Recent On-line Measurements of Individual Anode Currents at Alouette

James W. Evans[1,], Lukas Dion[2], François Laflamme[3] and Charles-Luc Lagacé[4]
1. Professor Emeritus,
UC, Berkeley, CA, USA
1. President
Wireless Industrial Technologies, Oakland, CA, USA
2. PhD Candidate in Engineering,
Université du Québec à Chicoutimi, Chicoutimi, Québec, Canada
3. Engineer in process control, Development and Technologies
4. Advisor in continuous improvements
Aluminerie Alouette Inc., Sept-Îles, Québec, Canada
Corresponding author: jim.w.evans@gmail.com

Abstract

Since early 2014, Alouette has used a system provided by Wireless Industrial Technologies (WIT) to measure individual anode currents on two pots. The system works by measuring the adjacent magnetic field generated by the current for each anode hanger. This paper summarizes initial difficulties and how they have been overcome. Recent current measurements show good agreement with alternative methods for measuring currents (e.g. mV drop along anode hangers). An algorithm has been developed for discerning an imminent anode effect from changes in the measured magnetic fields due to changes in anode currents. Practical reductions of anode effect frequency, compared to cells of reference, have been achieved by using the results of this algorithm to trigger corrective action through the pot control computer. Some additional potential benefits of anode current measurement are described in the paper.

Keywords: Anode current measurement; Wireless Industrial Technologies; anode effect prediction.

1. Introduction

Electric currents generate magnetic fields and the determination of a current by measurement of its field has been common since at least early in the last century. An example of the application of this principle in Hall-Héroult cells is the 2001 paper by Jim Barclay and Joe Rieg [1]. In the same issue of Light Metals, Jeffrey T. Keniry et al. [2] pointed to the diagnostic opportunities provided by such measurements. For example, anode effects could be detected a minute or so before the usual jump in cell voltage; at that time one or more of the anodes would start to lose current. A more detailed paper on the early detection of imminent anode effects by measurement of anode currents is that of Gary Tarcy and Alton Taberaux [3]. These investigators observed a distribution of the times at which an anode would lose current, ranging from zero to almost ten minutes. For 95 % of the anode effects, the "early warning" of an imminent anode effect was 30 seconds, or more, in advance of the voltage increase, providing sufficient time to prevent the anode effect.

In early 2012 Wireless Industrial Technology (WIT) installed a current measuring system at TRIMET Aluminium SE, Hamburg, Germany and the results were described by Andreas Lützerath et al. [4]. The system measured anode currents by measuring magnetic fields produced by the anode currents and measurements were relayed via the internet to the cloud. Results showed early warnings of anode effects as well as other cell phenomena such as cell instability or the current pick-up experienced by a new anode. As part of that investigation

TRIMET personnel correlated the magnetic fields from anodes with current measurements made by the well-known technique of measuring the mV drop along a known length of anode hanger. For an individual anode there was a very good correlation between the field and mV measurements. However, when comparing between anodes, the relationship between fields and mV's was poor. For example, the anodes displaying the largest mV's were not all the anodes displaying the largest fields. This is now thought to be due to the misalignment of the sensors that measured the magnetic field near each anode rod, a misalignment caused by a sensor enclosure that was not sufficiently robust to prevent bending during cell operations.

A more robust mounting of the sensors was used at a later installation at Nordural, Grundartangi, Iceland. Again, mV measurements on individual anodes were found to correlate with the corresponding magnetic fields. Figure 1 is a comparison between the two types of measurements for all anodes in a campaign conducted in September. At first glance these results were encouraging with a coefficient of determination (R^2) of better than 95%. However, these results were obtained for a large range of currents (including many cases where the anode is a new one that is picking-up current). For a narrower range of current, say in the top right of the figure, the results show a weaker correlation. The implication is that the system would be useful for some purposes (e.g. early warning of anode effects or pick-up of current by a new anode) but not for others (e.g. telling that an anode was badly placed and therefore carrying incorrect current).

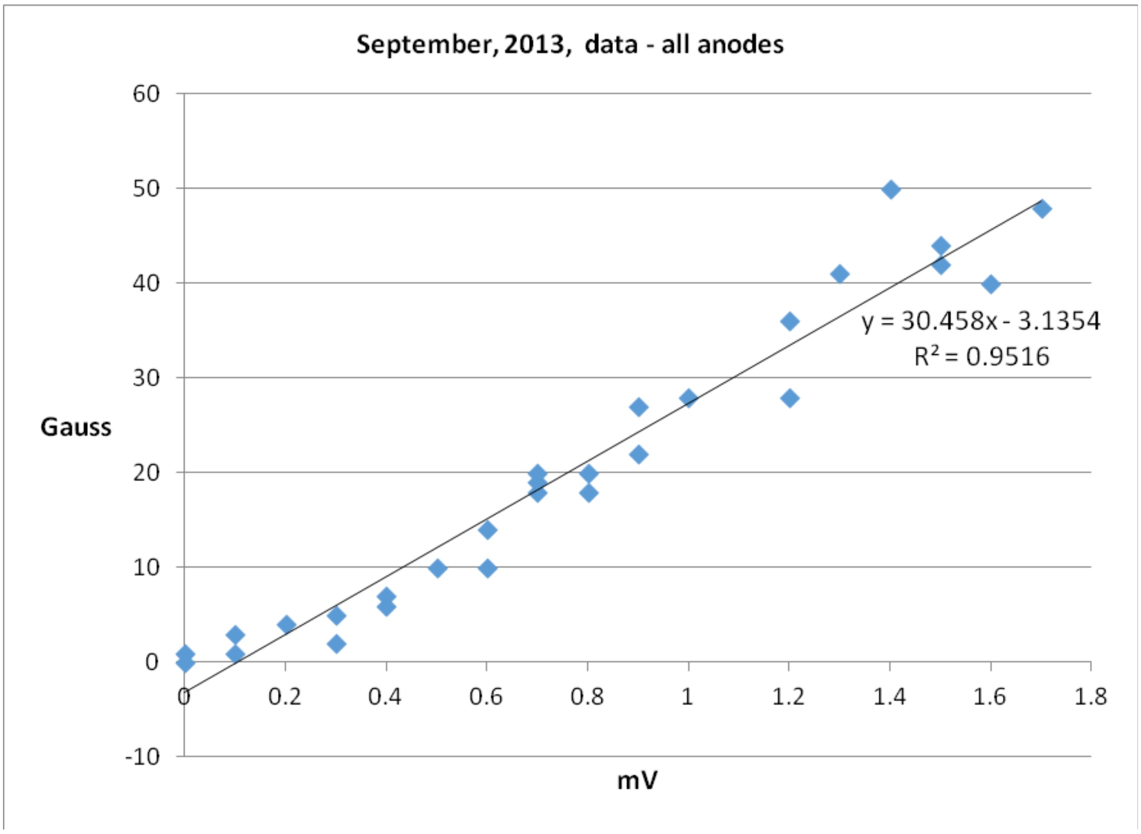

Figure 1. Correlation of magnetic field and mV measurements at Nordural.

In the WIT system the magnetic fields are measured by Hall effect sensors that are mounted on a printed circuit board, along with other electronic components to form a board referred to as a "slave" (as it is controlled by a "master" to which it is connected along with other slaves). The Hall effect sensors give very reproducible signals and are very linear over the magnetic field range of interest. This is seen in Figure 2 where the output from a representative sensor is plotted against the actual field experienced by the sensor. The sensor was mounted on the axis of an electromagnet that was itself calibrated, at various currents, by a gauss meter. Poor performance in comparing one anode's current with another's was therefore puzzling.

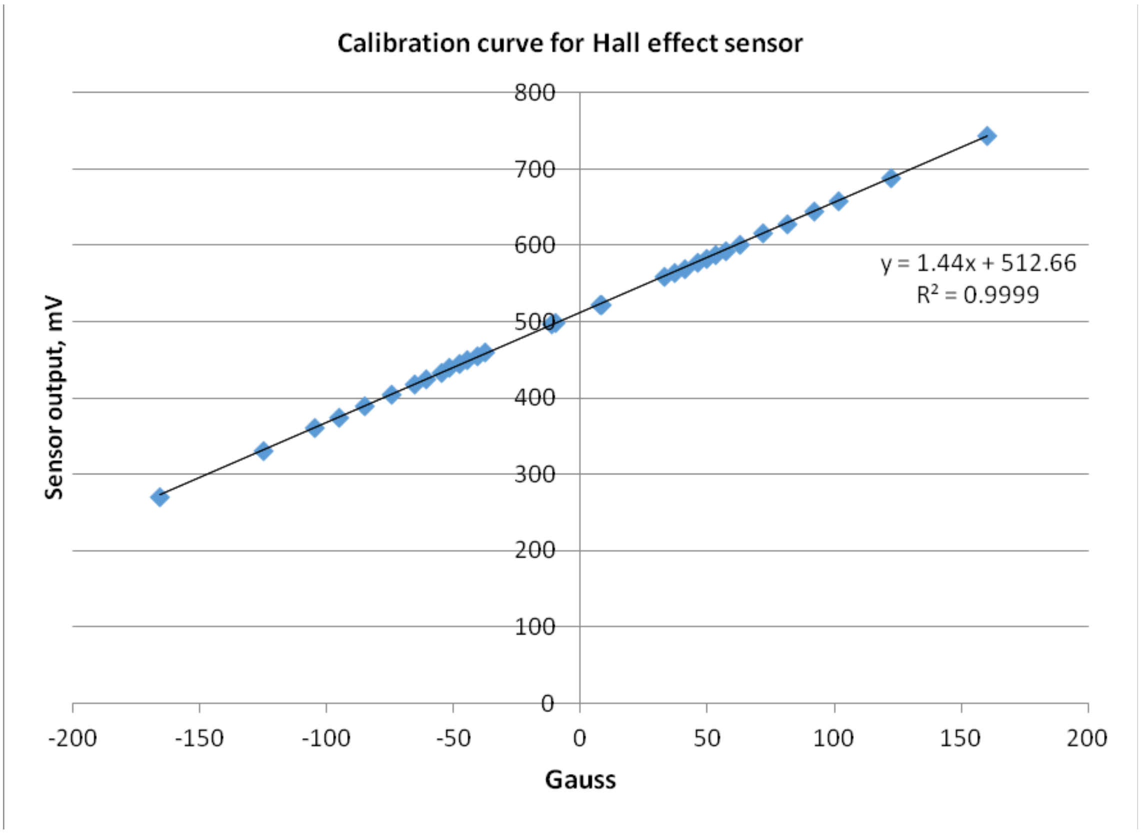

Figure 2. Linearity of Hall effect sensor.

The Hall effect sensors are 2 mm by 3 mm by 0.64 mm and measure the field component perpendicular to the 2 mm by 3 mm face. Consequently, they must be mounted flat on the slave circuit board and that board must be mounted perpendicular to the field that is to be measured. The latter requirement was met at Nordural but it is now likely that the former requirement was not. Figure 3 is a photograph, taken from the side, of a Hall effect sensor mounted on its circuit board. The sensor is making an angle of almost 5° with the circuit board onto which it was supposed to be mounted flat by the circuit assembly house. With this tilt, the slave would become sensitive to the magnetic field produced by the current in the anode busbar as well as that produced by the anode. The consequence is an error which would depend on the degree of tilt and the proximity/magnitude of the anode bus current and therefore vary from anode to anode. Of the representative sample of slaves examined, that of Figure 3 was the worst, but many slaves had tilted sensors. Slaves are now bought by WIT with a specified maximum tilt sufficient to avoid this error but this was subsequent to the investigation described in the present paper. The objective of this investigation was to determine whether

1. The WIT system with tilted sensors could be manipulated to yield accurate currents when comparing one anode with another, and;
2. What practical value could be extracted from such measurements with regard to avoiding anode effects and otherwise.

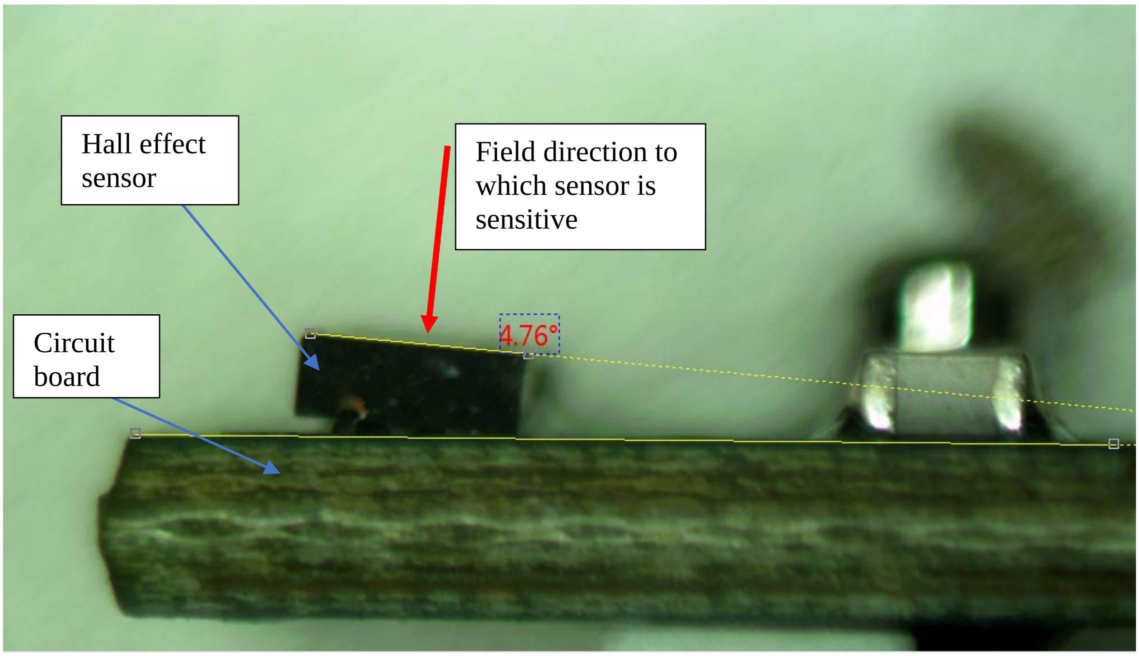

Figure 3. Side view of Hall effect sensor improperly mounted on slave circuit board. Yellow lines from angle measuring software.

2. The Installation at Alouette

A WIT system was installed on two Alouette cells in early 2014. The system has been described by Lukas Dion et al. [5] and consists of twenty robustly mounted slaves per cell, one mounted behind each anode hanger. A single cable is positioned along each side of the cell (running under the anode bus) connecting ten slaves to one master at the end of the cell. The cable carries signals to the masters (two per cell) which supply power to the slaves along the same cable. The masters are connected to the cell voltage to provide power and to permit monitoring of cell voltage. Masters communicate their data once per second to a small industrial computer mounted nearby and from there the data flow wirelessly to the Alouette computer system and also, via the internet, to the cloud for data display and processing. In this previous work the authors report success in seeing imminent anode effects well before the onset of a voltage increase and in following the dissolution of alumina into the electrolyte. More recently Lukas Dion et al. [6] have used the anode current measurements in a study of low voltage emissions of PFCs (polyfluorinated carbons).

2.1. Refinement of current measurement

The sensors having the tilt described above, a correction was made as follows. The slaves use two Hall effect sensors to measure fields at two points at different distances (~ 26 mm and 92 mm) from the surface of the anode hanger. The difference between these measurements (henceforth “delta”) is sensitive to the current in its hanger but insensitive to fields in other hangers, risers etc. [See Nobuo Urata and James W. Evans [7] for details.] Consequently the measured field should drop to zero when an anode is disconnected during anode change. In fact, the field is not exactly zero and the residual field, delta of the order of 10 Gauss is presumably due to contamination of the measurement by field from the current in the anode bus as described above. The first correction then was to subtract this residual field from the field measured when the anode was carrying current. This is an inexact correction because the bus current will be altered when an anode is removed.

A second correction was in the conversion of measured magnetic fields (deltas) to anode current. This was achieved by multiplying the vector of deltas by a matrix obtained from a mathematical model [7]. Calibration experiments were carried out where anode currents obtained in this way were compared to anode currents measured by a clamp-on current meter from Halmar®. The matrix was then corrected to make the calculated currents conform to the readings as closely as possible. Optimisation of the matrix was performed using the "solver analysis tool" from Microsoft Excel© to minimize the summed error of every anode position.

Figure 4 shows the correlation between the measurements from the clamp-on current meter and the currents from the WIT system before the calibration, while Figure 5 shows the correlation after the calibration. The data of the latter figure were a separate set of data from those used in the calibration. Clearly the correlation was significantly improved by the calibration; the coefficient of determination increased from 0.525 to 0.7516. However, the correlation was still disappointing to the authors and they look forward to additional measurements using slaves that do not suffer from the tilt problem. It is emphasized that the weak correlation seen in these figures has no impact on early warnings of anode effects; those warnings rely on the fields detected at each anode, rather than currents interpreted from those fields. The results of using such fields in cell control are described in the next section.

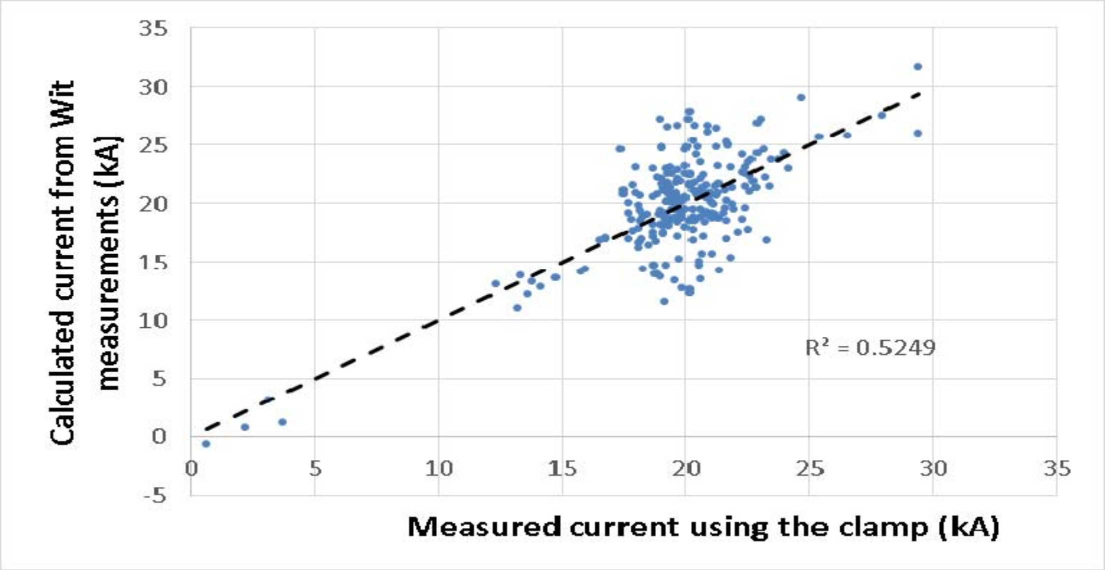

Figure 4. Correlation of anode currents derived from the WIT system with those from a clamp-on ammeter before the calibration described in the text.

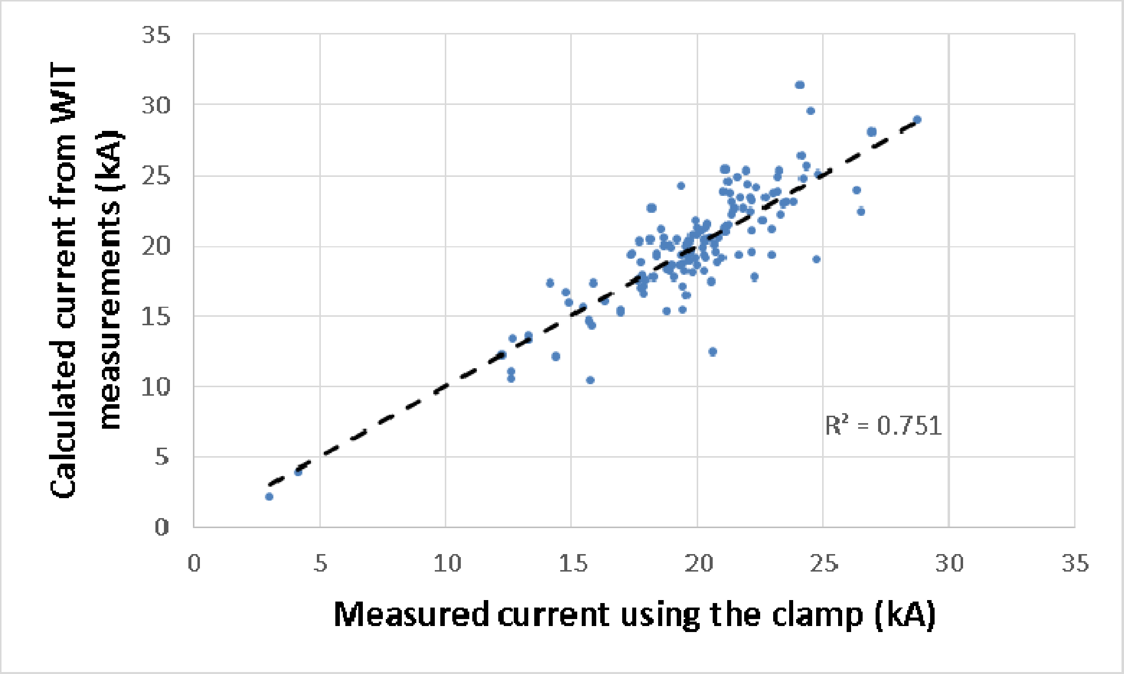

Figure 5. Correlation of anode currents derived from the WIT system with those from a clamp-on ammeter after the calibration described in the text.

2.2. Implementation of process control.

The prior investigations at Alouette had been ones where the cells have been *monitored* rather than *controlled*. That is, data from the cloud were examined and analyzed subsequent to the on-line measurements, usually days later. Starting in December, 2015, a connection was made between the WIT industrial computer and the cell control computer so that the latter could respond rapidly to data from the WIT system without human intervention. In particular, an algorithm was developed that would discern the dropping of current by anodes, in the few seconds/minutes before an anode effect, and cause the control computer to launch an anode quench procedure before the actual anode effect had occurred. The algorithm operates on the magnetic field data and is a hybrid of two “sub-algorithms”. One sub-algorithm compares short-term current averages (represented by their magnetic fields) with long-term ones to detect rapidly changing currents in the presence of measurement noise. The second subsidiary algorithm uses as its basis the maximum values of the anode currents or the magnetic fields representing those currents; it compares those maxima over a recent period to those over a prior period.

Implementation of this process control has been improved over the six months since December. Consequently, three periods are distinguished in the results below:
Before implementation of control: September 1st 2015 – December 10th, 2015.
First period under control: December 17th – March 31st, 2016,
Improved period of control: April 1st – June 13th, 2016.

The results were subjected to an Anova analysis comparing the two test cells to six reference cells that were similar to the test cells but operated without benefit of the anode effect control. Figure 6 shows the anode effect frequency for test and reference cells normalized to the potline average. The effect of the preventive control is statistically significant. While both the test and reference group were a little higher than the potline average at the start (A), the total number of AEs was similar. However, after the implantation of the preventive treatment strategy (B), a decrease by approximately 50 % in the total number of anode effect is observable in the test group. Further improvements applied to the system (C) resulted in an average AE frequency roughly three times lower than the reference group.

It is possible to notice that some optimisation related to process control was simultaneously performed on all the cells during the test. The continuous decrease in the anode effect frequency of the reference group is directly related to these changes in the feeding strategy. However, Figure 6 illustrates that the benefits of such alteration are not as important as the preventive treatment strategy deployed in the test group.

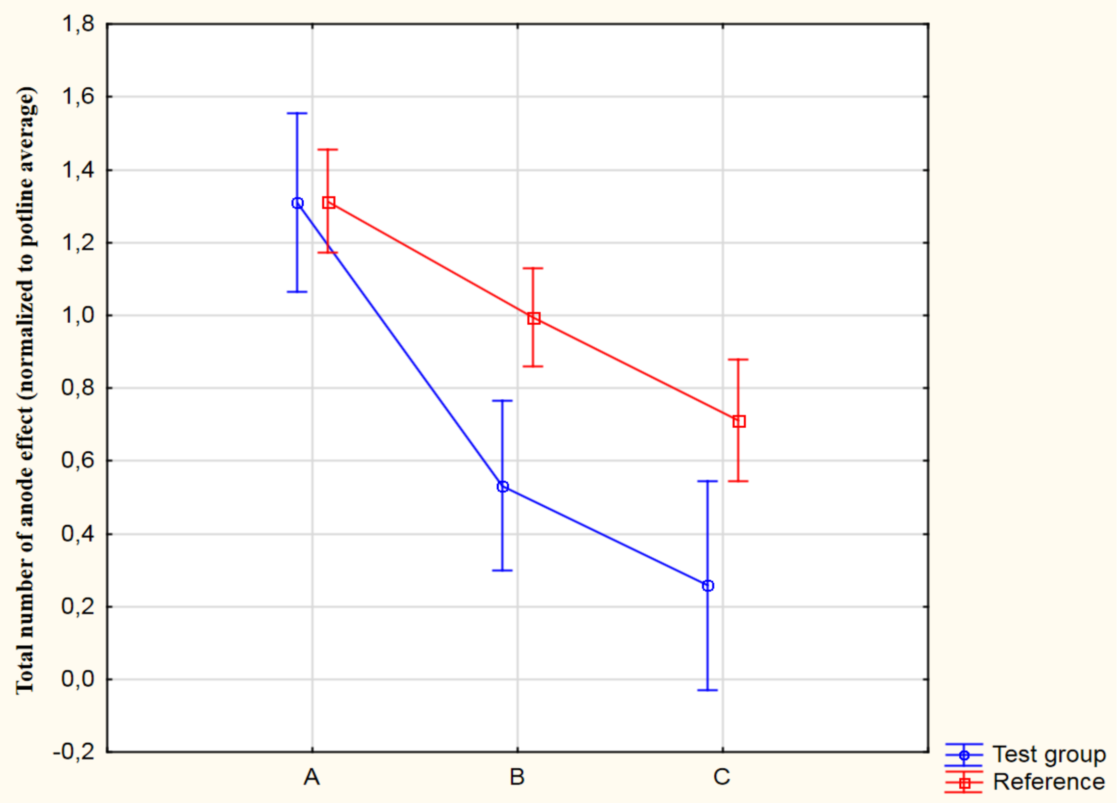

Figure 6. Anova analysis of anode effect frequencies (normalized by potline frequency) for the test and reference group of cells.

Figure 7 illustrates the anode effect overvoltage (AEO) for the test cells compared to the reference cells. In this case, ANOVA analysis was not applicable due to the distribution shape of the data points. However, a continuous decrease in the overvoltage is observable while the reference group remains close to the potline average.

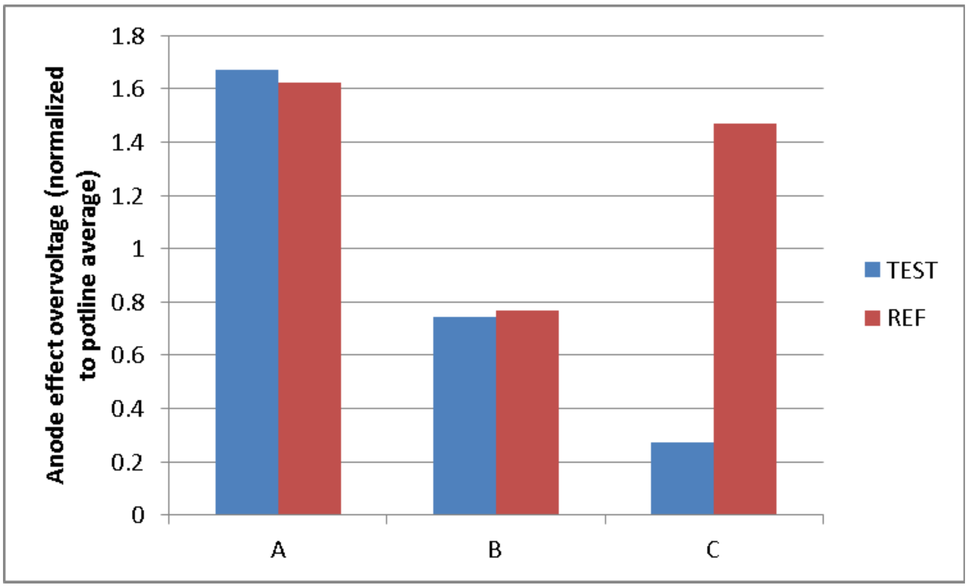

Figure 7. Analysis of anode effect overvoltage (normalized to potline average).

Finally, it was observed that the anode effect mitigation, brought about by using the data from the WIT system, had a beneficial effect on cell stability as shown in Figure 8. In this case, the test cells performed better than the reference cells before implementation of the anode effect control but the difference in performance appears to have been increased by the new control. Under optimal conditions (C), the reference group average instability is still slightly higher than the potline average while the test group average instability has been lowered by 40 %.

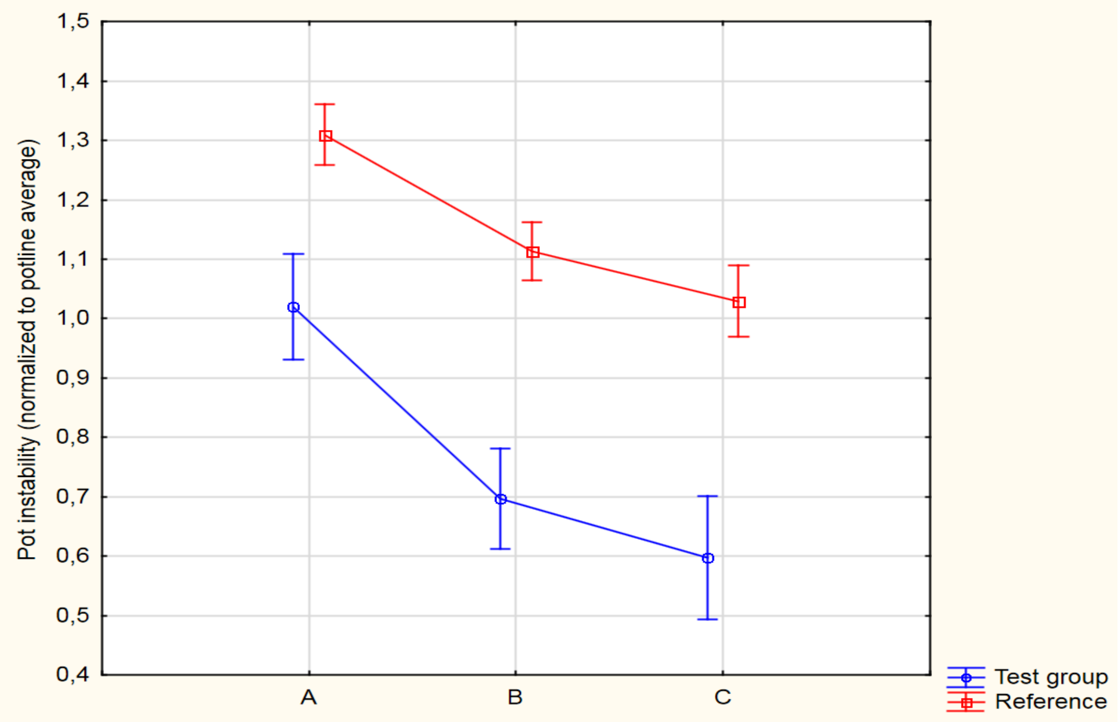

Figure 8. Anova analysis of cell stability (normalized to potline average).

3. Conclusions

The WIT system appears to have been impacted by the tilting of the Hall effect sensors on the printed circuits boards (slaves) supplied by the circuit assembly house. Due to this problem, the correlation between individual anode currents from the WIT system and those measured by a clamp-on meter are not as strong in the field as the verification performed under a controlled environment. However, this has no bearing on early warnings of anode effects but impacts other practical results such as the detection of an anode carrying abnormal currents. Future slaves will come from a different circuit house with a mandate to mount the sensors flat on the circuit boards.

Soon after its installation at Alouette, the WIT system allowed early warning detections for most anode effects by detecting the rapid changes in anode currents, reflected in the magnetic fields produced by those currents. Recently those warnings have been fed to the cell control computer, consequently launching a quenching procedure. The preliminary indications are that anode effect frequency, anode effect overvoltage and cell stability improved with these actions.

4. References

1. Jim Barclay and Joe Rieg, Control electrochemical cell dynamics with electrode current measurements, *Light Metals* 2001, 1219-1224
2. Jeffrey T. Keniry et al., Digital processing of anode current signals: an opportunity for improved cell diagnosis and control. *Light Metals* 2001, 1225-1232.
3. Gary Tarcy and Alton Taberaux, The initiation, propagation and termination of anode effects in Hall-Héroult Cells, *Light Metals* 2011, 329-332
4. Andreas Lützerath, James W. Evans and Ron Victor, On-line monitoring of anode currents: experience at Trimet, *Light Metals* 2014, 739-741
5. Lukas Dion et al., On-line monitoring of individual anode currents to understand and improve the process control at Alouette, *Light Metals 2015*, 723-728.
6. Lukas Dion et al., Using artificial neural network to predict low voltage anode effect PFCs at the duct end of an electrolysis cell, *Light Metals* 2016, 545-550. See also a paper by Dion et al. in the September, 2016, Journal of Metals.
7. Nobuo Urata and James W. Evans, The determination of pot current distribution by measuring magnetic fields, *Light Metals* 2010, 473-478,