Testing cell controller algorithms using a dynamic cell simulator

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The two main tasks of an aluminium reduction cell controller are firstly to collect and process the raw cell amperage and voltage, and then secondly to use that information to manage the cell efficiency. For this it must send instructions both to the point breaker feeder in order to control the dissolved alumina concentration in the bath, and to the anode beam to control the Anode Cathode Distance (ACD).

There is obviously a major advantage to be able to test a modification to the cell controller algorithms using a simulated cell instead of putting real cells at risk. This is true as long as the behaviour of the simulated cell is realistic enough to provide reliable feedback. In order to achieve that goal, the Dyna/Marc cell simulator has been continuously improved since 1994. It has already demonstrated its ability to reproduce measured cell dynamic evolution, as shown in previous publications [1, 2].

Testing cell voltage noise filtration algorithms

Since version 1.0 issued in 1998, the Dyna/Marc has offered the option of adding noise to the amperage and voltage tracks in the simulation. For the cell voltage that noise is an output from the simulation. Thus at the end of each time step noise is added to the calculated noise free-voltage to present disturbances by the bath-metal interface motion and by bubble release. The level of the added noise is function of the ACD, the thickness of the metal pad, the amount of sludge and the fraction of the anode surface covered by frozen bath. This noise level, which can be made to affect current efficiency, can be reduced by automated voltage treatment since version 1.4 issued in 1999.

The cell controller cannot directly use the noisy cell voltage to calculate the slope of the cell resistance, since this would lead to useless results. Since version 13.0 issued in 2011, Dyna/Marc offers linear and quadratic Root Mean Square (RMS) noise filtration algorithms [3]. Fig. 1 shows the comparison between the noise-free and the noisy evolution of the cell pseudo-resistance, which is the slope of the voltage/current curve. The purpose of the noise filtration algorithm is to allow the cell controller to use the noisy data so as to estimate the evolution of the slope of the noise-free curve. This slope can serve to estimate percent dissolved alumina and so to control the feeding rate. Fig. 2 compares the target noise-free slope evolution with three estimates of the slope evolution estimated using three

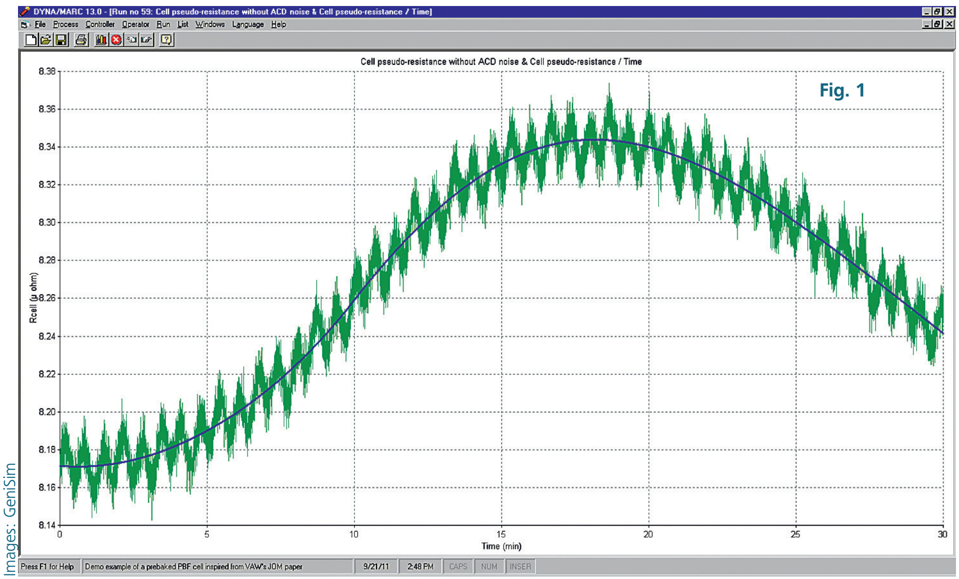


Fig. 1

Images: GeniSim

different mathematical modes of noise filtration applied to Fig. 1.

In Fig. 2 the first curve on the left results from linear RMS fitting using 60 datapoints that are themselves each an averaged value of the raw cell voltage measured over 5 seconds at a 10 Hz frequency. As can be seen, the resulting estimation is still a bit noisy. The second curve in the middle results from using 120 datapoints instead of 60 datapoints. The result is almost noise-free, but now the estimation is lagging 5 minutes behind the noise-free target slope that is being estimated. This is to be expected, as it is the best linear fit of cell voltage evolution using the last 10 minutes of datapoints collected, so it best represents the state of the slope 5 minutes ago. In the example presented in Fig. 2, the slope doubles in 5 minutes during a no-feed observation, so the estimated value is noise-free, but it is about half of the real value. The third mode of filtration on the right of Fig. 2 shows the result of quadratic RMS fitting, also using 120 datapoints. Quadratic RMS fitting of the cell voltage evolution eliminates the drag in the slope estimation, which is important, but for the same number of datapoints used, RMS generates a more noisy estimation.

Testing feed control algorithms

These days, the majority of algorithms used to control alumina feed in aluminium reduction cell are based on continuous tracking or else on underfeeding and overfeeding cycles, where the shift from underfeeding to overfeeding is dictated by a trigger value, which is based on either the slope of the cell pseudo-resistance or the slope of the cell normalised voltage. One of the earliest versions of that algorithm can be found in Fig. 3 [4]. That algorithm is available in Dyna/Marc simulator under the name Pechiney Tracking Feed Control [5].

The basic concept that lead to the development of that algorithm was the observation that the cell current efficiency is maximised by operating very lean in alumina, and so very close to the anode effect conditions. The algorithm then takes advantage of the fact that during underfeeding, the slope of the cell pseudo-resistance starts to rise significantly before the anode affect. Fig. 3 shows the results by running that feed control algorithm in Dyna/Marc. The top graphic shows the 24 hours evolution of the cell pseudo-resistance. Metal is tapped out at noon and anodes are changed at 18 hours. It can be seen that the cell is more noisy after the anode change. The middle graph shows the noise-free evolution of the slope of the cell pseudo-resistance in blue. It also presents the estimated slope evolution that results from using linear RMS fitting with 60 datapoints, each datapoint being the results of 5 seconds cell pseudo-resistance evolution averages. At that time scale, the 2.5

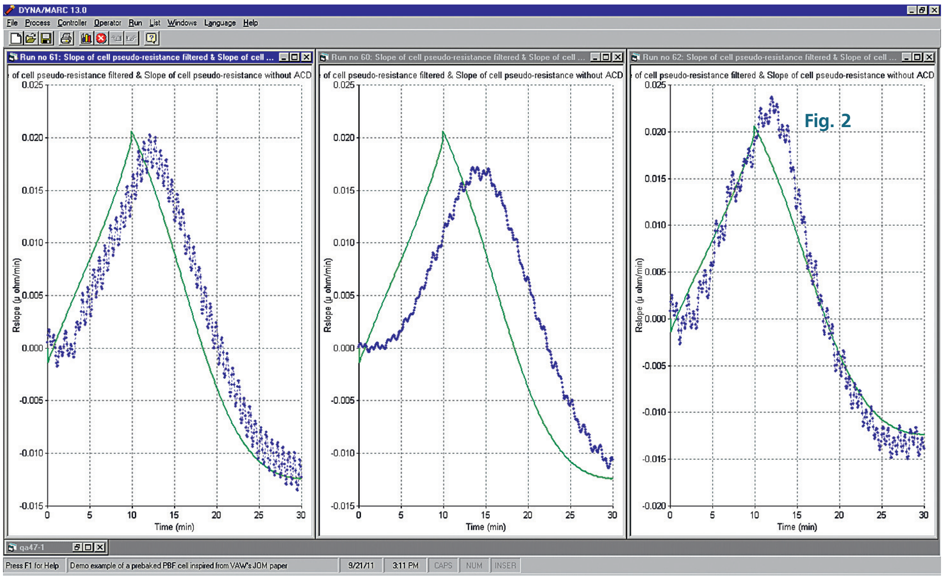


Fig. 2

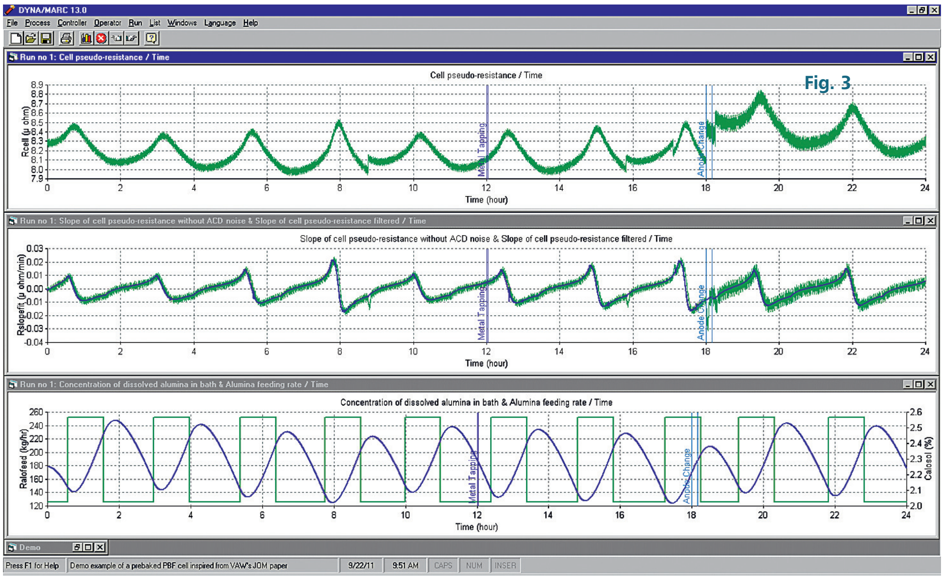


Fig. 3

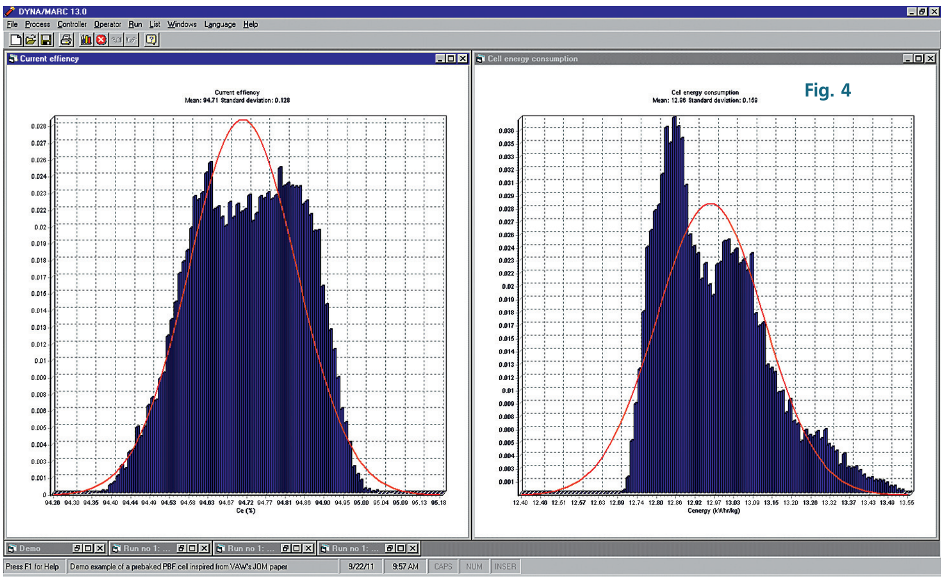
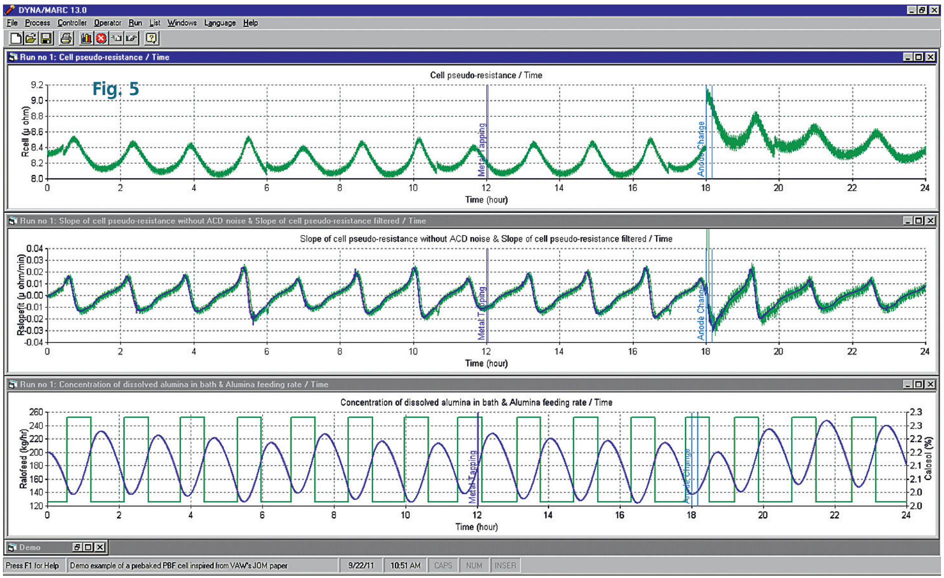
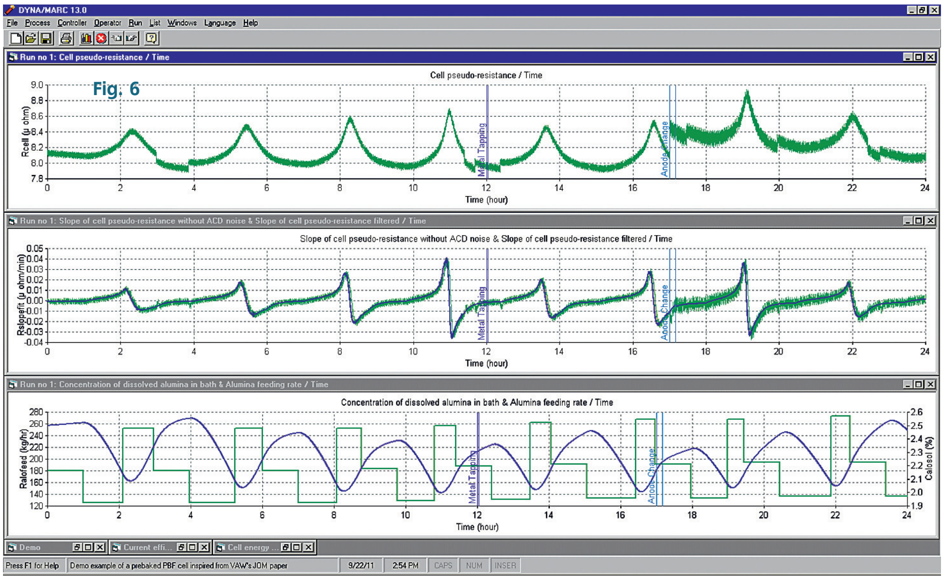
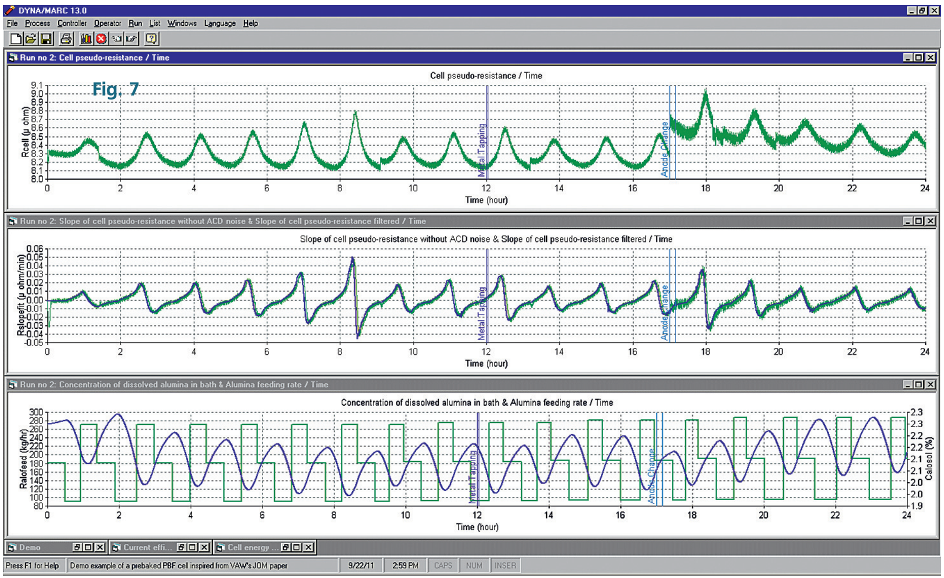


Fig. 4

minutes delay of the noise-free pseudo-resistance evolution compared to the estimated pseudo-resistance evolution is not noticeable, but it does affect the timing of the feeding regime shift. The third, lowest graphic shows the feeding periods resulting from the algorithm decision. The underfeeding rate is 70% of the nominal feeding rate while the overfeeding rate is 140% of the nominal feeding rate. The overfeeding rate duration was set to 1 hour. As a result, the resulting evolution of the dissolved alumina concentration in the bath in the same graph varies from around 2% to around 2.5%, 2% being the alumina concentration that would trigger an anode effect.







It is important to notice when the feeding rate is increased that the alumina concentration continues to decrease by about 0.1% before starting to increase because the alumina takes time to dissolve. That delayed response will trigger an anode effect if the increase in feeding regime is done too late; hence the importance of eliminating as far as possible the delay in the pseudo-resistance slope estimation. Fig. 4 shows the resulting 24-hour averaged specific power consumption and current efficiency: 12.96 kWh/kg and 94.71% respectively.

It is now well recognised that this type of continuous tracking feed control algorithm achieves significantly increased current efficiency over compared with feed control algorithms which used a steady feeding rate most of the time. It is also well known that the shorter feeding cycle also increases current efficiency; this can be tested using the cell simulator. Fig. 5 shows results obtained using a shorter, 40 minutes overfeeding rate duration. As a result, the dissolved alumina concentration only varies from around 2% to around 2.3%. This leads to a predicted improvement of the current efficiency from 94.71% to 94.78%, and a slight increase of the specific power consumption to 13.01 kWh/kg if the ACD is kept constant.

The demand feed control algorithm developed by Kaiser and implemented in Celtrol cell controller [6] is also available in Dyna/Marc. The same reduction of the feeding cycle study presented above can be repeated, this time using the demand feed control algorithm. Fig. 6 presents the base case results: 12.91 kWh/kg and 94.67% current efficiency, while Fig. 7 presents results for the case with shorter feed cycles: 13.09 kWh/kg and 94.65% current efficiency. Despite a very similar increase of the feed cycles and reduction of the range variation of the dissolved alumina concentration, the two algorithms predict different results on the global process efficiency: the current efficiency is hardly affected and the specific power consumption increases more. The reason for these differences is that with Kaiser algorithm, it was not possible to maintain the same average ACD and operating temperature, which both increased for the shorter cycles case.

Developing and testing new feed control algorithms

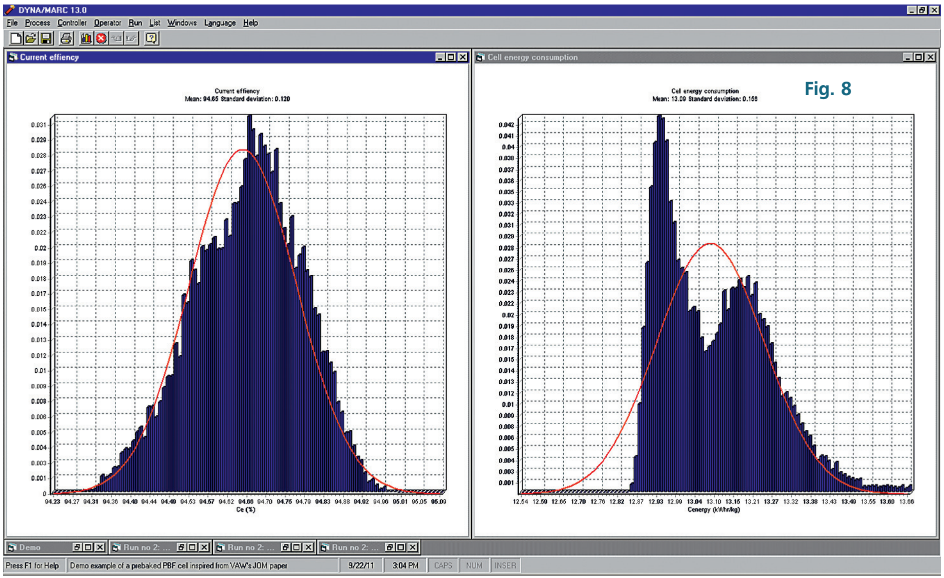
A dynamic cell simulator can be even more useful for developing a completely new feed control algorithm without putting real cells at risk. One such innovative new feed control algorithm was recently tested using Dyna/Marc cell simulator: it is the *in situ* feed control algorithm [3, 7-9].

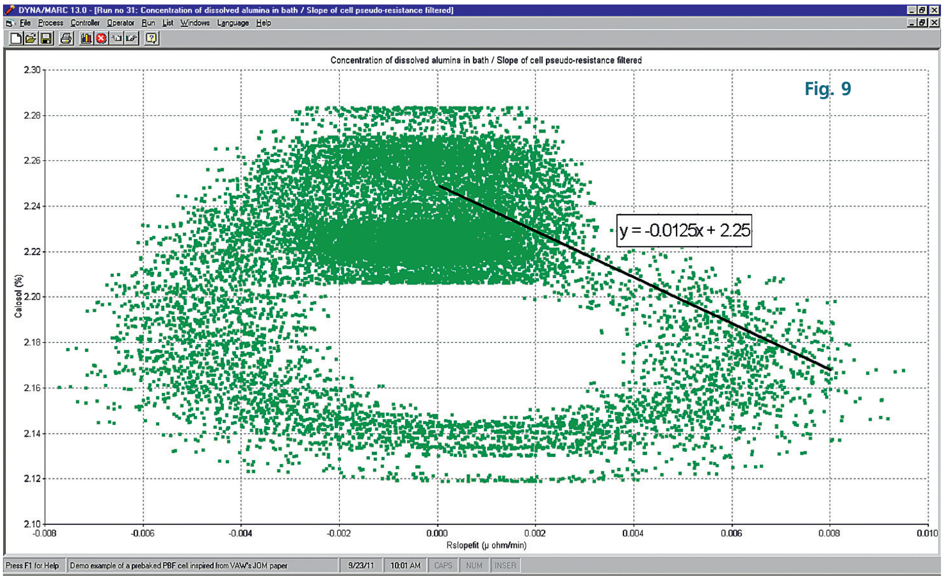
The main innovation of the new *in situ* feed control algorithm is that it can indirectly measure the concentration of dissolved alumina in the bath during a no feed track. It does this by numerically establishing the relationship between the alumina concentration and the slope of the normalised cell voltage. In fact, that correlation is implicitly used in all continuous tracking algorithms that monitor the slope of the pseudo-resistance (or the slope of the normalised cell voltage) to decide when it is time to shift from underfeeding to overfeeding.

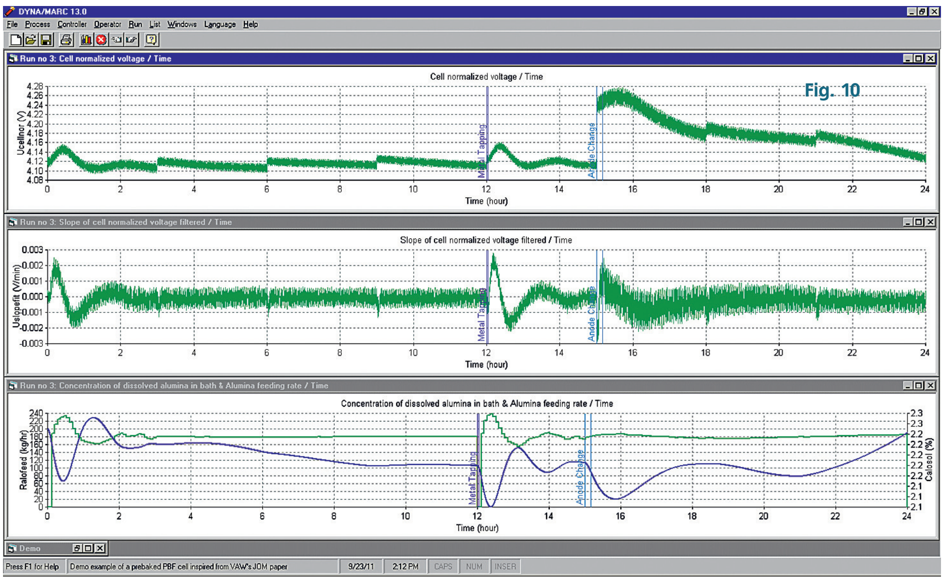
The cell simulator can quite easily verify that there is a unique correlation between the concentration of dissolved alumina in the bath and the slope of the normalised cell voltage, and can numerically establish that unique correlation if it exits. Fig. 8 presents the results by running the *in situ* feed control algorithm in Dyna/Marc for 24 hours. A no feed-track is called every 3 hours in order to evaluate the dissolved alumina concentration. Fig. 9 shows the correlation between the slope of the normalised cell voltage and the falling dissolved alumina concentration. At the top of the hysteresis loop, the black line is the fit of the average path during the tracking, and all 8 tracks follow the same trajectory. This is why the *in situ* feed algorithm can use the equation shown to establish the alumina concentration at the end of each track. So there is a unique correlation, because each track starts from identical conditions, the conditions the *in situ* feed algorithm is trying to maintain.

The second innovation at the core of the *in situ* feed control algorithm is its use of the primary calibration surface [3], at the end of each track, to estimate the ACD after it has estimated the dissolved alumina concentration. Then, based on an estimated evolution rate of the ACD, that same primary calibration surface is used, together with an assumed ACD value, to estimate every 5 minutes the dissolved alumina concentration from the cell normalised voltage. Finally, a simple PID controller serves to maintain the estimated dissolved alumina concentration on its target value. In the example shown in Fig. 8, that target concentration was set to 2.25%.

Fig. 10 presents the results of a second run, calling for a track every 12 hours only, this time with the normal anode change event that was removed in the previous run in order to keep things more simple. The corresponding 24-hour averaged specific power consumption







and current efficiency are: 13.02 kWh/kg and 94.77% respectively. Those results are quite similar to those obtained using the continuous tracking feed control algorithm with shorter cycles, but with far less risk of having anode effects.

Conclusions

The author hopes that this demonstration study highlights the value of using a dynamic cell simulator to optimise existing cell controller algorithms, and to test new ones, without putting real cells at risk. The Dyna/Marc cell simulator used in this study is available to the whole aluminium industry through GeniSim Inc. Version 13 included the linear and quadratic RMS noise filtration algorithms and the *in situ* feed controller algorithm. The Dyna/Marc cell simulator can also be used as a cell design tool, as demonstrated in [10].

References

[1] I. Tabsh and M. Dupuis, 'Process Simulation of Aluminum Reduction Cells', Light Metals 1996, ed. W. Hale (TMS, Warrendale, Pa), 451-457.
[2] M. Dupuis, I. Eick and F. Waldman, 'Modelling Thermal Dynamic Response to a 3-Hour Total Power Shutdown Event', 9th Australasian Aluminium Smelting Technology Conference and Workshops, (2007).
[3] M. Dupuis and M. C. Schneller, 'Testing In Situ Aluminium Cell Control with the Dyna/Marc Cell Simulator', COM, (2011), to be published.
[4] Y. Macaudiere, 'Recent Advances in Process Control of the Potline', Light Metals, 1988, ed. L. G. Boxall (TMS, Warrendale, Pa.), 607-612.
[5] M. Dupuis and H. Côté, Dyna/Marc Version 13 User's Guide, (2011).
[6] K. R. Robilliard and B. Rolofs, 'A Demand Feed Strategy for Aluminium Electrolysis Cells', Light Metals, TMS (1989), 269-273.
[7] M. C. Schneller, '*In Situ* alumina feed control', JOM, 61(2009)11, 26-29.
[8] M. C. Schneller, '*In Situ* aluminum feed control', Light Metals 2010, ed. J. A. Johnson (TMS, Warrendale, Pa), 563-568.
[9] M. C. Schneller, 'A new approach to alumina feed control', ALUMINIUM, 86 (2010) 9, 98-102.
[10] M. Dupuis and V. Bojarevis, 'Retrofit of a 500 kA Cell Design into a 600 kA Cell design', ALUMINIUM 87 (2011) 1-2, 52-55.

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