Discussion on Development of Intelligent Control Technology for Aluminium Reduction Cells

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Abstract

Since the invention and application of the Hall-Héroult process in 1886, aluminium electrolysis production technology has been improving cell design, production control and operation management. The industry will continue to face the challenge of low energy consumption for a long time to come in the new situation of constantly upgrading technology in combination with low-carbon and clean energy and how to make large-scale aluminium electrolytic cells operate stably and maintain good performance.

Performance indicators have become the focus of industry. In this article, the author uses the current leading large-scale aluminium electrolysis cell technology and related processes in the aluminium electrolysis industry in China and abroad to discuss intelligent cell control. With the theoretical basis as the background, the strategies and achievements of some existing intelligent control technologies are listed, and finally the future vision of technological innovation and development in this field is proposed.

Keywords: Large aluminium electrolytic cell, Low energy consumption and low carbon emissions, Intelligent cell control.

1. Introduction

Intelligent and innovative development of aluminium electrolysis that combines low energy consumption and low carbon emissions is the main development direction of the global primary aluminium industry and is also the focus of China in this field. It is the key to implementing the new development concept, cultivating new quality productivity and catching up with the world's leading level.

Recently, the research team of Academician Huang Xiaowei (led by Professor Li Jie of Central South University) published a paper, which not only affirmed the achievements made since the reform and opening up, but specifically mentions the three new normal problems that China's aluminium electrolysis industry still faces in its current development stage [1]:
1) Extreme operating conditions put the MHD stability in the cell in a difficult situation;
2) The operating conditions of large or super-large prebaked cells are complicated, and the traditional centralized and decentralized control system cannot be controlled by different zones in the cell;
3) The deterioration of aluminium smelting resources has seriously impacted the stable operation of aluminium electrolytic cell production.

The article also mentions seven key points about the greater challenges that future technological innovation will face. However, I believe that future technological challenges should be divided into two categories. In other words, research work should be accelerated in two different stages:
1) Intelligent and innovative development of traditional aluminium electrolysis process in terms of low energy consumption and low carbon emissions;

2) Research and testing of new aluminium smelting processes, such as the current research and application of large-scale inert anode cells and other technologies such as experimental research on new smelting processes, such as HaLZero.

In the future, the development and research of net zero carbon emissions in traditional aluminium electrolysis process or new aluminium smelting process still has the following problems to be solved:
1) Renewable electricity,
2) The traditional aluminium electrolysis process still needs to solve the problems:
- Emission-free alumina and anode production,
- Transportation of all materials, including alumina, by electric ships, electric trains and new energy vehicles,
- Carbon Capture, Utilization and Storage (CCUS).

3) Recycling and utilization of post-consumer aluminium waste.
4) Successfully testing and implementation of different aluminium production processes (non-consumable anodes, HaLZero).

However, for now, intelligent innovation and development of traditional aluminium electrolysis process in terms of low energy consumption and low carbon emissions is still the best choice.

In recent years, and even for a considerable period of time in the future, the existing primary aluminium production capacity in China and abroad is the priority for further development.

2. Background of Cell Technology Development

At present, the overall technology of large and super-large aluminium electrolytic cells in China and abroad is becoming more and more mature. The main characteristics of the operation of leading large aluminium electrolytic cell technologies outside China are:
1) Anode current density is high (0.90–1.0 A/cm2), the current efficiency is high (94–95 %), and specific energy consumption is typically 12.8–13.5 kWh/kg Al.
2) Leading low energy consumption is Hydro's HAL4e Ultra cell with 11.79 kWh/kg Al, with next goal of 10 kWh/t Al [2].
3) The leading design technologies of large and super-large aluminium electrolytic cells in the world outside China are HAL4e Ultra of Hydro Aluminium, AP60/APXe of Rio Tinto, DX+ Ultra and EX of Emirates Global Aluminium (EGA) and RA-550 of RUSAL.

China is now leading the design of large and super-large aluminium electrolytic cell technologies. The emergence of 300 kA electrolysis cells in China was 12 years later than that in the West, and the emergence of 500 kA cells was 10 years later. It took about 10 years for China and other countries to increase the current from 300 kA to 500 kA. It took 12 years in Pechiney to develop 600 kA cells, but only 5 years in China. Chinese ultra-large capacity cells are SAMI SY500/SY600, NEUI600, GAMI GP500/GP530 and Central South University technology CSU530. NEUI600 and SAMI600, 600 kA technology has been massively implemented in China in 20 potlines (a few still under construction).

In addition to the 38 AP60 600 kA pilot cells built by Rio Tinto in Québec, Canada, there are 92 more cells currently under construction and will start up in 2026. China’s development is much faster; there are already 20 potlines with 600 kA technology (NEUI600 and SAMI600), built in the last 10 years and many more with 500 kA technology. These are at the forefront and are the mainstream cell technologies for newly built aluminium smelters.

Almost all production lines of super-large aluminium electrolytic cells are built in China, accounting for about 60 % of the total domestic aluminium production capacity, and this number is still rising with continuous replacement of existing lower amperage production capacity.

Except for the low anode current density (0.72–0.82 A/cm2), the other main key performance indicators (KPIs) in China are not far behind the world's leading level, particularly in low specific energy consumption, and there is great potential for improvement.

3. Basic Theory of Aluminium Electrolysis Cell Control

The control of aluminium electrolysis cells and stable operation of various parameters of energy balance is the key to achieving low energy consumption and low emissions. The relationship between the cell control quality and energy balance of the aluminium electrolysis cell is shown in Figure 1. Changes in various process parameters will lead to changes in the overall stability and energy balance of the aluminium electrolysis cell. Disturbances between equilibria are of varying magnitude and speed.

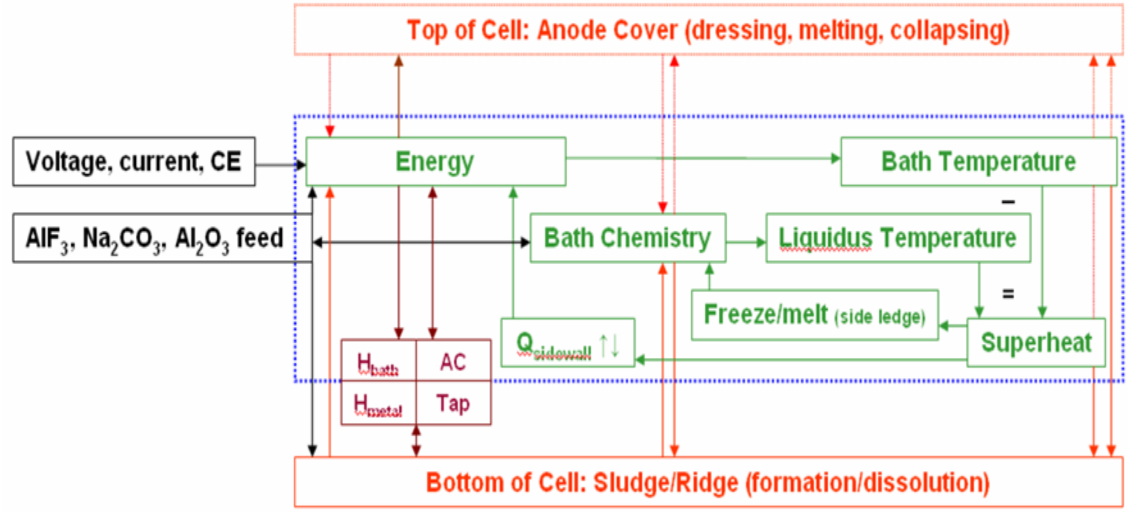

Figure 1. Relationship between mass and energy balance of an aluminium reduction cell [3].

A large amount of practical and theoretical analysis in China and abroad shows that it is very important to master the relationship between the material balance and energy balance of aluminium electrolytic cells. While lowering the electrolyte liquidus temperature, controlling the superheat and rationally utilizing the working net cell voltage can not only achieve high current efficiency, but also effectively improve energy utilization, reduce the anode effect frequency, and make the cells run more stably and achieve a longer cell life.

Each process technology has an optimal chemical composition-temperature-energy performance area. The effect of electrolyte temperature, liquidus temperature and superheat on current efficiency is great. Under the premise of determining the electrolyte composition of the aluminium electrolysis cell, finding the best superheat is the key to good performance. The superheat is usually kept at around 10 °C to achieve the best current efficiency. Figure 2 shows the best chemical properties of aluminium electrolysis cells. The above-mentioned optimal effects can be obtained by operating stably in the chemical composition-temperature-energy performance region.

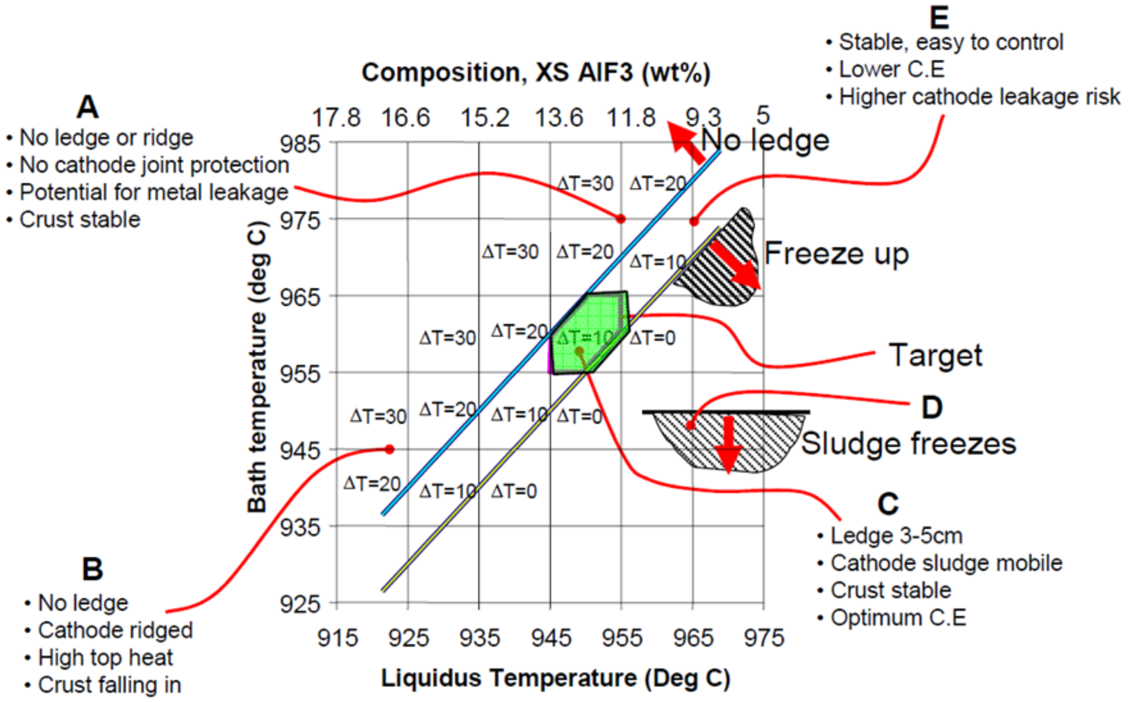

Figure 2 The corresponding range of the appropriate liquidus and bath temperature and excess AlF3 under normal cell operation [4].

Production practice and theoretical research show that the key to achieving good KPIs is to control the cell within the ideal material and energy balance to make the physical fields stable and minimize current efficiency loss. The electrolysis temperature is mainly determined by the heat balance and the chemical composition of the cell. The liquidus temperature is determined by bath composition.

4. Current Status of Control Technology and Large Model Application

4.1 Historical Development Outside China

Computer control technology for aluminium electrolysis began in the 1960s [5]. Over the past few decades, the control principles of computers have remained unchanged, but the scope has been expanded to manage all operational activities required of cells to become more efficient, safer and more eco-friendly. Computer control system platform has also developed. The computer control has evolved from central processing unit to distributed control, where one or two or several reduction cells can be controlled locally in the electrolysis plant by a microcomputer, and this is still the basic control method of aluminium reduction cell control system today [5].

The most advanced cell control systems today use adaptive alumina feeding, smart crust breaking and feeding, model predictive control and Digital Twin. Potline operational safety is also a priority, such as open-circuit detection and automatic detection of tapping. Effective anode effect prediction and elimination reduce PFC emissions and protect environment. Examples are Rio Tinto's ALPSYS [6], EGA's Advanced Pot Control System [7], based on PLCs, Hydro Aluminium's Pot Control with Nonlinear Model Predictive Control (NMPC) and Digital Twin [8, 9]. Alcoa developed QLC with an integrated control system, including STARprobe-based electrolyte composition and superheat measurements [10, 11]. Most recently, Rusal developed Automated Process Control Systems (APCS) integrated with Digital Twin and other digital tools for proactive cell control [12].

Hydro Aluminium's Nonlinear Model Predictive Control (NMPC) uses a process model (Estimator) to predict near-future values of parameters and reconciles them with the measurements to generate control system inputs (Figure 3) [8]. More recently, pursuing Industry 4.0, they included Digital Twin of the cell and Advanced Analytics in the controller to produce estimates of 100 variables every 5 minutes [9].

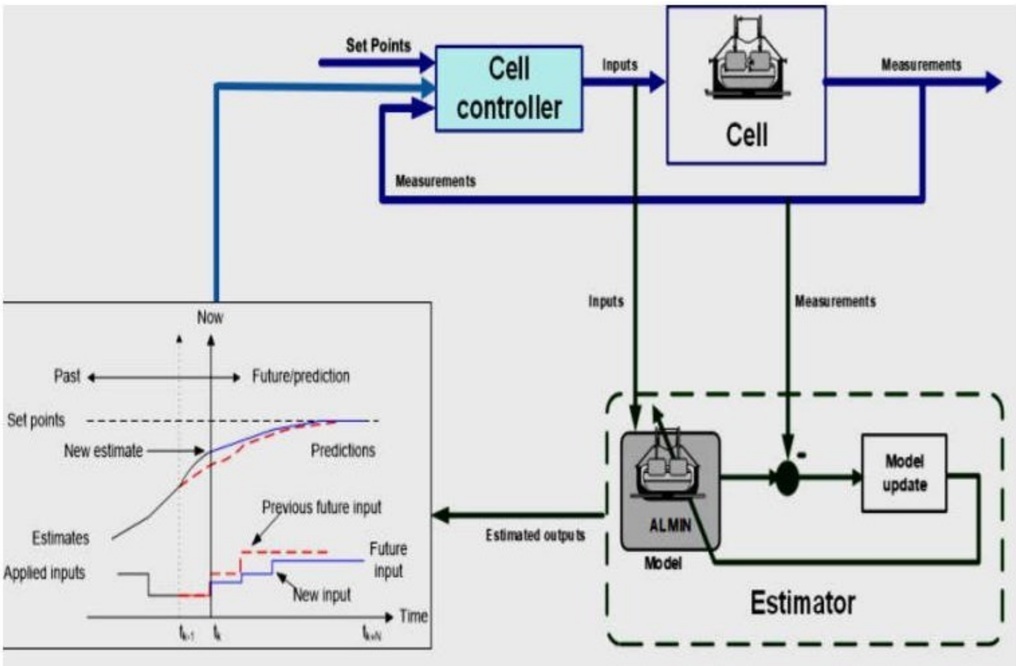

Figure 3. Logic diagram of Hydro Aluminium's NMPC cell control. The future predictions block in the lower left is now produced by Digital Twin of the cell [6, 7].

4.2 Development of Cell Control Systems in China

Chinese cell technology suppliers SAMI, GAMI and NEUI (North Eastern University Engineering and Research Institute) and CSUI (Central South University Institute) have developed their own high amperage cell technology (≥ 500 kA) and cell control systems [13–15]. Central South University (CSU) is a leading institution for cell control system development [16], smart aluminium electrolysis plant concept [17] and electrolysis digital twin [18] in cooperation with Hunan ALWIT Technology Corporation. Ltd. (ALWIT), which is a smart technology equipment supplier. The CSU Digital Twin concept is shown in Figure 4. The CSU Digital Twin deployment is described by Jiaki Li et al.[18]:

"To date, the digital twin technology has been implemented throughout 16 production series inside 11 aluminium electrolysis plants in China, and its adoption is currently witnessing swift and widespread proliferation. The successful integration of this technology into practical production processes, particularly inside electrolysis cells ranging from 350 to 600 kA, has been demonstrated. The control of alumina concentration, which is a crucial factor in the production process, is regarded as the most successful aspect of this digital twin system, allowing local alumina concentration control deviations of less than 0.1 wt%. By integrating the capabilities of physics-based and data-driven modelling approaches, the hybrid analysis and modelling framework facilitates the generation of better-informed feeding decisions."

The benefits of CSU Digital Twin deployment in China are shown in Figure 5.

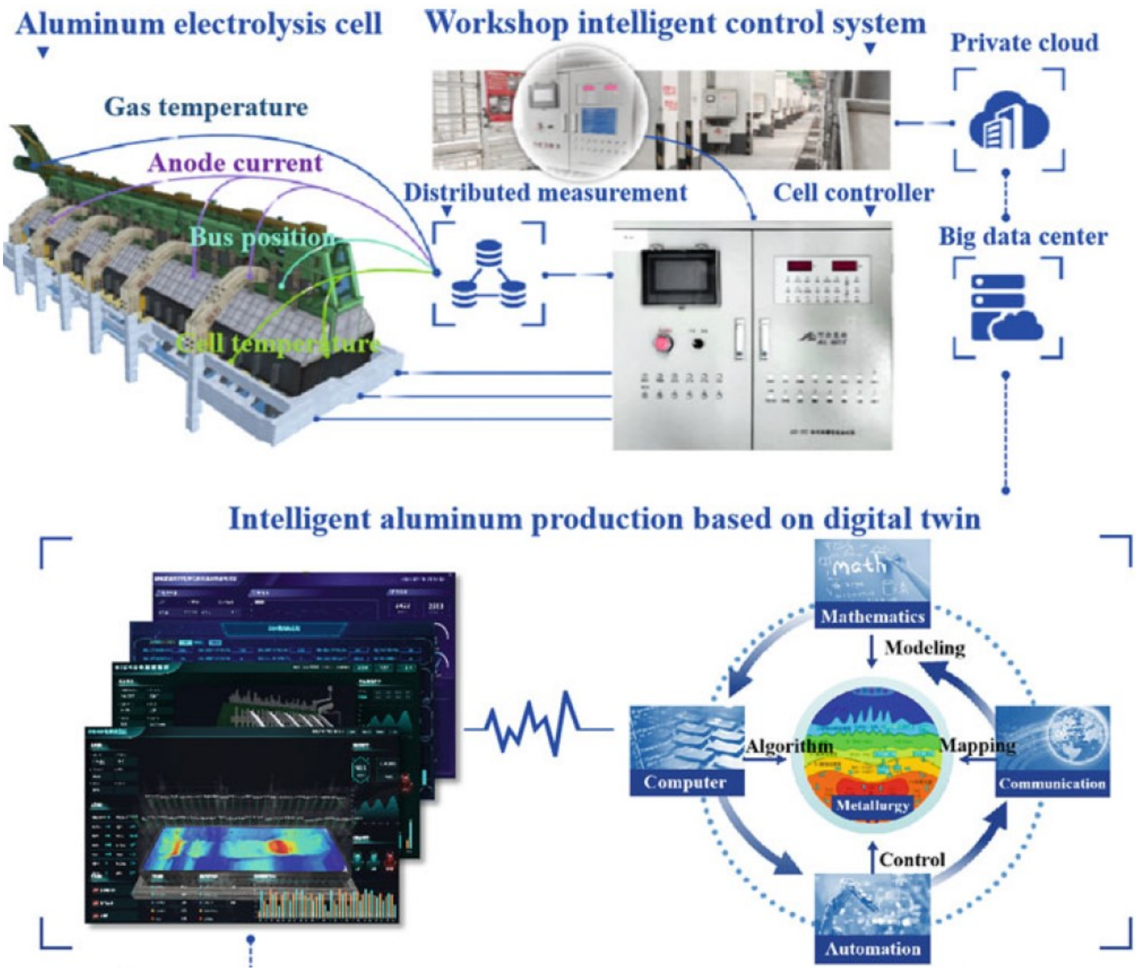

Figure 4. Implementation plan of the Digital Twin in Intelligent Manufacturing of aluminium electrolysis [18].

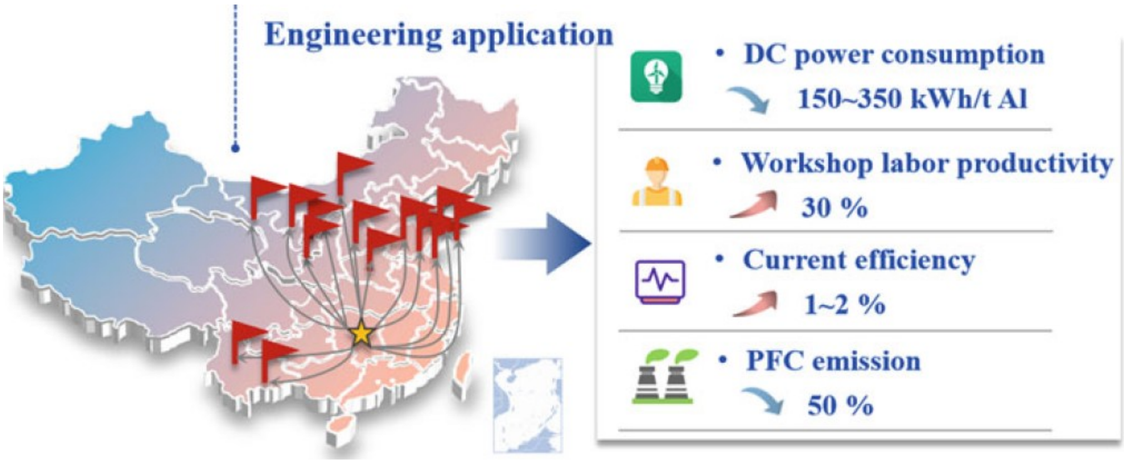

Figure 5. Result of Digital Twin implementation in Chinese smelters [18].

5. Development of Innovative Control System Technology

With rapid development of technologies in recent years, deep integration of new generated information technologies such as artificial intelligence and big data into large-scale aluminium electrolysis cells is the key to empowering the creation of a digital, intelligent, and flexible modern aluminium industry chain, and is also a necessary path to achieve future smart aluminium smelters.

At present, most large aluminium companies in the world not only have advanced large-scale cell technology, but also have their own cell control technology and equipment [6, 7, 12, 14]. However, there is a significant gap in the control technology and equipment level of these companies, and still great room for improvement. The cell control technology and equipment must be improved, otherwise, it will be difficult for smelters to achieve better production performance and obtain better economic, environmental and social benefits.

5.1 Innovative Development of Aluminium Reduction Cell Control Technology and Systems

5.1.1 Development or Upgrade of Large Models

Based on the theoretical basis, at present, the application of computer large models in the process control technology of large aluminium electrolytic cells needs to optimize and solve the following problems:
1) Cell control layer. It mainly includes AI big models of intelligent optimization calculation in real-time, such as alumina feeding and regional concentration control model, intelligent crust breaking and efficiency. The control layer model and operation are usually completed by the control box in front of each cell or a few cells. One-step upgrade requires software optimization, hardware expansion and enhancement of connections with intelligent network platforms.
2) Intelligent control layer for aluminium electrolysis production. It includes the development and application of AI large models for intelligent control of aluminium electrolysis production, such as prediction models for various physical fields, mass and energy balance model, parameter self-optimization control model and aluminium electrolytic cell operation status evaluation model. The development of these models must be coordinated with intelligent measurements, transmission and calculation platform for overall data of aluminium electrolysis cells.
3) Development and application of dynamic simulation and calculation models for aluminium reduction cells. It mainly includes AI models for cell simulation and real-time dynamic calculation, such as real-time current distribution of the cell. Similarly, the development and application of the above models must also be combined with intelligent measurements.
4) Integration of the measurements, transmission and computing systems.
5) Intelligent self-learning, training and HMI interface of cell control system. It mainly includes the learning of aluminium electrolysis cell process theory, cell operation skills, personnel training and the development of AI large models of neural networks.

These developments and applications lay a solid foundation for the network platform for the AI big model for overall management of smart factories in the future.

5.1.2 Development and Application of Intelligent Measurement Equipment

The operating data in aluminium electrolysis production is composed of many control parameters that interact with each other, such as cell amperage, cell voltage, excess AlF_3, bath temperature, superheat, potshell temperature, alumina concentration and anode current distribution.

The real-time measurement and control of intelligent data cannot be completed directly by the control box. In addition, there are many large potlines with many cells. If all the cells are equipped with fixed measurement instruments, the capital investment would be prohibitive, and moreover, the failure rate may be high due to the harsh potroom environment. This requires using mobile measurement equipment.

a) Development and application of intelligent fixed measurement equipment

Presently, only cell amperage and cell voltage are measured in real time with fixed measurement equipment. The measurement of individual anode currents is still limited to small groups of cells in the potline, because of complexity and cost in China and abroad.

In China, in order to avoid the complications with anode changes, CSU made individual anode current measurement using anode beam voltage probes in 2015. The industrial test was carried out on several 400 kA cells. The measurement was integrated with the cell controller [19].

At EGA a system with smart sensors with voltage probes on the anode beam was developed [20]. This paper gives a review of all the trials of individual anode current measurements in different companies since 1969 on Alcoa's P-225 cells.

Recently, measurements of anode zone currents by fibre optic current sensors (FOCS) [21] has been proposed and is being tested in China for local alumina concentration control and anode effect prediction [22]; wider implementation of this system will also depend on cost.

For these new systems, software and hardware of the cell controllers must be upgraded with increased storage, computing speed, cell control software and HMI with graphic display.

b) Development and application of intelligent mobile measurement equipment

Cell parameters that cannot be measured continuously – bath temperature, metal height and bath height, cathode voltage drop, potshell temperatures are measured periodically, such as once per day, once per two days or once per every few days, and entered into the computer database manually or increasingly by Wi-Fi transmission. Commonly, bath composition (excess AlF_3, CaF_2, LiF, MgF_2) is measured once every few days, e.g., every 4 days, by taking samples which are then analysed in the laboratory. This delay makes the excess AlF_3 control difficult. However, new mobile measurement equipment has been developed and is used in many western smelters, which analyses the data on the spot at each cell immediately after a bath sample is taken. This equipment is more and more intelligent and transmits the data to the computer automatically by W-Fi. For example:

1) STARProbe measures bath temperature, superheat, excess AlF_3, CaF_2 and alumina concentration. It can directly send out the data within 3 minutes after each cell is measured, and upload it directly to the cell controller and factory host computer management system. This is not only faster than manual measurement and analysis of sampling data, but also more accurate and measurements can be made more frequently, such as once per two days. Figure 5 shows this schematically [16]. StarProbe is used in Alcoa and some other smelters [23].

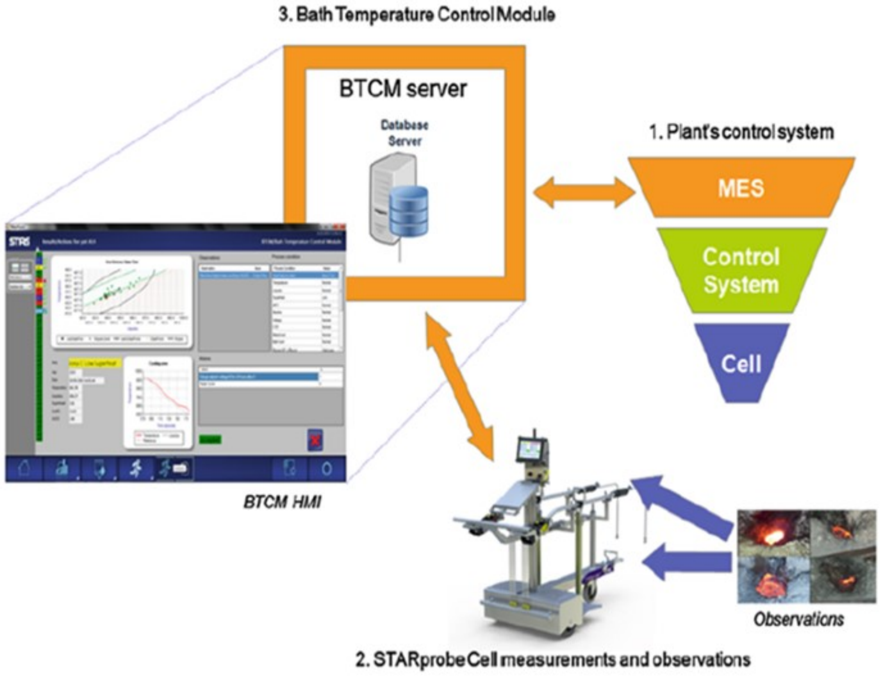

Figure 5. The STARProbe intelligent mobile measurement system [11]. BTCM = Bath Temperature and Chemistry Control Module.

2) FiberLab (Figure 6) measures bath temperature, superheat, excess AlF3 and alumina concentration. It uses optical fibre for temperature measurement and FiberLance for superheat and bath chemistry. FiberLab is used in many western smelters, often just for bath temperature measurements.

Figure 6. FiberLab mobile measurement equipment [24].

3) In China, potshell and collector bar temperatures are monitored by robots in the potline basement [25, 26] which make automatic and frequent temperature measurements in many locations which were not possible with manual measurements. These measurements are used for detecting thermal balance problems of the cell and raising alarm for corrective actions before a cell tap-out occurs.

c) Development and application of soft sensors

Soft sensors are data-driven computational models using Artificial Intelligence (AI) techniques to predict cell variables that cannot be measured or are not measured frequently enough for good process control. Li et al., [27] developed a soft sensor for alumina concentration which was tested and validated in Zunyi Aluminium Factory. Emirates Global Aluminium (EGA) developed a soft sensor for bath temperature [28] which predicted bath temperature every hour from the measurements every two days. Intensive research and development in this direction is taking place in several large companies within Industry 4.0 framework.

5.2 Ideas for an AI Cell Control System Structure for High Amperage Cells

With continuous increase of cell amperage and production capacity, and increasing use of renewable energy, the cell operation and control are becoming more and more complex and require new control strategy. Rapid development of AI technology, internet and computers enable the integration of measurement data, digital twins, soft sensors, big data analytics, machine learning and self-optimization into an intelligent large scale cell control system as shown in Figure 7.

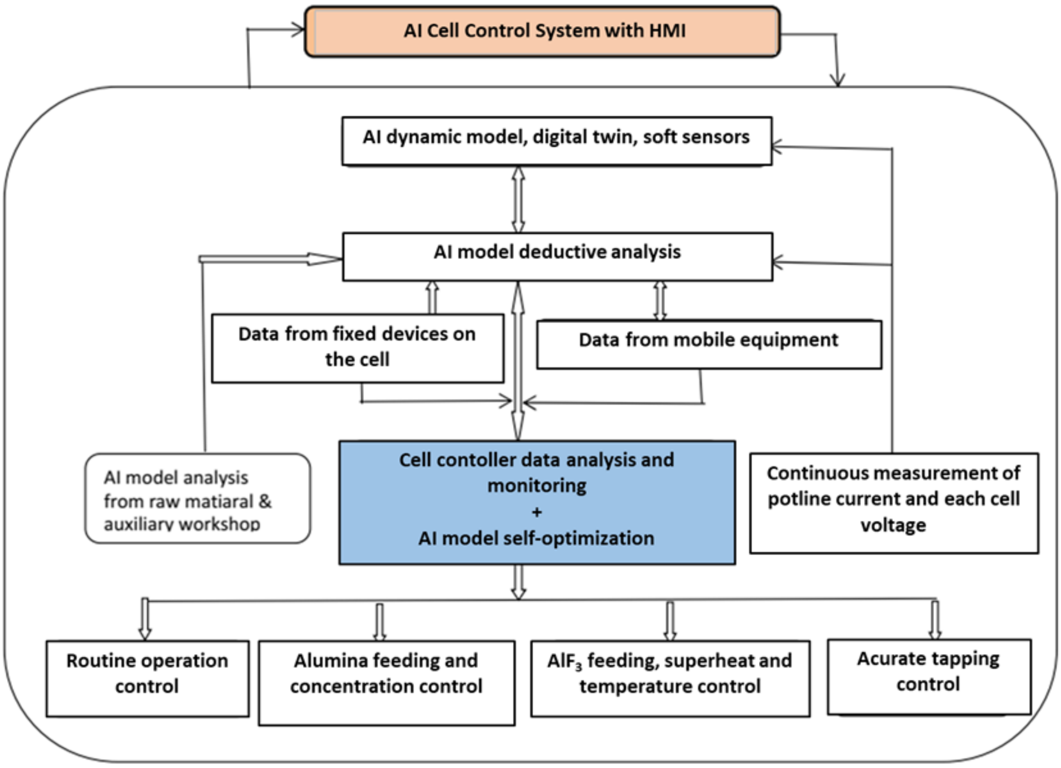

Figure 7. Structure of an intelligent large-scale cell control system.

6. Conclusions

With the rapid development of contemporary internet and digitalization, artificial intelligence and large-scale aluminium electrolysis cell technology, it is necessary to continuously adjust and improve cell operation and control. In this paper we presented the development ideas of intelligent control system:

(1) The pace of research and development of intelligent large models has accelerated with the development of artificial intelligence technology, relying on the support of big data and computing power,

(2) In addition to the urgent need to upgrade the existing control hardware and software, various fixed or mobile intelligent measurement instruments and components must be implemented in the potlines.
(3) In view of increasing the proportion of renewable energy, stable operation of the cells must be considered as the primary condition. It is necessary to create better response for the dynamic control of cell energy balance. This will be achieved with future intelligent control system technology.

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