frac{\omega_{Al_2O_3}}{\omega_{Al_2O_3(\mathrm{sat})}}\right]^{2.77} \quad (6)$$

where, $\omega_{Al_2O_3}$ is the concentration of Al_2O_3 (wt.%),

$\omega_{Al_2O_3(\mathrm{sat})}$ is the saturated alumina concentration (wt.%).

In the cell, overvoltage is also produced in the carbon surface. Because the cathode overvoltage and concentration overvoltage have a little effect on cell voltage [17], it is assumed that the cell overvoltage is only due to the anode. According to Tafel equation, anode overvoltage is dependent on the anode current density (i_a) [18]:

$$\eta = a + b\lg i_a \quad (7)$$

where, a is the Tafel constant (0.5), b is the Tafel slope (0.25).

According to Ohm's law, R=U/I, $R_{reaction}$ and R_{over} can be calculated.

In this paper, it is assumed that the interpolar distance (ACD) changes with the liquid aluminum fluctuation. The ohm resistance of electrolyte can be obtained [16]:

$$R_{ACD} = \frac{ACD - b_b}{s \cdot \kappa} + \frac{b_b - d_b}{s \cdot \kappa (1 - 2\omega_{Al_2O_3})^{1.5}} \quad (8)$$

where,

κ is the conductivity of electrolyte (μS/cm),

b_b is the bubble thickness (cm),

s is the cross sectional area of anode block (cm^2),

d_b is the single layer bubble thickness (cm).

The bubbles increase the resistance of the electrolytic circuit, and this additional resistance can be calculated [16]:

$$R_{bubble} = \frac{d_b}{\kappa(1 - 1.26 f_c)s} \quad (9)$$

where f_c is the fraction of anode covered by bubbles (%).

A 400kA electrolysis cell is used in this study. The main design parameters are shown in table 1.

Table 1. Main design parameters of the 400kA electrolysis cell

Name	Size	Name	Size
Anode carbon block size/mm	1550×1320×620	Potline current/kA	400
Anode carbon block number	24	Temperature/^{o}C	950
Anode stub number per anode	6	Anode rod number	24
Cell voltage/V	4.2	ACD/cm	4.0
Concentration of the alumina/%	3	Bath ratio	2.3

Simulation model

The typical pre-baked aluminum electrolysis cell has multi-piece of anode carbon blocks, current flows into the block from different anode rods, goes through electrolyte, liquid aluminum, and finally reaches cathode block. Therefore, in this study the electric circuit is considered as a 24-branch parallel circuit, each branch containing the anode rod, 6 steel stubs, two anode carbon blocks, and the electrolyte under anode block, and all the branches current going to the liquid aluminum and cathode block.

In this study, the simulation model of the equivalent circuit with 24 anode branches has been built using Matlab/Simulink simulation software. Figure 2 is a two-branch model, which is the part of the 24-branch model. In this model, simulation system includes several software modules, such as Control Current Source, RLC Branch and Scope. At the same time, it also contains some self-designed modules, for instance, reaction resistance module (R_reaction), overpotential resistance module (R_over), electrolyte resistance module (R_ACD), bubble resistance module (R_bubble), and anode resistance module (R_anode). According to the formulae (3)-(9), the output resistance of these self-designed modules changes with ACD, bubble coverage rate, concentration of the alumina, current, and so on. In addition, in Figure 2, the fixed resistance module r represents the resistance of anode rod and steel stub; other resistance module simulates cathode resistance and cathode bar resistance; T module says the electrolysis temperature; Al2O3% module shows the concentration of alumina; fc module is fraction of bubble coverage; ACD module represents the change of ACD caused by liquid aluminum fluctuation.

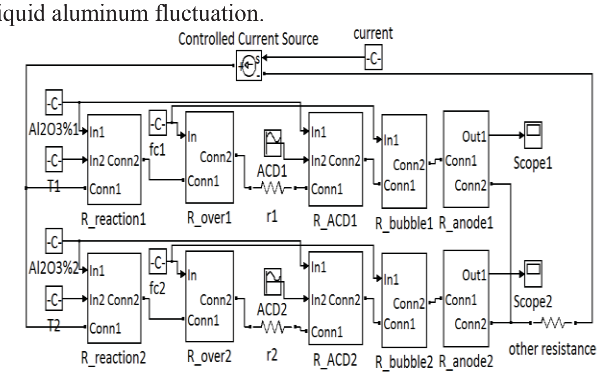

Figure 2 Schematic diagram of the two-branch Matlab / Simulink simulation circuit

Assumption

Aluminum electrolytic process is a very complex dynamic process. This simulation is based on the following assumptions:

1. Cell temperature is maintained at 950^{o}C and magnetic is stable;

2. Current flow through the cell is mainly vertical, and the horizontal current is negligible;
3. Electrolyte bath ratio is 2.3, and alumina concentration is 3%.
4. Cathode overpotential has little effect on the cell voltage, so it is assumed that the cathode overpotential has no impact on the anode current distribution;
5. Anode gas is produced stably on the anode surface, so the anode surface coverage and bubble resistance are constant;
6. Anode consumption is very slow and the distance between cathode and anode interface is invariant within a short period of time;
7. Liquid aluminum fluctuation frequency under different anode carbon blocks is different, and the fluctuation is a sine wave.

Simulation investigation under ordered sequence series frequency

Simulation conditions

Aluminum electrolytic process is a very complex dynamic process. In order to investigate the effect of liquid aluminum fluctuation on the anode current distribution and cell voltage, it is assumed that the cell is stable in a short time, the bubble is released uniformly, the fraction of bubble coverage on anode surface is steady at 40%, bubble layer thickness is 1cm, single bubble thickness is 0.5cm, electrolysis temperature is maintained at 950°C, alumina concentration is stabilized at 3%, so the problem is simplified.

According to literature [19], the fluctuation period of liquid aluminum is about 50s, i.e. the fluctuation frequency is 0.02Hz, and waveform is arc-shaped. So this study assumes the waveform of the liquid aluminum as standard sine wave, satisfying the equation:

$$y = A\cdot\sin(2\pi\cdot f\cdot t+\theta) + h \quad (10)$$

Where A is the variation amplitude of ACD change caused by the liquid aluminum fluctuation (cm), f is the frequency of the liquid aluminum fluctuation (Hz), t is time (s), θ is the initial phase (rad), h is the average height of the ACD (cm).

According to equation (10), it is further supposed that variation amplitude of ACD change (A) remains at 0.5 cm, and average height of the ACD (h) is 4.1 cm. As the liquid is flowing, initial phases of the liquid aluminum fluctuation under different anode carbon blocks are different. In this paper, the phase difference between two adjacent anode blocks is assumed to be 0.544π. Electromagnetic force and the disturbance generated by the emission of the anode gas are the major factors of the liquid aluminum fluctuation. However, the difference of current distribution will cause difference in electromagnetic force. In the meanwhile, the emission of the anode gas is also uneven, so the fluctuation frequencies of liquid aluminum under different anodes are different. Therefore, this paper assumes that the fluctuation frequencies of the 24 branches are respectively 0.015, 0.0154, 0.0158, ···, 0.0242Hz, all of which are around 0.02Hz [19]. This series is an ordered arithmetic progression, and its tolerance (Φ) is 0.0004Hz. This series frequency is defined as Series 1, and the waveform is standard sine wave.

The simulation time is set to 10000s, discrete time is 2s, i.e. sampling frequency is 0.5Hz. Simulation cell voltage and the current flowing through branch 1 are shown in Figure 3.

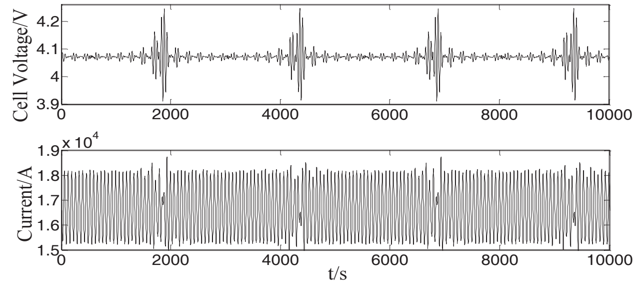

Figure 3 Simulation cell voltage and current flowing through branch 1 under frequency series 1

Simulation results analysis

As is shown in Figure 3, larger voltage fluctuations occur two times during 5000s simulation time, with the maximum fluctuation amplitude reaching 330mV. When the cell voltage reaches maximum amplitude, the current distribution shows relatively small fluctuation. According to the assumptions, each branch has different frequencies, but the values are very close, which causes a sudden increase in the cell voltage. This paper defines this simulation phenomenon as cell voltage resonance effect.

The frequency response of the simulation signals is studied in this paper by means of Fourier spectrum analysis. Figure 4 shows the power spectrum of the cell voltage and branch current, both of which are shown in Figure 3. In Figure 4, the main frequency of the current is 0.015Hz, which is the same as the frequency of the liquid aluminum fluctuation in this branch; while the main frequency range of cell voltage is between 0.015—0.0242Hz, containing all the fluctuation frequencies of the liquid aluminum.

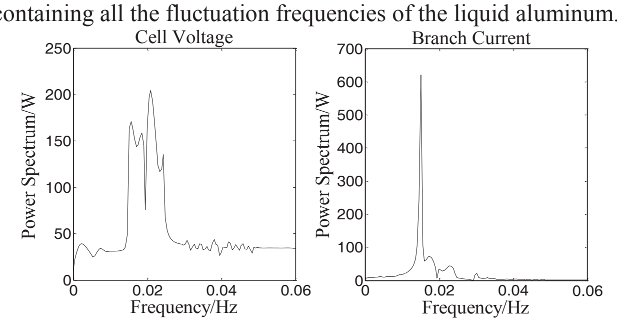

Figure 4 Power spectrum of the simulation cell voltage and current under frequency series 1

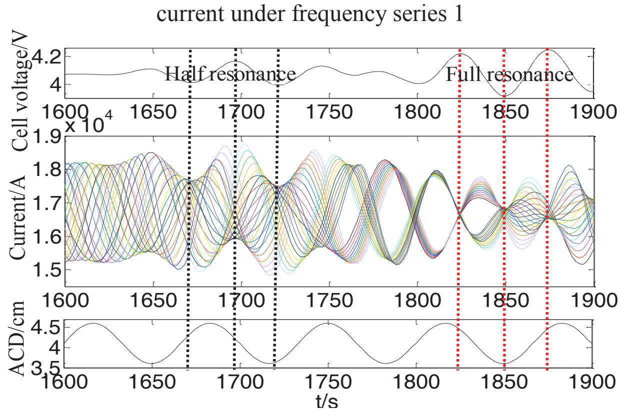

Figure 5 The change of cell voltage, current and ACD of one branch during resonance effect

In order to further observe and analyze, the data obtained during 1600s-1900s is plotted in Figure 5, when the resonance effect occurs. Figure 5 shows the cell voltage curve, the current curves of the 24 branches and the ACD change curve of one branch, whose frequency is 0.015Hz.

In Figure 5, cell voltage at wave peak corresponding with the red vertical dotted line area is amplitude of voltage fluctuation at the maximum, when the current curves are almost in the balance position, and their values are nearly equal. When cell voltage is at its wave valley, amplitude of voltage fluctuation is at the minimum, the current value is very close and tends to be equal too. During this time, the maximum fluctuation amplitude of the cell voltage reaches 330mV, and lasts for more than 100 seconds, which is defined as full resonance effect in this paper.

In Figure 5, larger cell voltage fluctuation also occurs in the area corresponding with the black vertical dotted line, with the fluctuation range reaching 170 mV and lasting more than 100 seconds. When the voltage peak or valley appears, compared with the previous normal case, the current distribution range of 24 branches is significantly reduced, and part of the branch current size is very close, which is defined as half resonance effect in this paper. In fact, the half resonance effect is the resonance of part of the 24 branches.

In addition, it can be seen from the ACD change curve that when the cell voltage is at its wave peak or wave valley during resonance effect, the ACD is not necessarily located at the peak or valley. That is because the aluminum electrolysis cell is multi-anode and it is difficult to make the 24 branches have the same liquid aluminum fluctuation situation, i.e. resonance effect. Figure 6 shows the current through branch 1 (0.015Hz, black cure) respectively compared with branch 2 (0.0154Hz), branch 8 (0.0178Hz), branch 14 (0.0202Hz), branch 20 (0.0226Hz) and branch 24 (0.0242Hz), all of which are used in red cure.

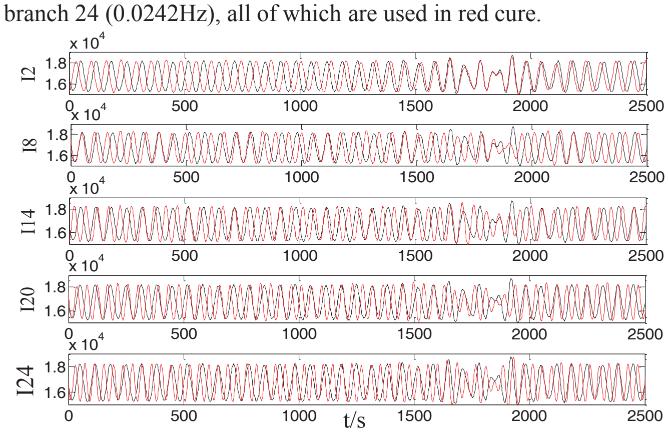

Figure 6 The comparison of the current resonance effect between branch 1 and some other branches

In Figure 6, the frequencies of current I1 and current I2 are the closest, the two lines coincide with each other one time during 2500 seconds, and the coinciding time is relatively longer, lasting more than 200 seconds. As the frequency increases, two lines coincide more times, but last less time. Almost no apparent sustained resonance effect appears between current I1 and current I24. So when the frequency of the current fluctuation gets closer, the current of the two branches has a greater chance of resonance lasting a longer time.

Investigation of resonance effect

The previous study investigates the resonance effect under the ordered sequence frequency series whose tolerance is 0.0004Hz. Keeping frequency series as arithmetic sequence, and changing tolerance (Φ), nine series of frequency are simulated by using the above simulation model. These frequency series tolerances（Φ）are respectively 0.0005Hz, 0.00045 Hz, 0.0004 Hz, 0.00035 Hz, 0.0003 Hz, 0.00025 Hz, 0.0002 Hz, 0.00015Hz and 0.0001Hz. According to the simulation results, the duration of each resonance is different. The duration time is defined as resonance span (t) in this paper. The duration between two times resonance is also different, which is defined as resonance cycle (T). So this paper researches on the influence of tolerance change on the resonance span, resonance cycle, and also the maximum amplitude of the voltage fluctuation (A), respectively shown in Figure 7-9.

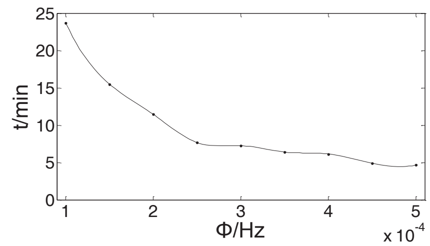

Figure 7 Resonance span under series frequency with different tolerances

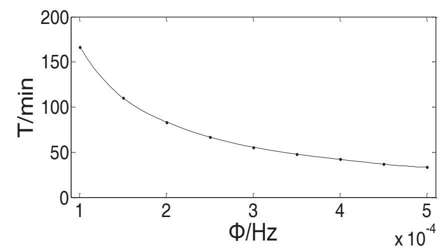

Figure 8 Resonance cycle under series frequency with different tolerances

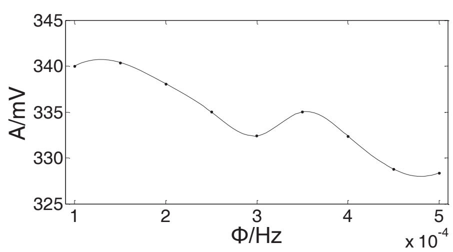

Figure 9 Maximum amplitude of the voltage fluctuation under series frequency with different tolerances

When the tolerance frequency increases, the frequency difference of two adjacent branches becomes greater. As is shown in Figure 7 and Figure 8, the resonance span and the resonance cycle are reduced as the tolerance increases. Namely the resonance effect occurrence is more and more frequent, and the duration time is shorter and shorter. For example, when the tolerance is 0.0005Hz, the resonance cycle is about 33 minutes, and the duration time is about 4.6 minutes. It is said that there will be a larger amplitude of cell voltage fluctuation every 33 minutes. The resonance effect is so frequent that it inevitably has a bad effect on the cell production. In Figure 9, as the tolerance increases, the maximum amplitude of cell voltage fluctuation is wave-like reduced and the values are all between 328-341mV, so the maximum amplitude value is very close. Therefore, the small frequency change in each branch has little effect on the maximum amplitude. Although the frequency change will change the feature of liquid aluminum fluctuation, the effect on cell resistance is very little, so the fluctuation amplitude will change little when the cell voltage resonance effect occurs.

Simulation investigation under random sequence series frequency

In the previous section, the series of liquid aluminum vibration frequency under different anodes is an ordered sequence. In this case, the simulation results show that significant resonance effect will occur to the current distribution and cell voltage. However, in the actual production process of aluminum electrolysis, liquid aluminum fluctuation under different anode carbon block may be different, due to the larger bulk of the cell, the complexity electromagnetic force, bubble effect as well as some other factors. Their fluctuation frequencies may be random and difficult to meet the case of arithmetic sequence. So the following studies will investigate such a case where the frequency series is a random sequence.

<u>Investigation of cell voltage and current distribution</u>

Based on the previous simulation model, we changed the fluctuation frequency of liquid aluminum and resimulated without changing the other conditions. The liquid fluctuation frequencies under each anode block are assumed as 0.015Hz, 0.0153Hz, 0.0159Hz, 0.0161Hz, 0.0162Hz, 0.0166Hz, 0.0176Hz, 0.018Hz, 0.0185Hz, 0.0187Hz, 0.0191Hz, 0.0199Hz, 0.0203Hz, 0.0208Hz, 0.021Hz, 0.0214Hz, 0.0219Hz, 0.0223Hz, 0.0228Hz, 0.0232Hz, 0.0235Hz, 0.0239Hz, 0.0241Hz and 0.0245Hz, all of which are around 0.02Hz too. This series frequency is defined as Series 2. The simulation time is still 10000 s; the sampling frequency is 0.5Hz. Figure 10 shows the simulation cell voltage. Figure 11 shows the power spectrum of the cell voltage and one branch current, whose liquid fluctuation frequency is 0.015Hz.

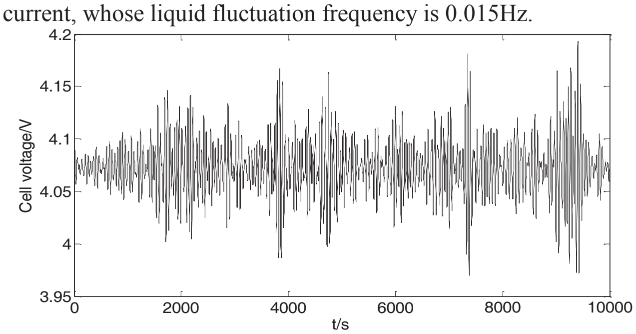

Figure 10 Simulated cell voltage under frequency Series 2

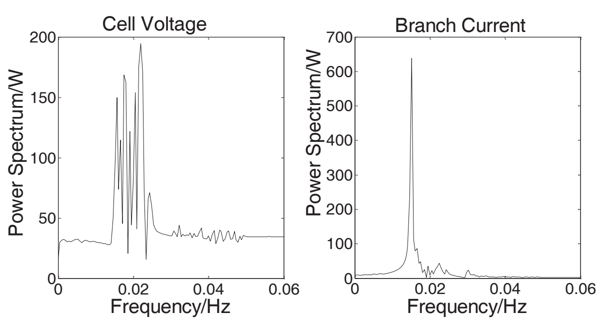

Figure 11 Power spectrum of the simulation cell voltage and current under frequency Series 2

In Figure 10, cell voltage fluctuation is more random compared with Figure 3, and the cell voltage in Figure 3 is more regular. In the 10000 s period, there are still larger fluctuations of cell voltage for many times in Figure 10, the maximum fluctuation occurs during 9000-9500s, reaches 220mV, but the amplitude reduces significantly compared with Series 1, whose fluctuation amplitude is 330mV. Figure 12 presents the cell voltage and current distribution during the simulation time of 9000-9500s. It is found that the half resonance effect has occurred from the current distribution. Similarly, the simulation data is analyzed when the cell voltage fluctuation amplitude is larger than usual. This indicates that because of the randomness of the frequency series, the correlation among these datum is weakened, and the occurrence of the full resonance effect is significantly reduced. Under frequency Series 2, the resonance span and cycle are not fixed, both of which are changing.

In the power spectrum of Figure 11, the fluctuation regularity of the cell voltage is different between frequency Series 1 and 2, but the main frequency ranges of both simulation cell voltages data contain all the fluctuation frequencies of the liquid aluminum. The main frequency of the current branch is the same as that of the liquid aluminum fluctuation of this branch.

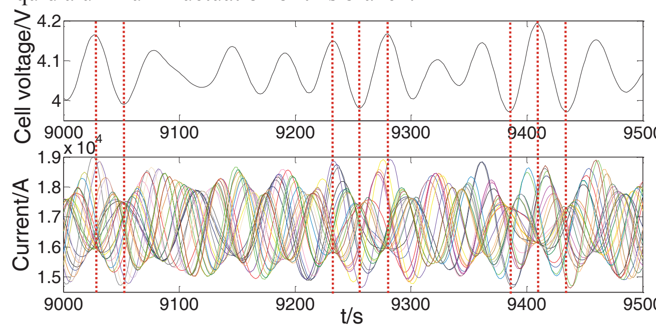

Figure 12 Cell voltage and current distribution during simulation time 9000-9500s

In Figure 12, it can be seen from the current curves of 24 branches that half resonance effect has occurred. The currents of most branches are very close in a short time, and this phenomenon appears many times during this 1500 s period, as the area of red dotted line shows. According to the simulation results, when the cell voltage has a greater fluctuation, current distribution is more uniform, so the resonance effect may have a close relation with current distribution of the 24 branches. Therefore, this study introduces a dispersion criteria to characterize this phenomenon. The standard deviation of the 24 branches current at a certain time is calculated, which is defined as the current dispersion of 24 branches:

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2} \tag{11}$$

Where:

n is the total number of the electrical circuit branches, n=24,

x_i is current value of the i-th branch,

$\bar{x}$ is the average current value of the n branches at the same time.

Figure 13 is the diagram of the dispersion (σ) with time. From the dispersion curve, it is difficult to distinguish the trend of the dispersion change due to data randomicity, so the moving average method is used in this research to study the dispersion curve. Moving average method is a simple smoothing forecasting technique, which is based on time series data, goes on step, and successively calculates the average value containing certain number of time sequence, so it can reflect the long term trend. With the graduation and smooth effect on the original sequence, this method can weaken the fluctuation of the original sequence data and effectively eliminate the random fluctuation in prediction. For a given series of data, $x_1, x_2, \ldots, x_m, \ldots$, their m-order moving average value can be calculated by the following formula:

$$\frac{x_1+x_2+\cdots+x_m}{m},\ \frac{x_2+x_3+\cdots+x_{m+1}}{m},\ \frac{x_3+x_4+\cdots+x_{m+2}}{m},\ \ldots \qquad (12)$$

Where, m is the order, i.e. calculating cycle, m=10 in this paper.

The trend line of the dispersion (σ_{10}) is also shown in Figure 13. From the trend line, it is shown obviously that current dispersion of 24 branches is smaller when cell voltage resonance effect occurs, as is shown in the red dotted line area of Figure 13. When the fluctuation amplitude of cell voltage increases, the trend line decreases. It also shows that when resonance effect occurs, the current of each branch tends to be equal. The smaller the current dispersion is, the greater the intensity of resonance effect.

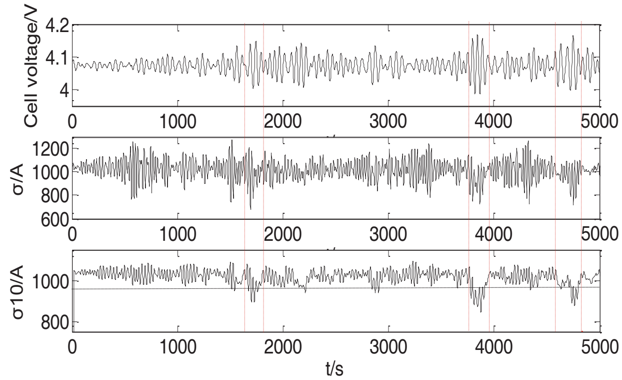

Figure 13 Current dispersion (middle) and its trend line (inferior) corresponding to cell voltage (superior)

Conclusions

An electrical equivalent circuit of aluminum electrolysis cell has been implemented using the Matlab/Simulink simulation software. In normal production conditions of aluminum electrolysis, when the liquid aluminum fluctuation frequency is not the same under different anode carbon blocks, the fluctuation of cell voltage is investigated. The causes of the cell voltage fluctuation are explored, and the preliminary results are as followed:

(1)Because of the differences in liquid aluminum fluctuation frequencies and the change in the anode current distribution, the resonance effect may occur, resulting in the sudden increase in cell voltage fluctuation. Then, the voltage will fluctuate within a larger range, which even reaches more than 300mV and lasts for more than 30 minutes. In real production, this may indicate that cell's operation status is out of order. So the resonance effect may be an important reason for the cell voltage fluctuation.

(2)When full resonance effect occurs, the current flowing through each branch is very close in a short time, and tends to be equal. When half resonance effect occurs, the current distribution dispersion decreases significantly.

(3)If liquid aluminum fluctuation frequencies of two branches are closer to each other, there is a greater probability of resonance effect with longer duration time. The fluctuation frequency of liquid aluminum is closely related to the resonance span and cycle, but has little effect on the voltage fluctuation amplitude.

(4)The resonance effect can be determined by calculating the current dispersion of all the branches at a certain time, using the dispersion trend line.

Acknowledgement

The authors wish to thank the financial support by the National Key Technology R&D Program of China (2012BAE08B09).

References

[1] X. Shen. The mechanism of voltage fluctuation in aluminum reduction cell and its precautions. Light Metals, (In Chinese), 2008(9):31-35.

[2] A.I. Berezin, et al. Neural network qualifier of noises of aluminium reduction cell. TMS Light Metals, 2003: 437-440.

[3] B. Larry, C. Dai, B. Philip. Noise Classification in the aluminum reduction process. TMS Light Metals, 2003:431-435.

[4] J. Marianne, et al. Bubble noise from soderberg pots. TMS Light Metals, 2007:353-356.

[5] E. E. Einarsrud, E. Sandnes. Anodic voltage oscillations in hall-heroult cells. TMS Light Metals, 2011:555-560.

[6] L. Lu. Discussing on voltage vibration of 240kA prebaked electrobath. Nonferrous Metals (Extrative Metallurgy) (In Chinese), 2004(5):22-25.

[7] W. Haupin. Interpreting the components of cell voltage. TMS Light Metals, 1998: 531-537.

[8] J. Frederic, T. Lelievre, C. LE. Metal pad roll instabilities. TMS Light Metals, 2002: 483-487.

[9] J. Antille, R.V. Kaenel. Using a magnetohydrodynamic model to analyze Pot stability in order to identify an abnormal operation condition. TMS Light Metals, 2002: 477-482.

[10] P. Zhou. A research on mathematical models of electromagnetic hydrodynamics and numerical simulation of metal pad flow in aluminum reduction cells. (In Chinese) Changsha: Central South University, Doctoral Dissertation. 2002.

[11] J. Xue, A Harald. Bubble behavior-cell voltage oscillation during aluminium electrolysis and the effects of sound and ultrasound. TMS Light Metals, 1995: 265-271.

[12] Y. Wang, L. Zhang, X. Zuo. Fluid Flow and Bubble Behavior in the Aluminum Electrolysis Cell. TMS Light Metals, 2009: 581-586.

[13] A. Panaitescu, A. Moraru. Research on the instabilities in the aluminum electrolysis cell. TMS Light Metal, 2003:359-366.

[14] Y. Tian, H. Wang. Study of ACD model and energy consumption in aluminium reduction cells. TMS Light Metals, 2011:567-568.

[15] N. Feng, J. Peng, Y. Wang. Energy reduction technology for aluminum electrolysis: Choice of the cell voltage. TMS Light Metals, 2013:549-552.

[16] N. Feng. Aluminum Electrolysis. (In chinese) Beijing: Chemical industry press, 2006.

[17] T. Drengstig，S. Kolas，T. Støre. The Impact of Varying Conductivity on the Control of Aluminum Electrolysis Cells. TMS Light Metals, 2002, 205-216.

[18] J.Zoric, I.Rousar, J.Thonstad. Mathematical modelling of industrial aluminimum cells with prebaked anodes Part I: Current distribution and anode shape [J]. Journal of applied electrochemistry, 1997, 27: 916-927.

[19] Z. Wang, et al. Study of surface oscillation of liquid aluminum in 168kA aluminum reduction cells with a new type of cathode design. TMS Light Metals, 2010:485-488.