Analytics-Driven Control for Anode Effect Reduction in 85 kA Pots

Rajeev Kumar Yadav[1], Shanmukh Rajgire[2], Manish Jaisawal[3], Anand Sokal[4], Kulamani Meher[5], Md. Imroz Ahmad[6], Mahesh Sahoo[7] and Amit Gupta[8]
1. Scientist
2. Senior Scientist
8. Lead Scientist
Aditya Birla Science and Technology Company (P) Ltd, Navi Mumbai, Maharashtra, India
3. Assistant Manager
4. Assistant Manager
5. Deputy Manager
6. Manager
7. General Manager
Hindalco Industries Ltd, Hirakud, Odisha, India
Corresponding author: rajeev.yadav@adityabirla.com

Abstract

The Hall-Héroult process is used to produce aluminum from alumina using the electrolysis process in an aluminum reduction pot. Alumina is usually fed into the pot at regular intervals, using a point-feed mechanism. At very low alumina concentration (< 2 %) cryolite decomposition occurs and perfluorocarbon (PFC) gases evolve in the process. These gases form a highly electrical resistive layer underneath the anode, that suddenly increases the pot voltage resulting in an anode effect (AE). High anode effect frequency (AEF) and anode effect duration (AED) may lead to reduced anode life, high heat generation, crust collapse, ledge melting, low current efficiency, high fluoride emission, and the possibility of pot leakage. Therefore, high AEF and AED have a major contribution to the PFCs emission and global warming. Apart from the environmental challenges, AEs significantly increase the specific energy consumption and affects pot life. Aluminum smelter industries are belligerently examining ways to reduce the number of AEs as well as their duration. This paper discusses in detail the work related to reducing the AEF and AED in 85 kA retrofit pots. For improving the alumina concentration control in the electrolyte, feed logic has been optimized as well as also assessed reduced feed size/quantity. Moreover, real-time data analytics was used to predict alumina deficiency and the feeder hole choke, for early prediction and prevention of AEs. Various algorithms, based on anode lowering and ultra-fast feeding, have been developed and evaluated for AE termination. This AE termination logic has been deployed using PLC-based controllers to ensure the early termination of AEs, thus reducing the need for manual intervention. The trial was conducted in a section of pilot pots, wherein a reduction of more than 50 % in AEF was observed.

Keywords: Aluminum smelting, Anode effect prediction, Anode effect frequency, Specific energy, Anode effect termination.

1. Introduction

The Hall–Héroult process is the only industrial process for aluminum production. In this process aluminum oxide (alumina) is dissolved in molten cryolite (Na_3AlF_6), and electrolysed to produce aluminum and CO_2. This process operates in the range between 940–980 °C and produces 99.5–99.8 % pure aluminum. A few additives such as AlF_3, MgF_2, CaF_2, and LiF, etc. are added in the molten cryolite (Na_3AlF_6) to lower the liquidus temperature for more efficient electrolysis of dissolved alumina (Al_2O_3) [1]. The cross-section of a contemporary point-feed aluminum electrolysis cell (Hall–Héroult cell) is shown in Figure 1 (a). It is an energy-intensive process with electricity comprising 30–40 % of the cost of production. During the process, the dissolved alumina gets electrolyzed in the reaction zone, where liquid aluminum is formed and settles down on the cathode surface and CO_2 gas escapes from the top. Modern smelters run at current efficiencies close to 94 % with the benchmark of 96 % [2]. In the anode to metal pad zone, underneath the anode, a highly resistive layer of gas bubble forms at the low alumina concentration. The bubble formation and its growth are shown in Figure 1 (b). The gas bubble under the anode constrains the path of the electric current, the electric resistance increases resulting in increased specific energy consumption. When the gas bubbles become denser and cover the anode bottom surface completely it leads to an anode effect (AE) [3]. During AEs the rate of perfluorocarbon gases emission is high.

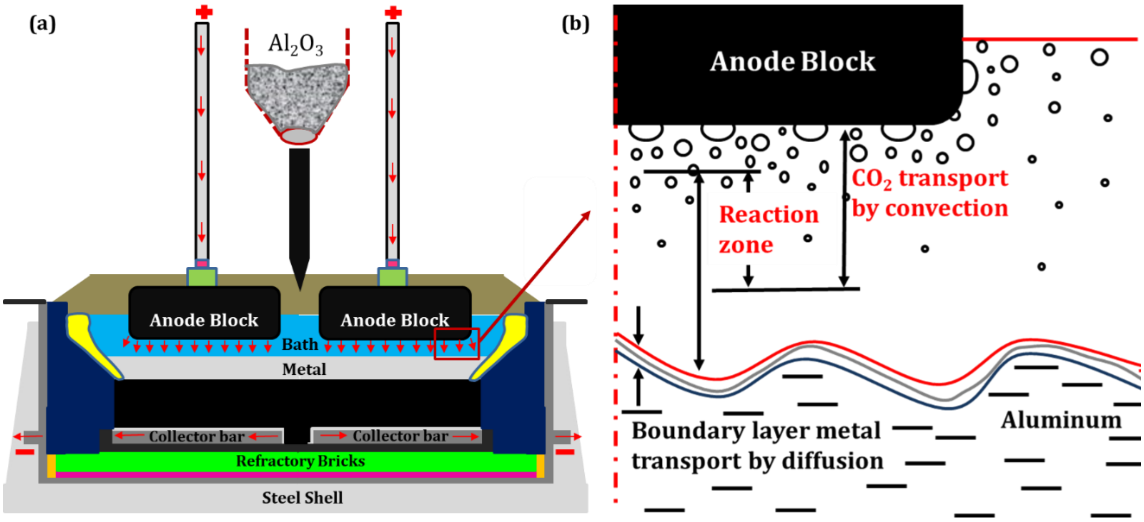

Figure 1. a) Schematic cross-sectional view of Hall–Héroult cell; b) Anode to metal pad reason presenting gas bubbles.

Earlier, automatic feed control systems were not present in the aluminum smelters. Therefore, Al_2O_3 had to be fed manually at regular intervals, if there is no anode effect (AE) during this interval, then feed quantity was kept constant. If AEs come frequently then the amount of alumina was increased and vice versa. The termination of the AE was done manually with iron rakes or green wood poles. However, nowadays there is consent that AEs are detrimental and must be avoided [4, 6]. Because the high voltage in the range of 10 to 80 V AEs increases the DC energy consumption and reduces the current efficiency. AEs caused the emission of harmful perfluorocarbon (PFC) greenhouse gases such as CF_4 and C_2F_6 which have extremely high global warming potentials [5]. Due to the availability of automatic feeders and computer-controlled feeding, but also automatic AE termination routines, the aluminum industry can eminently reduce the frequency and duration of AEs [4]. The rate of PFC emission during anode effects in aluminum cells is variable depending on the type of aluminum cell technology and the computer control anode effect termination (AET) algorithm [7]. Aluminum smelters are one of the largest anthropogenic sources of PFC emissions worldwide [8]. An AE occurs when the alumina (Al_2O_3) concentration in the electrolytic bath drops below approximately 1.5 %, the overall cell voltage rises, and the bath and carbon anodes begin to react and form PFC gases [2]. AEs typically start in a localized area of pre-bake electrolysis cells (on one or two anodes). As the AE reaction propagates to additional anodes in the cell, the overall cell voltage rise. When the cell voltage rises above a specific threshold (typically 8 V), an anode effect duration (AED) counter is initiated in the plant control system to allow tracking of AE minutes per cell per day. Most aluminum companies have initiated voluntary programs for actively reducing PFC emissions [9]. All modern pre-bake smelters have implemented automated methods for terminating anode effects. These methods vary by cell technology and operational control strategy; however, all have the same goal of minimizing the cumulative AED per cell per day at the operating condition. The pot feeding and monitoring programs have been continually optimized to reduce the AE duration as well as the frequency of these events. These systematic efforts have reduced anode effect-related PFC emissions from aluminum smelters by almost 90 percent since 1990 [10]. A focus on reducing AED via aggressive kill programs can also create an undesirable effect of increasing pot noise, as at a particular anode the voltage might be above normal but overall pot voltage is below the voltage limit to declare AE (8-9 V). Under these conditions, low voltage PFC emissions can be generated; however, the pot computer system will not register any AE time. This is just one example of root causes of low voltage PFC emissions [11]. Therefore, different smelters have different feed strategy systems to maintain the optimum alumina concentration in the bath. The feed strategies at Hirakud smelter are discussed in the next section.

1.1 Existing and New Control Feed Strategies at Hirakud Potlines

The variation of alumina percentage leads to variation in the cell resistance, and therefore the cell voltage. The voltage can also vary due to bath chemistry, anode to cathode distance, and anode current density. Thus, it is very crucial to understand the nature of voltage variation and accordingly take control action. When alumina concentration is on a leaner side then the voltage increases with alumina consumption. On the contrary, voltage decreases with alumina addition, as shown in Figure 2. Therefore, high variation in alumina concentration, can lead to difficulty in alumina feeding. Thus, alumina variation should not be high and should be maintained on leaner side. In existing control strategy, the high variation in alumina can thus create a problem in pot control and performance.

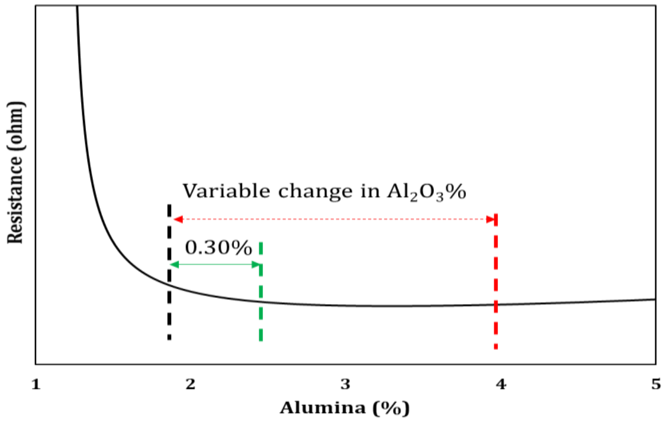

Figure 2. Alumina concentration variation with the existing (red) and the new feed strategy.

The existing and new control technology consists of feed strategies such as theoretical feeding, underfeeding, and overfeeding. These feed strategies are defined as, when the feeding rate of alumina is the same as its theoretical consumption rate as per Faraday's law it is known as theoretical feeding (TF), for alumina feed rate lower than the theoretical consumption rate it is known as underfeeding (UF) and if the feeding rate is higher than theoretical consumption it is described as overfeeding (OF). Based on observation of the existing control system, overfeeding as well as underfeeding durations were found to be variable. However, in the new control system over feed duration and dumps are constant. Due to the dynamic nature of feeding, it is difficult to monitor the quantity of excess alumina fed to the system and regulate the change in alumina within desired range. Thus, it increases the dependence on voltage variation to understand the alumina concentration in bath and for feeding alumina accordingly. The change in Al_2O_3 percentage in the bath from OF to UF is shown in Figure 3, where the change in Al_2O_3 percentage is constant in the new feed strategy (0.30 %), however, it is variable in the existing feed strategy. Variable change in Al_2O_3 percentage may cause poor decision criteria, the above-mentioned reasons are one of the major factors for a relatively higher anode effect frequency (AEF) of around 0.5 per pot per day. In the existing feed strategy at Hirakud smelter, the alumina quantity and durations are variable for fast feeding. This causes a huge variation of alumina concentration as shown in Figure 3 (a). However, in the new feed strategy alumina quantity and duration are fixed for fast feeding. It can be observed that the new feed strategy helps in reducing alumina concentration variation and hence reducing the variation in cell operating voltage as shown in Figure 3 (b). New feed strategy will also ensure better alumina dissolution than the existing feed strategy. Thus, lowering the sludge forming tendency and reduced voltage variation, would improve the cell stability and provide a potential for reducing the operating voltage. The performance of these feed strategies running live on pots is shown in Figure 4**Figure 4**. Where the performance of both feed strategies (existing and new) can be seen with voltage variation. As the fast feeding trigger, a rapid drop in pot voltage was observed in new feed strategies. However, in existing feed strategies, it drops at a slower rate.

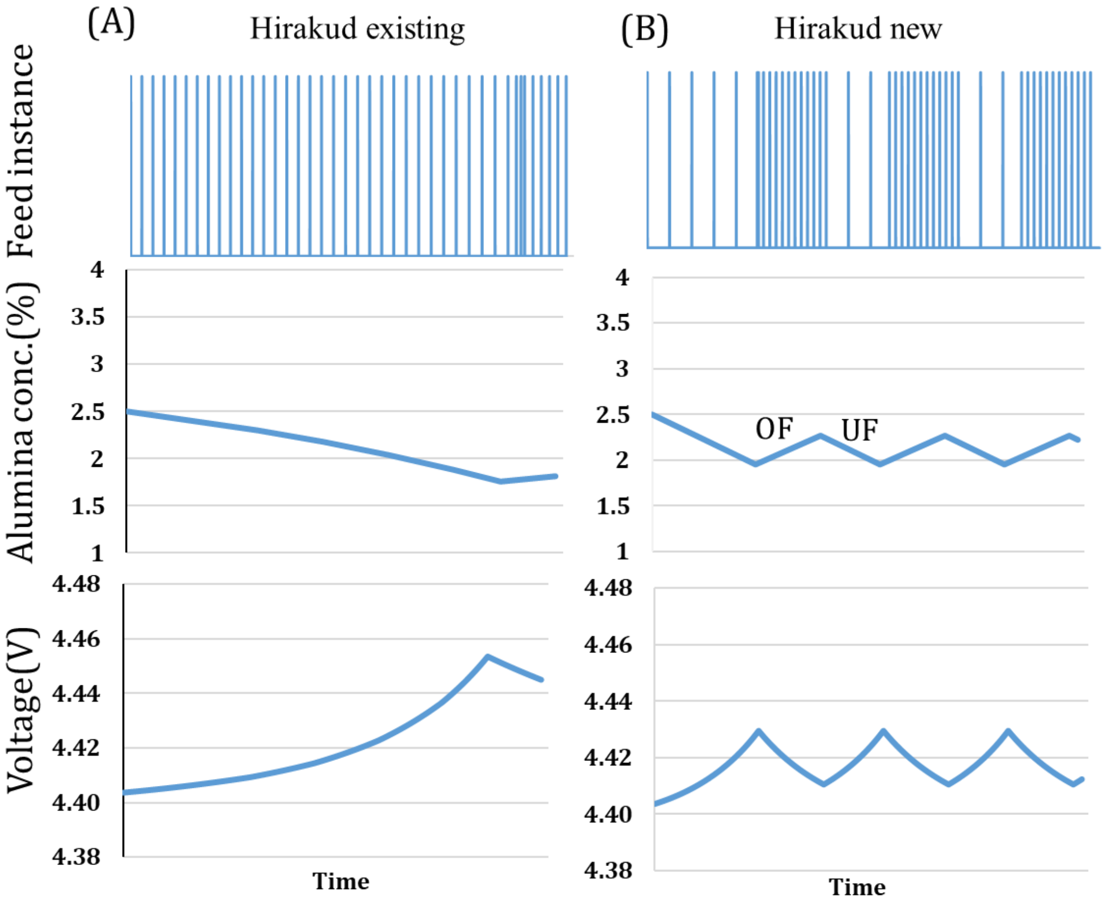

Figure 3. A) Effect of existing feed strategy; B) Effect of new feed strategy.

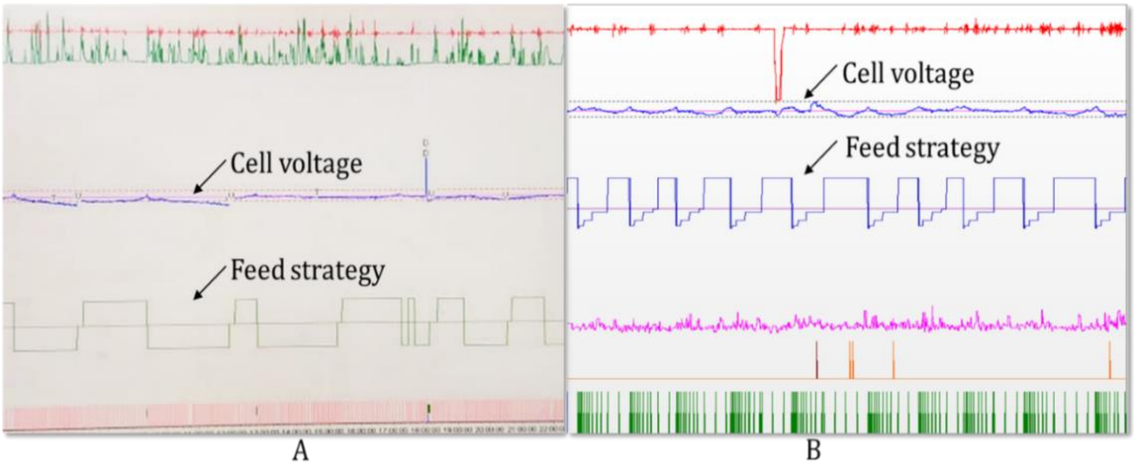

Figure 4. A) Existing control logic trend; B) New control logic trend.

1.2 Scope for Improvement

As mentioned in the previous section, feed strategies are dynamic in the existing control logic. To monitor the variation of alumina concentration, the overfeeding duration must be constant. A variable feeding interval can be provided where alumina feed rate is high initially and then gradually decreases, as there is an urgent need for alumina towards the end of underfeeding. The feed rates can be intensified compared to existing, this would increase the number of feed cycles from 5-8 per day to 18-24 per day, helping in maintaining pot at leaner alumina with improved decision making. Moreover, a reduction in alumina discharge from feeder by using a reduced feeder size would also improve the dissolution rate, resulting in better control of alumina concentration. In addition to using the cell voltage, the slope (derivative) and curvature (double derivative) of resistance would also help in better decision-making for feed strategy. To reduce the anode effect frequency, the detection time for AEs would reduce from 40 s to 12 s.

2. Methodology

Various methods and techniques have been tested and implemented in the new control system based on their performance to reduce the AEF and its duration. Al_2O_3 concentration plays the key role to control AEF and AED, too low concentrations eventually lead to an anode effect, while too high concentrations reduce further solubility, resulting in sludge and operational disturbances [12]. For alumina regulation, feed strategies have been developed and implemented for existing (1.8 kg/feeder) and reduced (1kg/feeder) feeder size at Hirakud smelter. To predict and prevent the AEs, anode effect prediction (AEP) logic has been developed and incorporated into the control system. Further, in the case of the AEs occurrence, different auto AEs killing logic also has been tested and incorporated. A detailed discussion of feed strategy, anode effect termination, and anode effect duration reduction methods are mentioned below.

2.1 Alumina (Al_2O_3) Feed Strategy

The solubility limit of alumina in the bath is 8 % by mass [1], beyond which the alumina does not dissolve, and it settles down on the cathode surface forming sludge/muck. In the range of alumina concentration (2 to 4 % by mass), the pot voltage increases with alumina consumption. However, when alumina concentration goes between 4 to 8 % mass, the pot voltage would decrease with alumina consumption and that may lead to a wrong decision in pot control. When alumina concentration is on the lower side (less than 2 %), a rapid increment in pot voltage may occur and it may lead to an anode effect. Therefore, several methodologies have been developed to control the alumina concentration to reduce the AEF.

2.1.1 Feed Strategy for Traditional 1.8 kg Feeder

Different combinations of feed strategies are used to feed alumina in the new control system, which includes theoretical feeding, underfeeding, fast feeding, and ultra-fast feeding. By Faraday's law, total aluminum production comes to around 640 kg per day for 85 kA current at 93.5 % current efficiency. The alumina requirement would be around 1209.5 kg per day. With a feed discharge weight of 3.6 kg from two feeders operating simultaneously at Hirakud, nearly 336 feeds or dumps are required per day to maintain the alumina concentration in the optimum range. For theoretical or normal feeding (NF), the interval between two successive dumps is around 252 s, known as the NF interval. The time interval of other feed strategies depends on NF interval, and these have been designed in such a way that, they can meet the required Al_2O_3 concentration in the bath, provided that there should not be any abnormality and mechanical fault. The resistance slope is defined as the change of smooth resistance (filtered resistance) with respect to time (w.r.t.) time. Whereas the curvature is the second-order derivative of smooth resistance w.r.t time.

2.1.2 Feed Strategy for Reduced 1 kg Feeder

It was observed that with the existing (traditional) feeder there is an increased possibility of sludge formation. Hence the control logic was modified for reduced feed size of 1 kg/feeder and deployed in one pilot pot. Reduced feeder size may help to improve Al_2O_3 dissolution and alumina concentration control. The only challenge that could be faced with reduced feeder size is the extra breaker movements that may reduce the breaker life and would increase the requirement of pressurized air. To overcome this type of challenge, the number of breaking times can be reduced. Theoretically, the aluminum (Al) production and Al_2O_3 requirement can be calculated as mentioned in the above section. The number of dumps was computed by dividing the size of the dump into the total requirement of Al_2O_3. Additionally, the consumption rate and feeding interval for underfeeding (UF), overfeeding (FF) and normal feeding (NF) have also been computed**.** Subsequently, a suitable combination of feed strategies has been identified. This logic has been designed in such a way that FF durations and dumps are constant with variable UF durations.

2.2 Anode Effect Prediction (AEP)

AEP algorithm has been developed and incorporated into the new control system. It can detect/predict an AE at an early stage. The primary reason for the AEs would be the deficiency of Al_2O_3 concentration in the bath, the deficiency may occur due to hole choke and lesser dump weight. Based on the observation, the following analytics-driven technique has been adopted at Hirakud smelter.

- If the change in the voltage response during the fast feeding is relatively small (< 20 mV), it might be partial hole choke leading to deficiency of Al_2O_3. Therefore, an empty breaking and hole choke annunciation is incorporated to ensure early prediction and prevention of AEs.
- Based on the analytical analysis, if the number of dumps per day is higher than theoretical requirement, it might indicate the condition for hole choke. Therefore, an annunciation is made to control hole choke condition.
- Extra dumps and empty breaking are carried out when the cell voltage lies continuously close to the upper control limit of the voltage control band.
- In case of low bath height (< 14 cm), empty breaking is being done every hour to avoid hole choke.

2.3 Reduction of Anode Effect Duration (AED)

Due to continuous operations and periodic manually intensive cell operations, there is difficulty in maintaining process and operational parameters such as bath height, metal height, bath ratio, and bath temperature, etc., in the optimum range. Deviation of these parameters from the optimum range can hamper the Al_2O_3 dissolution rate and as a result, leads to an anode effect. Therefore, it is very challenging to operate any aluminum smelter with zero AEF. Therefore, to reduce the harmful effects of anode effect, another critical parameter is AED. AED is the duration for which an AE persists in pot. Decreasing this can also significantly reduce the specific energy consumption as well as PFC emissions. An automatic AE termination (AET) logic has been developed and implemented in the control system; it activates at the onset on AEs. This logic comprises of primary and optional loop. The primary loop comprises of feeding, anode beam lowering and holding time occurring in predefined sequences. If the AE is not terminated during the primary loop, then optional loop is executed. In the optional loop, a repeated sequence of feeding and lowering is followed, with a holding time after each cycle. This logic has been tested and based on its performance few modifications were made in the primary loop only. Those modification are described in detail in the next section.

2.3.1 Anode Effect Termination Technique 1 (AET-1)

In AET-1, at the onset of AE, feeding is started first, followed by slight beam lowering to reduce the pot voltage and disperse the perfluorocarbon (PFC) gases at the early stage, and as a result, AE can be terminated. However, feeding and dissolution of the alumina in the bath would take at least 40 s, as mechanical movement of the feeder takes around 10 s to discharge alumina in bath, after which it takes 30 s for 80 % dissolution of this alumina [13].

2.3.2 Anode Effect Termination Technique 2 (AET-2)

AET-1 has been modified to further reduce the AED, as reported by Pablo Navarro et al. [14]. At the onset of AEs, firstly, slight anode beam lowering is done, followed by Al_2O_3 feeding. Due to low anode beam movement, the turbulence produced might not be sufficient to disperse the gas layer and kill the AE [15]. It was analyzed that, due to the high rate of generation of the gas bubbles this much beam movement might not be enough.

2.3.3 Anode Effect Termination Technique 3 (AET-3)

Slight beam movement might not have a significant impact on an anode effect; therefore, AET-2 is further modified. At the onset of AE, fast beam lowering was done followed by Al_2O_3 feeding. It was observed that due to fast beam lowering anode-cathode distance (ACD) squeezed rapidly and gas bubbles disperse and escape easily from underneath the anode, resulting in the fast killing of an AE. In this technique, after fast lowering, it holds for few seconds to avoid pot instability. A significant reduction in AED was observed after incorporating this technique.

Based on the beam movement and alumina feeding test, the anode moves down for 6 to 14 mm to terminate the AE, also extra 7.2 to 28.6 kg alumina is fed. Extra feeding alumina helps to maintain the alumina concentration in the bath. Figure 5 shows the screenshot of an AET technique being executed on a pot. It can be seen that at onset of AE the beam is lowered automatically along with alumina feeding. This is able to terminate the AE after which the beam position is restored, again reaching the set voltage band of the cell. The test had an AED of only 1.58 min and demonstrated that the auto AET technique performed as programmed and was able to successfully terminate the AE.

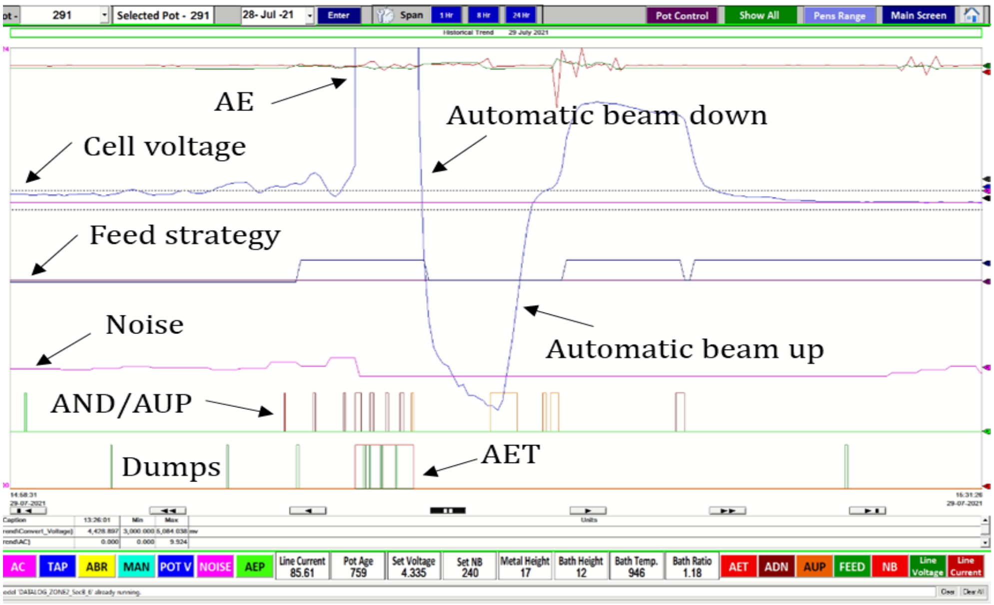

Figure 5. Programmed AET logic performance.

3. Result and Discussion

Feed strategy, anode effect prediction and termination logic have been developed and incorporated in PLC-based new control system to reduce the anode effect frequency and duration for traditional and reduced feeder size. Figure 6 shows a comparison of average monthly anode effect frequency (AEF) in Hirakud pots for PLC-based new control system and EPC-based old control system (reference) for traditional feed size of 1.8 kg/feeder. Similar age pots have been taken as a reference to observe the performance of the PLC-based new control system pot. It was observed that the average six months (February 2021 to July 2021) AEF for PLC-based (new control system) pots is 0.33 per pot/day. However, it is 0.75 per pot /day for the reference pots.

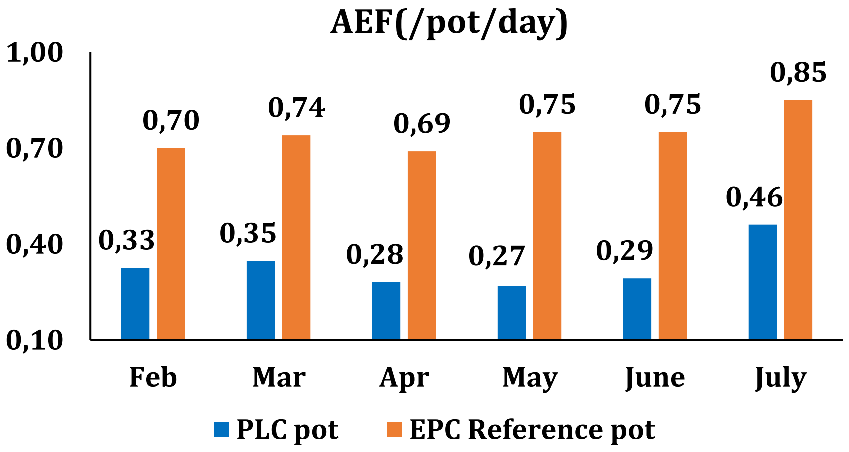

Figure 6. AEF for PLC and EPC (reference) pots.

The anode effect duration (AED) for pots with and without AET techniques is presented in Table 4**Table** , for a duration of 4 months (April 2021 to July 2021. Figure 7 shows an average four months AED comparison for different conditions (with and without AET), and it was observed that the pots which are running with anode effect termination (AET) logic have lower AED. A significant reduction in AEF can be seen in modified AET over existing AET logic. After comparing these data, 0.47 min reduction in AED was found in AET-1 whereas, in AET-2, the reduction in AED was found 1.17 min as compared to the pot with no AET logic.

Table 4 Monthly AED (min) with and without AET logic

	April	May	June	July
No AET	2.93	2.74	3.14	3.08
AET 1	2.30	2.98	2.27	2.48
AET 2	1.98	1.98	1.15	2.10

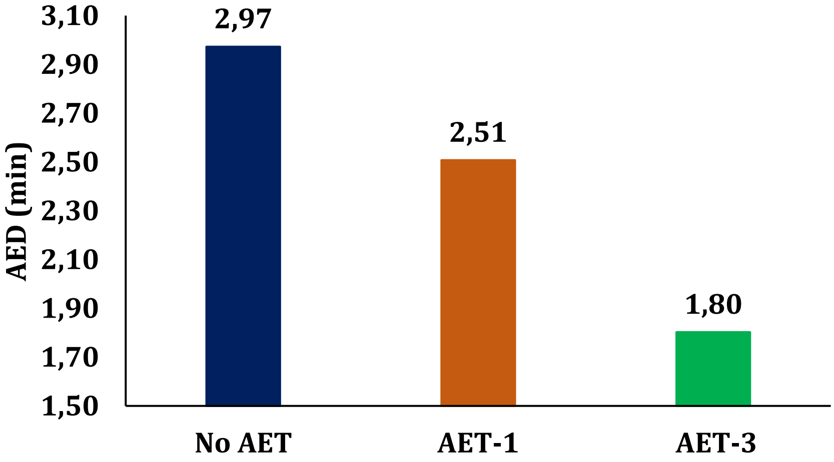

Figure 7. Average AED with and without AET logic.

To improve the alumina dissolution, 1 kg feeder along with modified control logic was also tested in a pot. The AEF was observed to be lower when feed size was reduced from 1.8 to 1 kg/feeder. AEF for reduced and traditional feeder for PLC based new control system pots is shown in Figure 8. Monthly average of AEF, for the period of May 2021 to July 2021, for pots operating at reduced feed size and traditional feed size was 0.26 and 0.33, respectively.

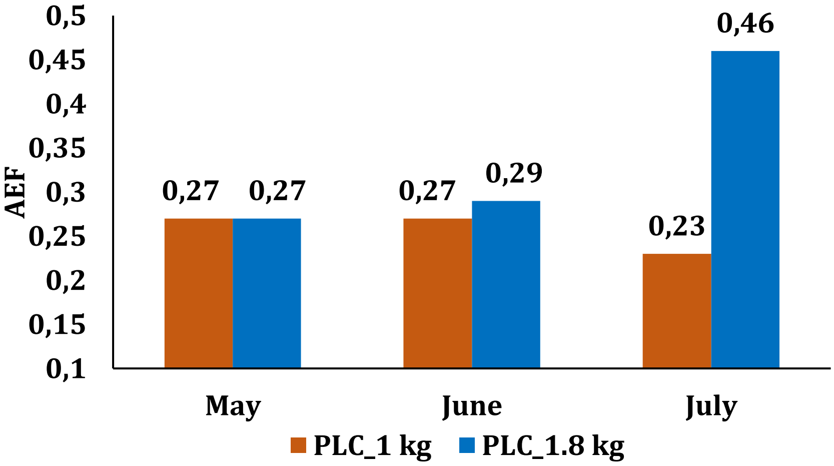

Figure 8. AEF for reduced feed size 1 kg/feeder and traditional 1.8 kg/feeder.

The noise analysis was done based on three-month historical data, it was observed that the pot with 1 kg feeder has been running under more stable conditions than 1.8 kg feeder, as shown in Figure 9. It was also observed during operation, that the pot with reduced feed size with 1 kg/feeder, has less tendency for sludge formation, which is reflected in noise data.

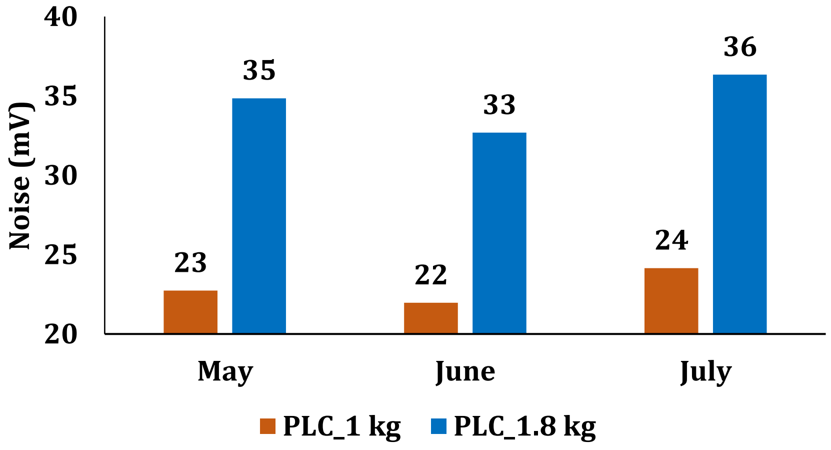

Figure 9. Noise for reduced feed size 1 kg/feeder and existing 1.8 kg/feeder.

4. Conclusion

Alumina feed strategy, anode effect prediction (AEP) and anode effect termination (AET) logic have been developed and incorporated in the control system (PLC-based). AEP logic was developed for predicting the AEs at the early stage, resulting in a reduction in anode effect frequency (AEF). The performance of AET logic was monitored and based on its performance, it was improved to further reduce the anode effect duration (AED). Logic-based auto AE quenching procedure is relying on pot resistance to activate and kill the anode effect. With the help of modified AET, AED was reduced by 1.17 min w.r.t no AET logic and 0.71 min w.r.t existing AET logic. The trial was also carried out in one pot with a feed strategy for 1 kg/feeder (earlier 1.8 kg/feeder), and over the last three months average AEF was observed to be 0.26 /pot-day. Hence, the drastic reduction in AEF and AED was observed after incorporating feed strategies, AEP and AET techniques in the new control (PLC-based) system.

5. References

1. George E. Totte et al., *Handbook of Aluminum Alloy Production and Materials Manufacturing*, 1st Edition, Volume 2, 2003, 736 pages.
2. Geir Martin Haarberg, Effects of electrolyte impurities on the current efficiency during aluminium electrolysis, *Proceedings of 33rd International ICSOBA Conference*, Dubai, 29 November - 1 December 2015, Paper AL27, *Travaux* 44, 761-767.
3. László I. Kiss, Transport processes and bubble driven flow in the Hall-Héroult cell, *Fifth International Conference on CFD in the Process Industries CSIRO*, Melbourne, Australia, December 2006.
4. Warren Haupin, Edward J. Seger, Aiming for zero anode effects, In *Essential Readings in Light Metals*: Volume 2 Aluminum Reduction Technology; Springer International Publishing: Berlin/Heidelberg, Germany, 2016, 767–773.
5. Kai Grjotheim and Halvor Kvande, *Introduction to Aluminium Electrolysis*, AluMedia GmbH: Düsseldorf, Germany, 2nd Edition, 1993, 212 pages.
6. Jomar Thonstad et al. Anode effect in aluminum electrolysis, Essential Readings, *Light Metals*: Volume 2 Aluminum Reduction Technology; Springer International Publishing: Berlin/Heidelberg, Germany, 2016; 131–138.
7. A. R. Ravishankara et al., Atmospheric lifetimes of long-lived halogenated species, *Science*, v. 259, 1993, 194-199.

8. R. Zander et al., Increase of stratospheric carbon tetrafluoride (CF_4) based on ATMOS observations from space, *Geophysi. Re. Lett.*, v. 23, 1996, 2353-2356.
9. The IPCC Guidelines for Reporting Greenhouse Gas Emissions, http://www.ipcc.ch/pub/gu ide.htm .
10. IAI, Results of the 2013 Anode Effect Survey, International Aluminium Institute, Report on the aluminium industry's global perfluorocarbon gases emission reduction program, http://www.world-aluminium.org/media/filer_public/2014/08/08/20l3_anode_effect_survey_report_2014.pdf .
11. Jerry Marks, et al., Perfluorocarbon (PFC) generation during primary aluminum production, *Light Metals* 2000, 365-371.
12. Pascal Lavoie, Mark P. Taylor and James B. Metson, A review of alumina feeding and dissolution factors in aluminium reduction cells, *Met. Mat. Trans. B* 47, 2016, 2690–2696.
13. Shui-qing Zhan et al., Analysis and modeling of alumina dissolution based on heat and mass transfer, *Trans. Nonferrous Met. Soc. China 25,2015*, 1648−1656.
14. Pablo Navarro et al. A New Anode Effect Quenching Procedure, *Light Metals* 2003, 479-486.
15. Jomar Thonstad et al., Aluminium Electrolysis – *Fundamentals of the Hall-Héroult Process*, Düsseldorf, Germany, Aluminium-Verlag, 3rd edition, 2001, pp. 186-215.