

## Development and Application of Aluminium-Steel Full-Section Direct Welding System for Cathode Voltage Drop Reduction

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### Abstract

For long-running aluminium potlines, the connection methods between cathode collector bars and peripheral busbar in electrolytic cells face several pain points, including traditional welding of explosion-welded transition joints or compression connections, which suffer from multiple weld seams, unstable construction quality, and high on-site magnetic field intensity. These issues lead to increased voltage drop at the connection points, thereby raising the specific power consumption per tonne of aluminium. To address such issues, the Institute has jointly developed a cathode energy-saving and voltage drop aluminium-steel full-section direct welding system. This paper introduces the core functional modules of the system, including the fully automated aluminium-steel bimetallic welding and forming module, the multi-physical field test data cloud-based expert decision comparison system, and the high-magnetic full-current online quality optimization welding technology module. Through practical applications in 180–420 kA potlines, the system demonstrates a significant reduction in cathode connection voltage drop after precise optimization, with comparative analysis and conclusions drawn based on production data.

**Keywords:** Cathode collector bar, Aluminium-steel direct welding, Energy-saving and consumption reduction, In-situ welding.

### 1. Introduction

The aluminium reduction cell, as the core equipment in aluminium electrolysis production, has its conductive efficiency, thermal equilibrium, and operational lifespan directly influenced by the connection method of the cathode collector bar [1]. Although traditional welding technologies such as explosion welding and compression joints are widely used, they exhibit significant drawbacks [2].

Explosion welding achieves the bonding of dissimilar metals through instantaneous high-temperature, high-pressure, and high-energy impact, but the process control is complex and prone to the formation of interfacial brittle phases and residual stress [3, 4]. Brittle intermetallic compounds (e.g., FeAl<sub>3</sub>, Fe<sub>2</sub>Al<sub>5</sub>, etc.) can significantly degrade the mechanical properties and conductive stability of the joint. During long-term operation, residual stress may induce crack propagation, severely compromising the safety and service life of the electrolytic cell. Mechanical compression joints, on the other hand, rely on physical contact fastening via bolts or hydraulic pressure, but they suffer from high contact resistance and susceptibility to oxidation. In high-temperature, highly corrosive environments within electrolytic cells, the crimped interface tends to loosen with increasing thermal cycles, leading to degraded conductivity, localized overheating, or even burn-through. This ultimately reduces electrolysis efficiency and increases energy consumption. Additionally, crimped structures incur high maintenance costs, requiring periodic

tightening or replacement of connecting components, which complicates production management [5, 6].

To address the above issues, Guiyang Aluminium and Magnesium Design & Research Institute collaboratively developed aluminium-steel full-section direct welding system for cathode voltage drop reduction. This system ensures high conductivity while optimizing welding materials and process parameters, achieving high-quality aluminium-steel connections. It combines excellent mechanical strength with long-term operational stability, providing a novel solution for upgrading the cathode connection structure of aluminium reduction cells.

## **2. Description of System Module Composition**

This cathode energy-saving and voltage-reduction aluminium-steel full-section direct welding system consists of three core modules: the aluminium-steel bimetallic fully automated welding and forming system, the multi-physical field test data cloud-based expert decision comparison system, and the high-magnetic full-current online quality-optimized welding technology.

### **2.1 Aluminium-Steel Bimetallic Fully Automated Welding and Forming System**

This system has successfully developed an aluminium-steel bimetallic welding fully automated forming module. Through systematic research on the automated surfacing process at the cathode collector bar end and the circumferential welding process, it has achieved automated technological upgrades in cathode collector bar welding, as shown in Figure 1. Core technological breakthroughs in the production line include:

- 1) The innovative development of a stabilized cathode collector bar transfer device, which utilizes an intelligent robotic arm cooperative operation system. Through inhouse-developed control software for the double-arm tilt welding process, it effectively resolves the technical challenges of inclined surface welding, ensuring stable and reliable weld quality.
- 2) Based on the characteristics of the aluminium-steel direct welding process, a streamlined welding production line has been established, equipped with three dedicated planar welding systems. By adopting a layered progressive welding strategy, each system is responsible for welding different material layers, forming an efficient assembly-line operation mode that improves welding efficiency by over 40 %.
- 3) A unique workstation was designed with inclined cathode group placement, where the coordinated interaction between an intelligent clamping system and the welding robot control system established a first-level collector bar adaptive transfer line, achieving seamless connectivity between welding processes.
- 4) The production line integrates key technologies such as precise robotic arm control, multi-station collaborative operation, and intelligent transfer, forming a complete automated solution for fused welding of cathode collector bars, providing efficient and stable intelligent production equipment for aluminium reduction cell manufacturing, significantly improving welding quality and production efficiency.

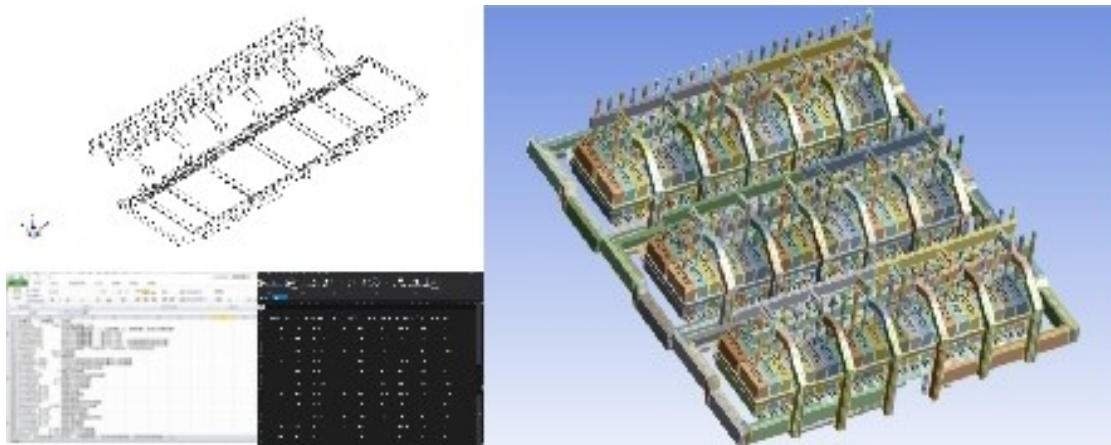
### **2.2 Multi-physical Field Test Data Cloud-Based Expert Decision Comparison System**

The multi-physical field test data cloud-based expert decision comparison system establishes an electrolytic cell optimization framework based on comprehensive lifecycle analysis of electric and magnetic field data, as shown in Figure 2. First, the system employs specialized instruments such as gauss meters, fiber-optic current sensors, and multi-point voltage drop testers to collect full-scale data from operating electrolysis potlines. Next, all test data is uploaded in real time to a cloud-based expert decision system, where intelligent comparisons are made against a vast database of operational data from peer electrolytic cells to accurately identify weaknesses in the current busbar system. Finally, the system utilizes machine learning algorithms to perform in-

depth analysis of historical optimization cases, automatically generating an expert recommendation report. This report includes process optimization plans, customized upgrade measures, and a detailed bill of materials for implementation. The intelligent analysis platform not only achieves precise diagnosis of the electrolytic cell's operating status but also provides data support and decision-making guidance for production process adjustments, significantly enhancing the scientific rigor and accuracy of electrolytic cell optimization and retrofitting. The entire system establishes a closed-loop management process spanning data collection, intelligent analysis, and optimization implementation, delivering reliable technical assurance for the efficient and stable operation of aluminium electrolysis production.



**Figure 1. Inclined dual-robotic arm surfacing process for collector bars and resulting weld quality.**



**Figure 2. Multi-physical field test data cloud-based expert decision comparison system.**

### 2.3 Multi-physical Field Test Data Cloud-Based Expert Decision Comparison System

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## 2.4 High-Magnetic Field Full-Current Online Quality Optimization Welding Technology

To address challenges in welding operations within the strong magnetic field environment of aluminium reduction cells, such as arc blow, spatter, and poor weld formation caused by magnetic interference, this system proposes an innovative solution, the high-magnetic field full-current online quality optimization welding technology, as shown in Figure 3. Traditional anti-magnetic processes (e.g., magnetic shielding) suffer from high costs and limited effectiveness, while conventional aluminium-steel welding techniques (e.g., explosion welding and friction welding) struggle to meet the requirements for online electrolytic cell modification.

To this end, this module has innovatively developed two core technologies: the welding magnetic field shielding and current-diverting busbar system and the strong magnetic field laser-magnetic welding equipment. By employing a precisely designed magnetic field cancellation solution, the former effectively eliminates magnetic eddy current interference during major repair cells, achieving a remarkable 75 % reduction in magnetic field. The latter maintains exceptional welding stability even in strong magnetic environments up to 1000 G, ensuring weld quality without additional magnetic reduction devices. The synergistic application of these two technologies provides an efficient and cost-effective complete solution for online electrolytic cell maintenance and modification, significantly improving welding quality and operational efficiency.



**Figure 3. High-magnetic field full-current online quality optimization welding equipment and field application pictures.**

## 3. Key Technology Simulation

### 3.1 Simulation of Different Connection Methods for Cathode Carbon Block Assemblies

For the connection methods between the cathode carbon block group and the peripheral busbar, there are three approaches: explosion welding, mechanical compression, and the novel aluminium-steel direct welding. Considering that mechanical compression involves the connection of the same type of metal, its performance primarily depends on the surface contact percentage between the two interfaces. Therefore, in this study, under the condition of ensuring identical input parameters such as cathode material and input current, we focus on comparing and analysing the 3D modelling and computational results of two dissimilar metal connection methods: in-situ welding combined with explosion welding and the novel aluminium-steel direct welding, as shown in Figure 4.

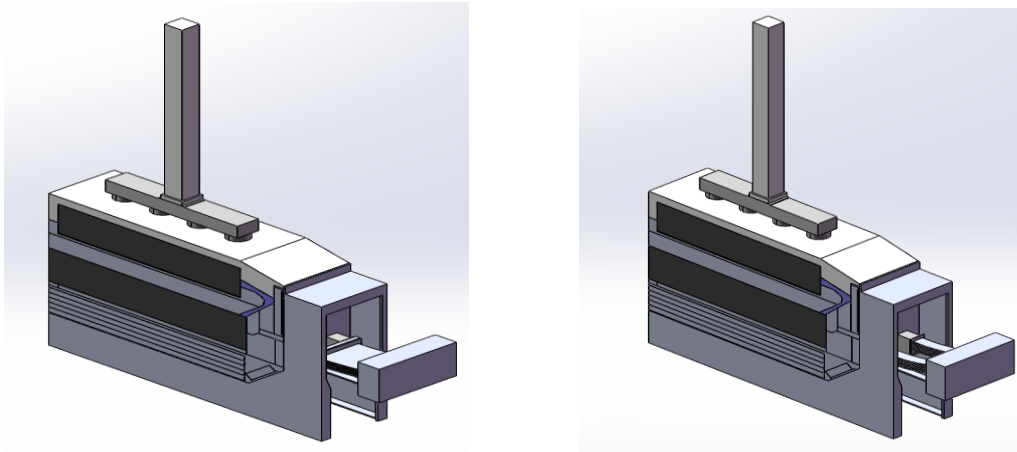


Figure 4. 3D simulation models of the two schemes.

Based on the current mature 500 kA-48 anode group configuration, the voltage drop data at the connection points and from the connection points to the perimeter busbar are extracted after input current simulation for two different connection methods, as shown in Figure 5.

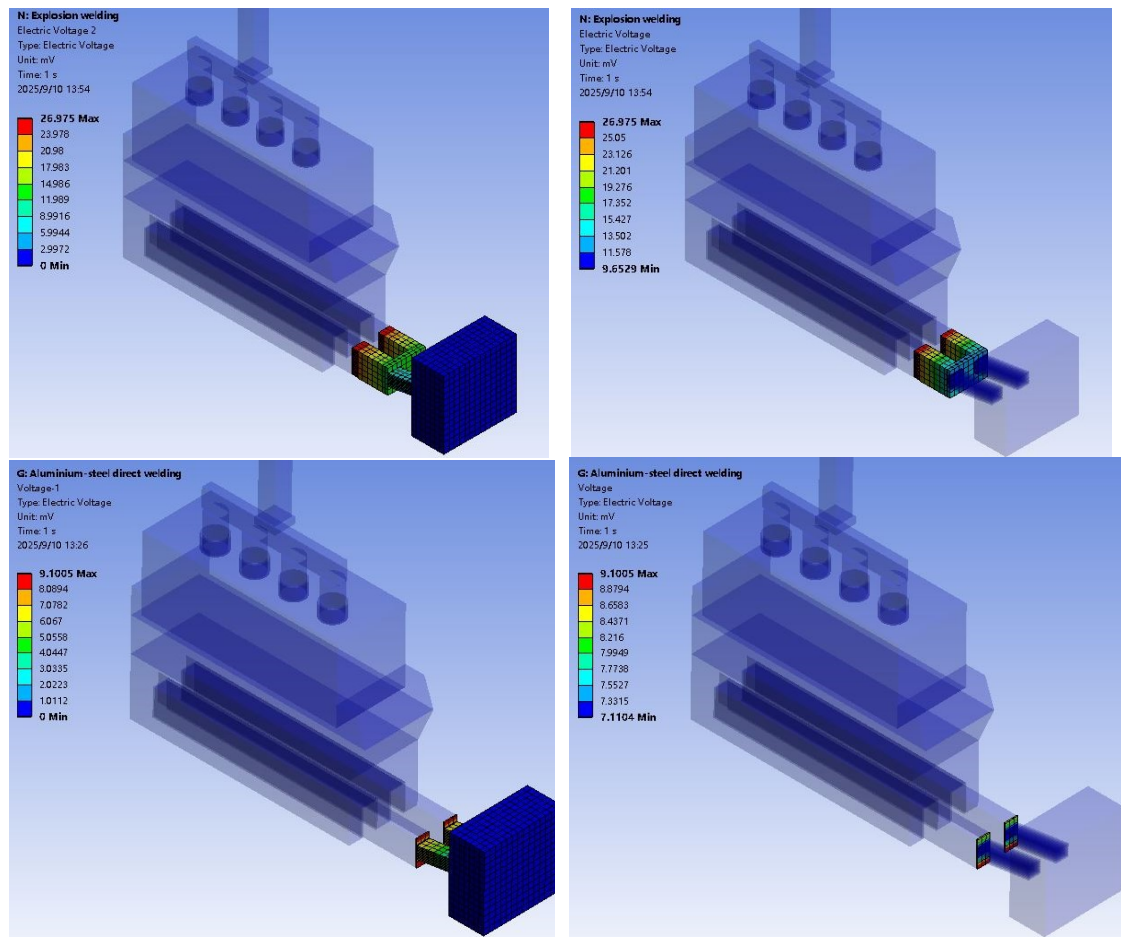


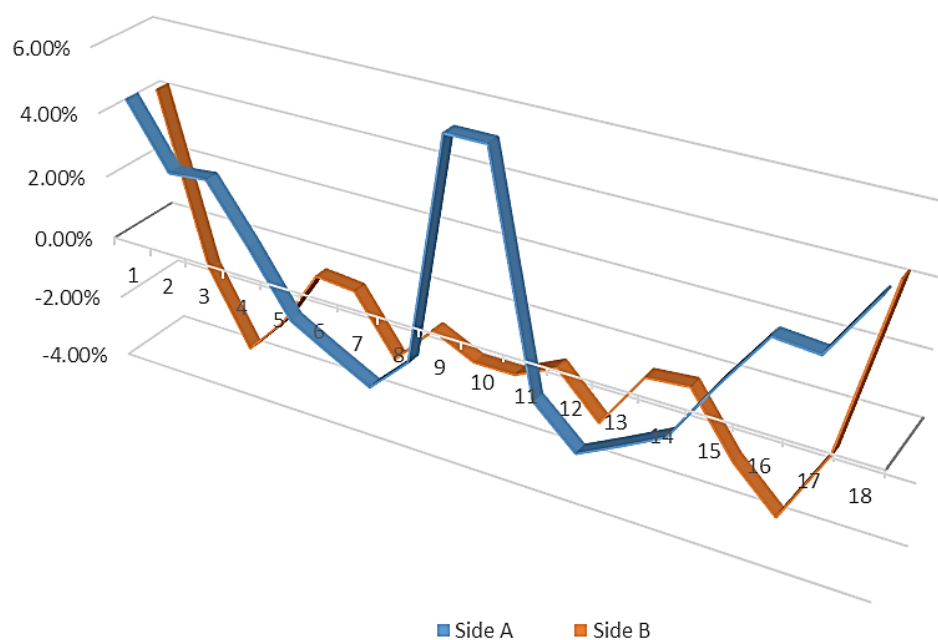
Figure 5. Simulation results under different connection forms.

The voltage drop across the connection body using the direct aluminium-steel welding method is 1.99 mV, which is 15.33 mV lower than that of the original explosion welding method (17.32 mV). The voltage drop from the connection point to the cell peripheral bus is 9.10 mV,

representing a reduction of 17.87 mV compared to the 26.97 mV observed with the original explosion welding method. The reduction in connection voltage drop is significant.

### 3.2 Multi-Physical Field Test Data Cloud-Based Expert Decision Comparison Simulation

Taking the optimization and upgrade plan of a 200 kA electrolytic cell as an example, this case study uses the 200 kA model as the baseline, aiming to safely and stably increase the operating current from 210–220 kA. The test data is imported into the multi-physical field test data cloud-based expert decision comparison system. The system performs deviation analysis on the current values at each set of cathode collector bars through a thermo-electric balance simulation. The analytical data is shown in Figure 6.



**Figure 6. Analysis of cathode current distribution deviation in the electrolytic cell under 210 kA current.**

The system employs machine learning algorithms to conduct in-depth mining of historical optimization cases, intelligently comparing the analysed data with vast amounts of operational data from electrolytic cells of the same level in the database. It accurately identifies weak points in the current bus system and automatically generates an expert recommendation report, which includes process optimization plans, customized upgrade measures, and a detailed list of required construction materials. As shown in Figure 7 of this case, the optimization plan indicates that after adjusting the cross-sections at the cathode positions of groups 8, 9, 10, and 11 on side A, and groups 1, 6, 7, 12, 13, and 18 on side B of the electrolytic cell, the number of welded aluminium flexible straps should be increased according to the new cross-sections.

The analysis results of cathode current distribution deviation in the electrolytic cell under 220 kA current, as shown in Figure 8, indicate that the overall distribution deviation is reduced and the current flow uniformity is improved after adopting the optimized solution, based on multi-physical field test data cloud-based expert decision comparison system.

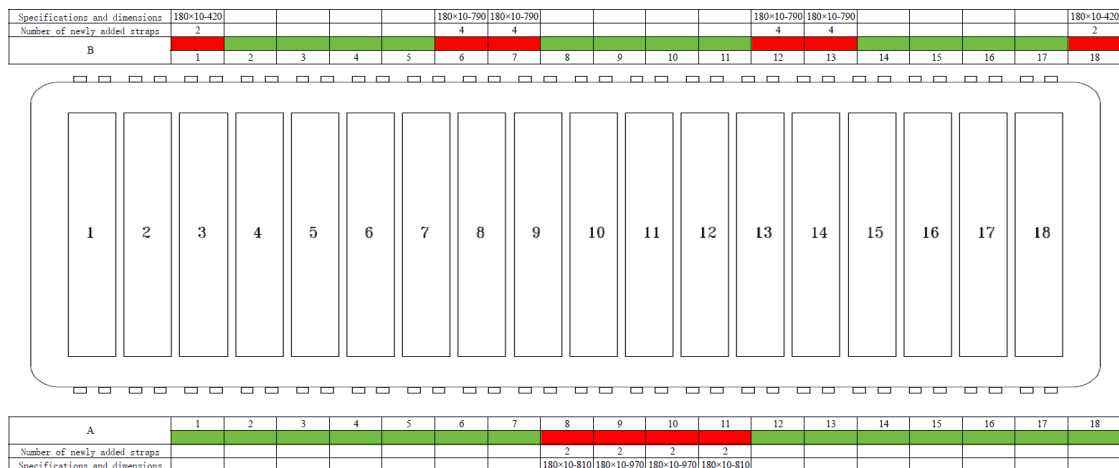


Figure 7. Optimization analysis results at 220 kA current.

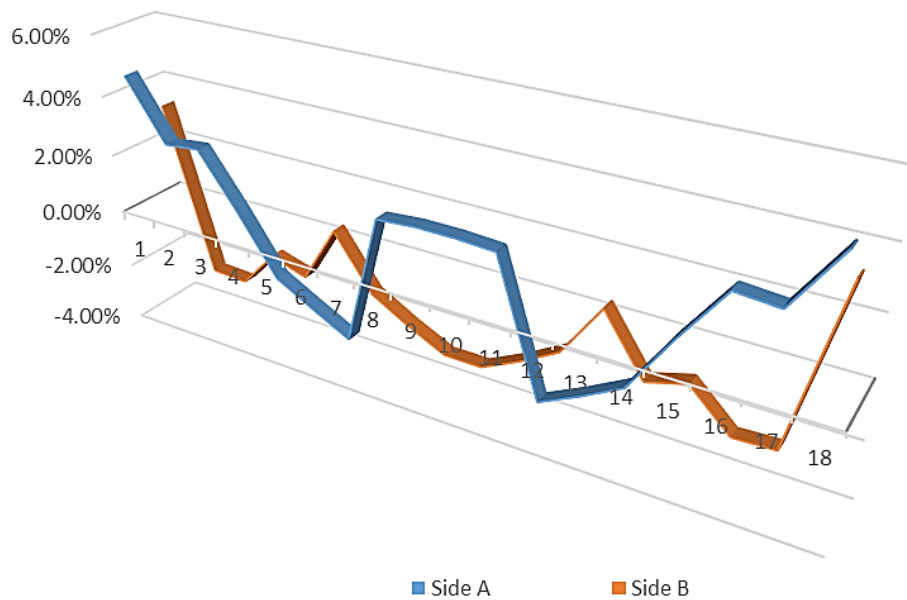
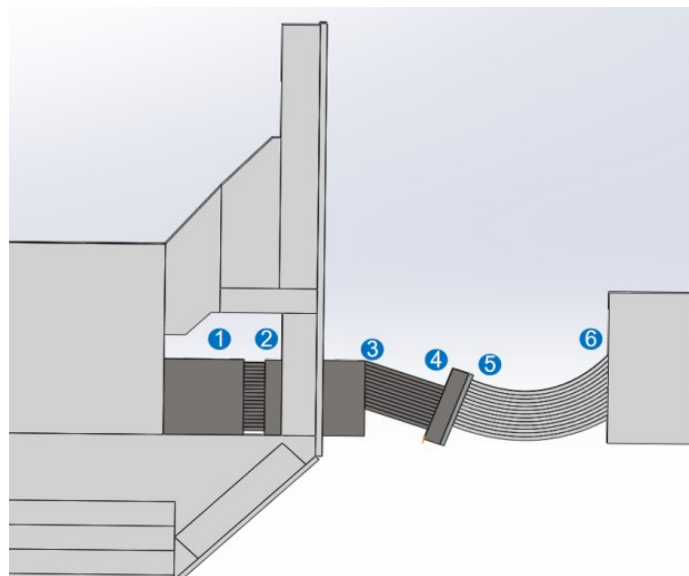


Figure 8. Analysis diagram of cathode current distribution deviation in electrolytic cells under 220 kA current.

#### 4. Practical Data Comparison

During the overhaul of aluminium reduction cells, the use of in-situ welding combined with explosion welding composite technology results in six welding connection points, as shown in Figure 9. The increase in voltage drop primarily stems from three factors: First, residual trace metal oxides and microscopic defects at the explosion welding interface lead to higher contact resistance. Second, the composite welding zone develops non-uniform metallurgical structures due to thermal stress, hindering electron migration. Third, localized high temperatures during in-situ welding cause annealing of the aluminium bus material, reducing its conductivity. Test data indicate that for every 10  $\mu\text{m}$  increase in interfacial gap within the welding zone, the voltage drop rises by 1.5–2 mV.



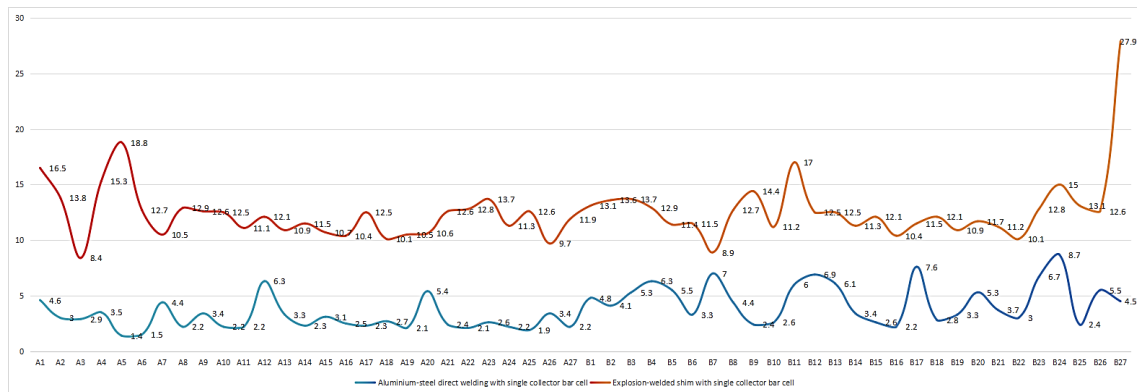
**Figure 9. Conventional cathode collector bar connection in the reline cell.**

In the newly rebuilt electrolytic cells, the cathode energy-saving and voltage-reduction aluminium-steel full-section direct welding system (as shown in Figure 10) replaced the original in-situ welding combined with explosion welding composite process. The overhaul plan optimized the welding connection points from six to two, reducing the number of welds and lowering connection voltage drop. Meanwhile, the system's high-magnetic full-current online quality-optimized welding technology achieved high-quality online full-current welding while avoiding risks and hidden dangers caused by conventional welding methods.



**Figure 10. Connection type of aluminium-steel direct welding cathode collector bar for reline cell**

Through practical application in a 400 kA potline, the original explosion-welded connection method was optimized to a direct aluminium-steel welding approach. A statistical comparison of voltage drops was conducted, specifically focusing on: The connection voltage drop between the collector bar end face (position ③ in Figure 9) and the joint of the explosion-welded block to aluminium flexes (position ⑤ in Figure 9); and the connection voltage drop between the collector bar end face (position ③ in Figure 9) and the peripheral bus near the cell (position ⑥ in Figure 9). As shown in Figure 11, the maximum reduction in voltage drop reached 23.4 mV for the end cathode collector bar, while the average connection voltage drop across the entire cell was 9.7 mV.



**Figure 11. Voltage drop (mV) comparison of optimized 400 kA cell-type cathode connections.**

Through practical application in multiple electrolysis series ranging from 180–420 kA, statistical comparisons were made between the connection voltage drop data before and after the major repair optimization. The final comparison table of connection voltage drop is shown in Table 1.

**Table 1. Comparison of voltage drops across cathodes with different cell types.**

Cell type (kA)	180	240	240	420
Implementation time	June 2023	November 2023	November 2023	June 2024
Original connection type	Explosion welding	Mechanical compression	Explosion welding	Explosion welding
Original average connection voltage drop (mV)	14.5	37.2	15.3	14.7
Optimized average connection voltage drop (mV)	3.3	4.1	3.2	3.6
Average reduction difference (mV)	11.2	33.1	12.1	11.1

According to the comparative data in the table, the cathode connection voltage drop of electrolytic cells using the new aluminium-steel direct welding technology can be reduced by approximately 11 mV compared to explosion welding, and by about 34 mV relative to mechanical compression connections.

## 5. Conclusions

The cathode energy-saving and voltage-reduction aluminium-steel full-section direct welding system developed in this study achieves high-efficiency, low-resistance welding for cathode connections through core technologies, including an aluminium-steel bimetallic fully automatic welding and forming system, a multi-physical field test data cloud-based expert decision comparison system, and a high-magnetic full-current online quality-optimized welding technology. Simulation and test results demonstrate that, compared to traditional explosion welding or compression joint methods, this system significantly mitigates connection voltage drop issues caused by weld defects, construction variability, and strong magnetic field interference. In the industrial application of electrolytic cells within the 180–420 kA potlines, the optimized welding joint voltage drop was reduced by an average of 15–20 %, with a specific power consumption reduction of 35–106 kWh/t Al. This provides a reliable technical solution for energy-saving and consumption reduction in aluminium electrolysis.

## 6. References

1. Yongtao Yu, Comparative Analysis on Two Connection Methods for Cathode Collector Bars in Aluminium Reduction Cells, *Light Metals*, 2023, (12): 25–28. <https://doi.org/10.13662/j.cnki.qjs.2023.12.006> (in Chinese).
2. Jiangyi Chen, Exploration of Cathode Collector Bar Welding Technology in Strong Magnetic Environment for 400 kA Series Aluminium Reduction Cells and Practices, *Green Environment Protection Building Materials*, 2018, (06): 217+219. <https://doi.org/10.16767/j.cnki.10-1213/tu.2018.06.162> (in Chinese).
3. Hong Ma, et al., Electric Welding Technology in the West Hydropower Series 420 kA Aluminium Reduction Cell Application and Research. *Sichuan Nonferrous Metals*, 2016, (02): 62–65 (in Chinese).
4. Li Li, et al., Improvement of Connection Type of Voltage Adapter for 240 kA Aluminium Reduction Cell, *Energy Saving of Nonferrous Metallurgy*, 2014, 30(03): 14–16 (in Chinese).
5. Lingfeng Wang, Analysis on the Relationship Between the Assembly Voltage Drop of Cathode Carbon Blocks and Pot Bottom Voltage Drop in Aluminium Reduction Cells, *Light Metals*, 2013, (02): 42–44. <https://doi.org/10.13662/j.cnki.qjs.2013.02.012> (in Chinese).
6. Yongtao Yu, Application of Crimped Connection of Cathode Collector Bars in Aluminium Reduction Cells, //Chinese Society for Environmental Sciences. *Collection of Excellent Papers from the 2008 Academic Annual Meeting of the Chinese Society for Environmental Sciences (Volume II)*, Qingtongxia Aluminium Group, 2008: 754–755 (in Chinese).