Application of Energy-Saving Anode Yokes in 500 kA Aluminium Reduction Cells

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Abstract

Anode voltage drop is an important component of the overall electrolytic cell voltage drop, and reducing the voltage drop of the steel yoke is significant for lowering the anode voltage drop. Currently, conventional yokes in aluminium electrolysis suffer from problems such as high resistance, high energy consumption, vulnerability to oxidation and corrosion at high temperatures, and continuous reduction in the diameter of the steel stubs. This paper describes the disadvantages of traditional steel yokes, compares the industrial test results of several new energy-saving anode yokes, and statistically analyses their voltage drop and mechanical stress. The results show that the voltage drop of new energy-saving yokes is generally lower than that of traditional ones, and the corresponding reduction in DC energy consumption per tonne of aluminium is significant for energy-saving and carbon emission mitigation in aluminium reduction cells.

Keywords: 500 kA aluminium reduction cell, Energy-saving steel yoke, Steel yoke voltage drop, Energy saving and consumption reduction.

1. Introduction

Electricity cost accounts for 30–40 % of the total production cost in aluminium electrolysis, a major industrial power consumer. Under the national dual-carbon policy and tiered electricity pricing system, reducing the energy consumption of the potlines, optimizing resource use, and achieving cost reduction and efficiency improvement are urgent tasks for aluminium smelters. Reducing the average electrolytic cell voltage and improving current efficiency can both help decrease power consumption in electrolytic cells [1].

Currently, major aluminium smelters are using larger cells, with their current efficiency approaching optimal levels, making further breakthroughs difficult; thus, reducing the average cell voltage has become the main research direction for smelters and academic institutions. To reduce the average cell voltage, the focus should be placed on both cathode and anode voltage drops. Cathode blocks have evolved from partially graphitic, 100 % graphitic, semi-graphitized and fully graphitized, to fully graphitized with copper inserts, lowering cathode voltage drop to about 160 mV, roughly 150 mV lower than the traditional graphitic cathode, but further reduction faces a bottleneck. The anode yoke with stubs for aluminium reduction cells, in contrast, exhibit high voltage drop, offering greater potential for energy savings.

2. Current Status of Traditional Anode Yokes

The anode yoke for the cells is a key structural component connecting the anode rod to the anode carbon block [2]. In terms of conductivity, the anode yokes with stubs must carry the high current of the cells. In a 500 kA cell, each yoke carries around 10 000 A on average, requiring good conductivity. In terms of mechanical performance, the anode yoke connects the aluminium rod and the anode carbon block [3, 4], which weighs about 1300 kg and operates at high temperature, requiring the anode yoke to have sufficient strength and stiffness.

Currently, ZG200–400 cast carbon yokes are used in most domestic cells; these yokes have relatively low strength, and their deformation and failure rate during operation can reach as high as 20–35 % [4, 5]. Moreover, the traditional connection between aluminium anode rod and yoke is typically in the form of an explosion-welded transition clad, which forms three weld seams (Al–Al, steel–steel, Al–steel) between the rod and yoke, increasing resistance and voltage drop of the joint and thus raising energy consumption. Meanwhile, due to significant differences in thermal expansion coefficients between the explosion-welded steel-aluminium clads in the high-temperature electrolysis environment, large thermal stresses are generated. These stresses cause the interface to shear and crack easily, leading to high labour and cost for annual maintenance of the anode rod assemblies, which in turn increases electrolysis production costs. To address these issues, this project upgrades the structure and materials of anode yokes with stubs of the cells to reduce anode yoke and stub voltage drop, and contribute to lower overall cell energy consumption, and achieve comprehensive energy saving throughout the potline, resulting in energy conservation and emission reduction.

3. New Energy-Saving Yoke Technologies

3.1 Aluminium-Steel Direct Welding Technology

Aluminium-steel direct welding enables direct joining of aluminium and steel, as shown in Figure 1. It revolutionizes traditional welding methods, effectively overcoming limitations related to explosion clad quality and welder skill, achieving improved welding quality and contributing to energy saving in aluminium smelters. Key features of the new welding method are:

- Elimination of explosion-welded clads: enables direct Al-steel welding without the need for intermediate explosion clad;
- High welding efficiency: primary welding is performed by a robotic arm, offering high efficiency, consistency, and reliable quality;
- Energy conservation: results in two fewer weld seams, lowers the overall voltage drop, and supports energy conservation.

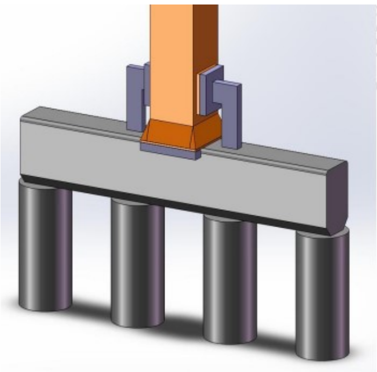


Figure 1. Aluminium-steel direct-welded yoke. Left: digital simulation, right: actual image.

3.2 Friction Welding Technology

Friction welding is a solid-state welding process commonly used for metal joining; as shown in Figure 2. Heat is generated by relative motion and friction between parts, combined with mechanical extrusion and deformation, to form a bonded interface. Advantages and main features of the technology are:

- The main process of inertia friction welding does not require filler material, produces a small heat-affected zone, achieves weld strength equal to that of the base material, offers strong material compatibility for both similar and dissimilar materials, significantly reduces production costs, greatly enhances productivity, extends product service life, and enables energy-saving, environmentally friendly, and fume-free production;
- This technology features low welding temperature and low energy consumption, with electricity consumption as low as 20 % compared to traditional welding processes;
- It facilitates fully automated production and intelligent production management (including online weld quality monitoring, remote equipment condition diagnosis, and cloud-based analysis of production data).

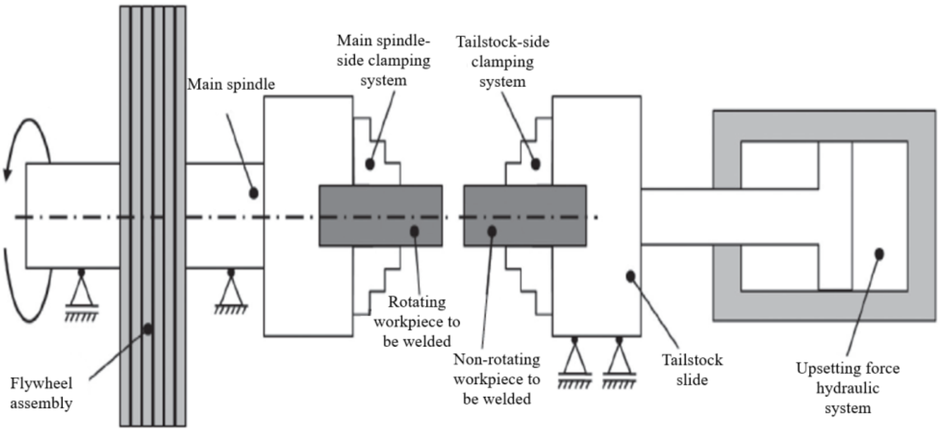

Figure 2. Diagram of friction welding system.

3.3 Low-Resistance Steel Yoke Technology

The concept and research method of low-resistance yoke and stub technology mainly involve studying the influence of key chemical components, alloying elements, and programmable heat treatment processes of highly conductive materials on conductivity, aiming to reduce resistance in the main conductive parts, enhance conductivity, and lower the overall voltage drop of the yoke and stubs. In addition, through computer simulations, a comprehensive analysis is conducted on current distribution characteristics and voltage distribution patterns across various models to identify the optimal structural combination, leading to the development of yoke structures suitable for high-temperature, heavy-duty conditions in the cells, as shown in Figure 3.

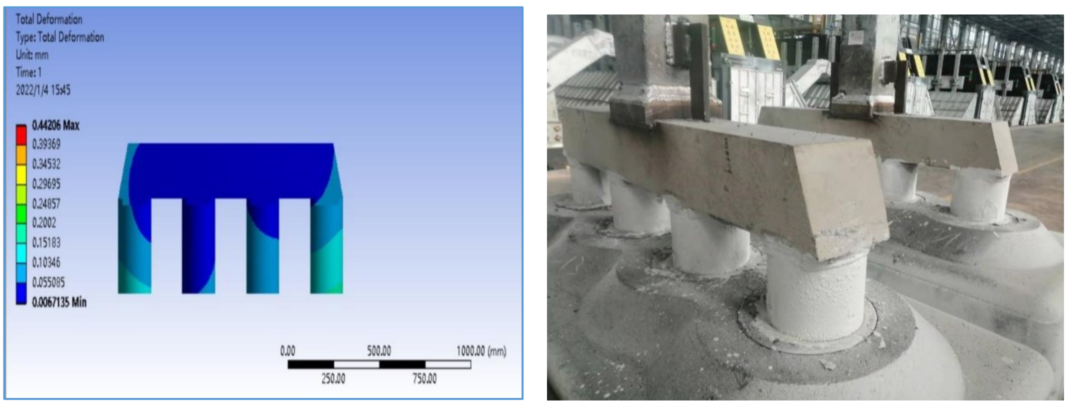

Figure 3. Low-resistance yokes with stubs. Left: digital simulation, right: actual image.

4. Test Conditions and Result Tracking

Using original 500 kA aluminium reduction cell yokes as a baseline, the voltage drops of four types of yokes (conventional cast yokes, aluminium-steel direct-welded yokes, friction-welded steel stubs, and low-resistance yokes and stubs) were analysed under identical working conditions. Taking into account the overall energy-saving and cost, a comparative analysis of energy-saving yoke performance was conducted, including:

- An innovative aluminium-steel direct-welded yoke developed by a certain smelter was tested on test cell #1724;
- An innovative yoke with friction-welded steel stubs developed by a certain smelter was tested on test cell #1408;
- An innovative low-resistance yoke and stubs developed by a certain university was tested on test cell #13626.
- In addition, cells #1722 and #1327 were used as control cells equipped with conventional cast yokes; Figures 4 and 5 show photos of the various energy-saving yokes.

Figure 4. On-site test yokes. Left: conventional yoke, right: aluminium-steel direct-welded yoke.

Figure 5. On-site test yokes. Left: low-resistance yoke, right: yoke with friction-welded stubs.

4.1 Test Conditions

During testing, all five cells operated stably under normal conditions without any fluctuations; neither the conventional yokes nor the energy-saving yokes showed anomalies such as dislodgement or anode rod breakage. On November 28 and December 1, the production control center measured the voltage drop of the energy-saving yokes, and the results are presented below.

4.2 Data Measurement Method

To ensure precision, analogue meters were modified and enclosed in iron boxes to eliminate magnetic field interference. The positions of the welded anode rebar and its measurement point—above the anode carbon block and up to the top of the explosion weld clad (Figure 6).

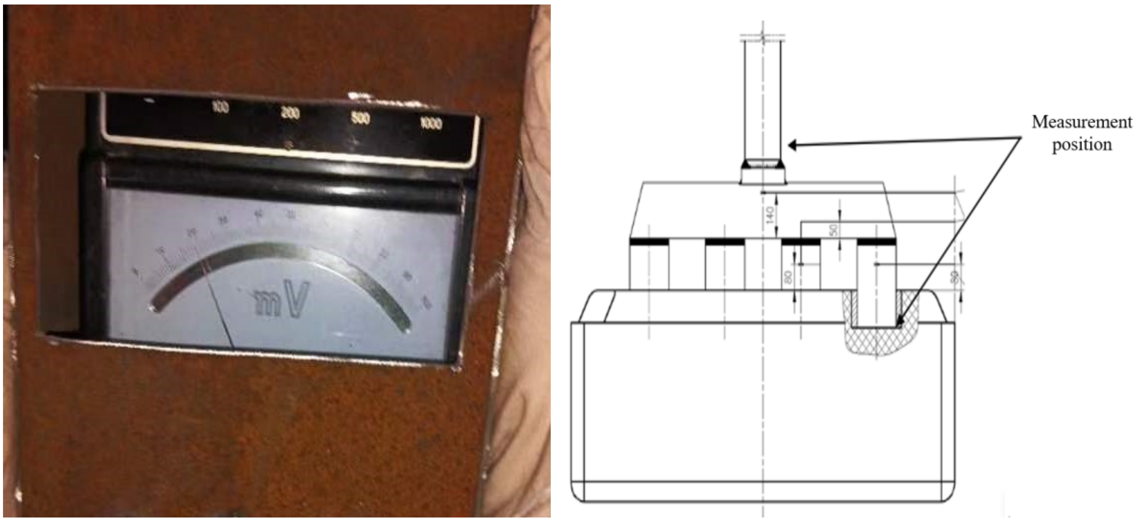

Figure 6. On-site data measurement. Left: modified analogue meter, right: rebar measurement points across the whole yoke.

4.3 Measurement Analysis

4.3.1 First Round of Measurement

After all test yokes had reached the appropriate cycle, the professional team conducted the first round of voltage drop measurements for the energy-saving yokes. The results are shown in Table 1:

Table 1. First round voltage drop measurements of test yokes and conventional yokes.

Voltage drop record of low-resistance yoke on cell #1326								
Serial number	**Anode number**	**Point 1**	**Point 2**	**Point 3**	**Point 4**	**Average value**	**Corrected value**	**Current distribution**
1	A9	128.4	110.7	113.1	116.7	117.2	130.3	1.8
2	A10	117.6	105.3	102.5	131.7	114.3	114.3	2.0
3	A23	141.2	136.4	131.7	124.5	133.5	98.9	2.7
4	B5	122.1	125.9	116.8	126.7	122.9	117.0	2.1
Average value		127.3	119.6	116.0	124.9	122.0	113.4	2.2

Voltage drop record of friction-welded yoke on cell #1408								
Serial number	**Anode number**	**Point 1**	**Point 2**	**Point 3**	**Point 4**	**Average value**	**Corrected value**	**Current distribution**
1	A7	146.2	135.8	133.7	143.8	139.9	103.6	2.7
2	A8	155.6	150.2	135.7	163.4	151.2	112.0	2.7
3	B15	138.5	131.2	111.8	136.3	129.5	143.8	1.8
4	B16	127.2	115.1	116.3	120.1	119.7	114.0	2.1
Average value		141.9	133.1	124.4	140.9	135.1	116.2	2.3
Voltage drop record of aluminium-steel direct-welded yoke on cell #1724								
Serial number	**Anode number**	**Point 1**	**Point 2**	**Point 3**	**Point 4**	**Average value**	**Corrected value**	**Current distribution**
1	A11	118.4	116.6	100.3	118.2	113.4	113.4	2.0
2	B5	113	103.3	109.6	106.9	108.2	135.3	1.6
3	B19	133.5	143.4	127.6	134	134.6	122.4	2.2
Average value		121.6	121.1	112.5	119.7	118.7	122.8	1.9
Voltage drop record of conventional yoke on cell #1327								
Serial number	**Anode number**	**Point 1**	**Point 2**	**Point 3**	**Point 4**	**Average value**	**Corrected value**	**Current distribution**
1	A10	168.7	154.2	162.3	154.2	159.9	139.0	2.3
2	B5	152.3	159.4	151.3	156.1	154.8	147.4	2.1
3	B17	188.2	184.7	175.8	187.1	184.0	147.2	2.5
Average value		169.7	166.1	163.1	165.8	166.2	144.5	2.3
Voltage drop record of conventional yoke on cell #1722								
Serial number	**Anode number**	**Point 1**	**Point 2**	**Point 3**	**Point 4**	**Average value**	**Corrected value**	**Current distribution**
1	A5	108.4	98.6	101.1	103.1	102.8	146.9	1.4
2	A19	151.4	141.6	149.7	164.7	151.9	144.6	2.1
3	B3	145.1	142.4	147.7	158.6	148.5	135.0	2.2
Average value		135.0	127.5	132.8	142.1	134.4	141.4	1.9

Based on the above results, the summary is shown in Table 2.

Table 2. Summary of first voltage drop measurements for test yokes and conventional yokes.

Yoke type	**Conventional yoke**	**Low-resistance yoke**	**Yoke with friction-welded stubs**	**Aluminium-steel direct-welded yokes**
Voltage drop (mV)	147.0	122.6	131.9	135.4

Based on the results of the first measurement, as shown Figure 7, the low-resistance yoke reduced the anode voltage drop by 29.6 mV compared with the conventional yoke, by 26.8 mV compared to the yoke with friction-welded stubs, and by 20.2 mV compared with the aluminium-steel direct-welded yoke, demonstrating the best overall performance.

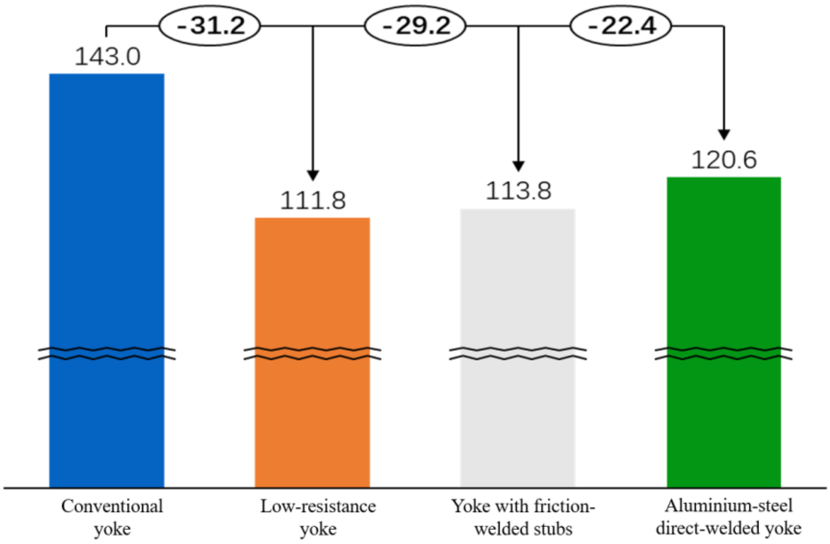

Figure 7. Comparison of voltage drop differences among various yokes in the first measurement.

4.3.2 Second Round of Data Measurement

To minimize error, the professional team conducted a second measurement of the voltage drop for both the test yokes and the conventional yokes one week later, and the summarized results are shown in Table 3:

Table 3. Second round voltage drop measurements of test yokes and conventional yokes.

Voltage drop record of low-resistance yoke on cell #1326								
Serial number	**Anode number**	**Point 1**	**Point 2**	**Point 3**	**Point 4**	**Average value**	**Corrected value**	**Current distribution**
1	A7	135.7	121.4	125.8	144.1	131.8	114.6	2.3
2	A8	119.5	108.1	107.5	112.6	111.9	106.6	2.1
3	B15	111.6	103.2	103.3	115.7	108.5	114.2	1.9
Average value		122.3	110.9	112.2	124.1	117.4	111.8	2.1
Voltage drop record of friction-welded yoke on cell #1408								
Serial number	**Anode number**	**Point 1**	**Point 2**	**Point 3**	**Point 4**	**Average value**	**Corrected value**	**Current distribution**
1	A5	124.3	118.4	104.6	131.7	119.8	126.1	1.9
2	A17	132.6	113.4	106.1	128.5	120.2	109.2	2.2
3	B11	141.2	124.3	116.5	138.6	130.2	113.2	2.3
4	B23	115.4	100.7	113.2	120.3	112.4	107.0	2.1
Average value		128.4	114.2	110.1	129.8	120.6	113.5	2.1

Voltage drop record of aluminium-steel direct-welded yoke on cell #1724								
Serial number	**Anode number**	**Point 1**	**Point 2**	**Point 3**	**Point 4**	**Average value**	**Corrected value**	**Current distribution**
1	A7	115.6	115.8	118.2	133.8	120.9	127.2	1.9
2	B3	132.4	117.1	127.5	128.9	126.5	126.5	2.0
3	B15	124.7	112.5	117.6	127.1	120.5	109.5	2.2
Average value		124.2	115.1	121.1	129.9	122.6	120.6	2.0
Voltage drop record of conventional yoke on cell #1327								
Serial number	**Anode number**	**Point 1**	**Point 2**	**Point 3**	**Point 4**	**Average value**	**Corrected value**	**Current distribution**
1	A10	168.7	154.2	162.3	154.2	159.9	139.0	2.3
2	B5	152.3	159.4	151.3	156.1	154.8	147.4	2.1
3	B17	188.2	184.7	175.8	187.1	184.0	147.2	2.5
Average value		169.7	166.1	163.1	165.8	166.2	144.5	2.3
Voltage drop record of conventional yoke on cell #1722								
Serial number	**Anode number**	**Point 1**	**Point 2**	**Point 3**	**Point 4**	**Average value**	**Corrected value**	**Current distribution**
1	A5	108.4	98.6	101.1	103.1	102.8	146.9	1.4
2	A19	151.4	141.6	149.7	164.7	151.9	144.6	2.1
3	B3	145.1	142.4	147.7	158.6	148.5	135.0	2.2
Average value		135.0	127.5	132.8	142.1	134.4	141.4	1.9

Based on the above results, the summary is shown in Table 4:

Table 4. Summary of second voltage drop measurements for test yokes and conventional yokes.

Yoke type	**Conventional yoke**	**Low-resistance yoke**	**Yoke with friction-welded stubs**	**Aluminium-steel direct-welded yoke**
Voltage drop (mV)	143.0	111.8	113.8	120.6

According to the results of the second measurement, as shown in Figure 8, the voltage drop of the low-resistance yoke was reduced by 31.2 mV compared with the conventional yoke, by 29.8 mV compared with the friction-welded yoke, and by 22.4 mV compared with the aluminium-steel direct-welded yoke, with the low-resistance yoke demonstrating the best performance.

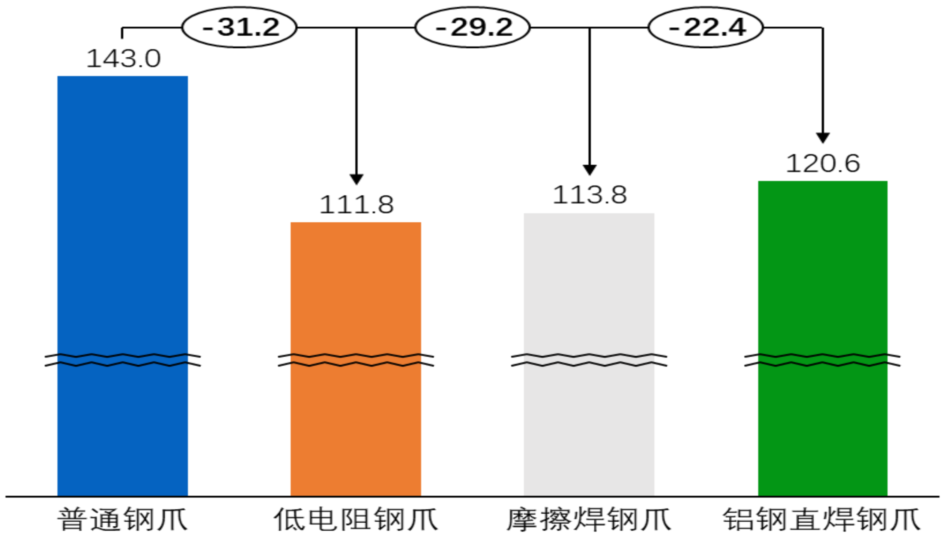

Figure 8. Comparison of voltage drop differences among various yokes in the second measurement.

4.3.3 Comprehensive Data Analysis

From the above two sets of data, the voltage drop measurements are summarized in Table 5:

Table 5. Summary of two voltage drop measurements for test yokes and conventional yokes.

Yoke type	Conventional yoke	Low-resistance yoke	Friction-welded yoke	Aluminium-steel direct-welded yoke
First voltage drop value (mV)	143.0	113.4	116.2	122.8
Second voltage drop value (mV)	143.0	111.8	113.8	120.6
Average (mV)	143.0	112.6	115.0	121.7

Based on the comprehensive results from both measurements, as shown in Figure 9, the voltage drop of the low-resistance yoke was 30.4 mV lower than that of the conventional yoke, the friction-welded yoke was 28 mV lower, and the aluminium-steel direct-welded yoke was 21.3 mV lower. All three energy-saving yokes effectively reduced the voltage drop, with the low-resistance yoke demonstrating a clear advantage.

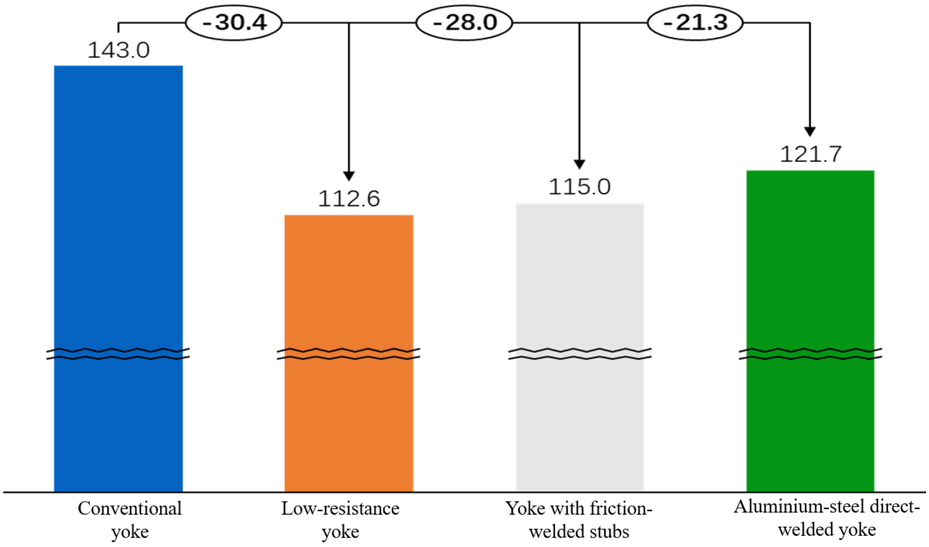

Figure 9. Comparison of voltage drop differences among various yokes in two measurements.

5. Conclusion

Since all three types of energy-saving anode yokes were introduced, the test cells have maintained stable operation and meet basic production requirements.

Throughout the test, the low-resistance yokes, yokes with friction-welded stubs, and aluminium-steel direct-welded yokes showed no signs of reddening or detachment, with good performance and no welding failures or rod breakages.

In terms of effectiveness, all three types of energy-saving yokes successfully reduced the anode assembly voltage drop. Among them, the low-resistance yoke delivered the best performance with a 30.4 mV reduction compared with the conventional yoke; the yoke with friction-welded stubs followed with a 28 mV reduction; and the aluminium-steel direct-welded yoke achieved a 21.3 mV reduction.

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