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CHALLENGES IN POWER MODULATION

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Abstract

Due to the increasing power prices and the increase in the spread between hourly power prices, various European smelters have started implementing power modulation, where amperage is increased during the usually cheaper night hours, while it is lowered during the day. The maximum leverage for power modulation can be achieved by a constant anode-to-cathode distance (ACD) approach. However, this solution has the biggest negative impact on the cell thermal behaviour. Therefore, it is important to evaluate the effects of extreme scenarios, ranging between a "constant ACD" approach and a "constant heat" approach. Typically, reduction cell operations are tuned to near constant amperage, while the cell voltage is being used to adjust the power input into the cells. No matter what modulation approach is chosen, traditional voltage-based control should be replaced by a purely energy-based control. This paper outlines some of the challenges that TRIMET Essen encountered in this process.

Introduction

TRIMET ALUMINIUM AG operates two primary aluminium smelters in Germany. Since December 1st, 2006, TRIMET owns and operates the former HAW smelter in Hamburg. In Essen TRIMET operates a 165,000 tpy smelter with 3 potlines of each 120 Hall-Héroult cells. The smelter was commissioned between 1971 and 1973 and was built using Alussuisse end-to-end prebake technology. Potlines 1 and 2 currently consist of EPT-14 technology, originally built for 140 kA operation. Prior to the take-over by TRIMET in 1994, potline 3 had been completely demolished, but was rebuilt between 1996 and 1998 with EPT-17 technology. Until late 2007, potline 1 has been operating at 162 kA, potline 2 at 165 kA and potline 3 at 175 kA. Current efficiencies above 94% and a specific energy consumption below 14 MWh per tonne of aluminium turned 2007 into a record year.

However, some dark clouds have been gathering over the TRIMET smelters, as they have for various western European smelters. Since the liberalization of the energy market, which started in 1998, Germany has seen a steady increase in energy prices. On the European Energy Exchange (EEX), energy is traded on an hourly basis and typically there is a clear spread between day and night hours[1]. This spread is mainly driven by consumption pattern today. As Germany has decided to phase-out its nuclear power plants, which currently generate approximately one third of the total energy and almost half of the baseload energy, the spread might even increase in the future due to the reduction in baseload power generation. On average during the summer of 2008, the difference between the cheapest and the most expensive hour reached 80 €/MWh, with a daily average price of 67 €/MWh.

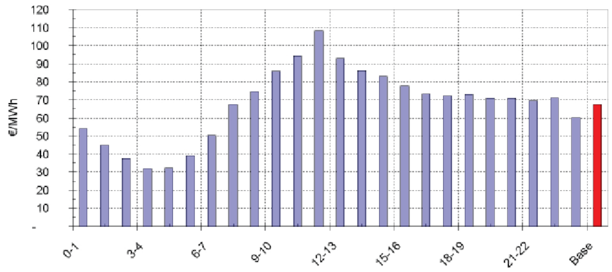

Figure 1: Price profile on the EEX (Jun. 1st – Aug. 20th 2008).

With the escalating power prices, affected smelters are forced to look at alternative operational strategies to maximize profitability. Whereas typically, maximum profitability of a smelter is reached by a minimum specific energy consumption, the driving forces for these smelter are different. Maximum profitability can only be reached if the power consumption can be reduced during peak periods and increased during off-peak periods. In the past, various smelters have reported partial shutdowns and/or power reductions during peak periods, but these were typically due to non-availability of energy at certain hours[2]. Now some European smelters have started implementing operational strategies to modulate their power consumption based on the hourly power prices[3]. Having a baseload power contract, even to competitive prices, cannot protect a smelter from these considerations as long as the power purchased under that agreement is tradable. This was shown in its most extreme form by the smelter shutdowns in the Pacific Northwest of the USA during the Californian energy crisis in 2000-2001.

TRIMET has also been focusing on using the energy exchange, not only to maximize profitability, but also to ensure long-term survival under these harsh conditions. Operating potlines at variable amperages, poses some mighty challenges, as the modulation is likely to deteriorate the smelter's performance. However, measures can be taken to minimize the negative effects and keep running at high efficiencies – if not the very best ones possible. This paper will outline some of the major challenges encountered while doing power modulation.

Power Modulation

Power modulation is by no means a new idea. In 1992, Alcanbrasil reported wide-scale power modulation at their Aratu and Ouro Preto smelters[4]. In general, power modulation can be done in various ways:

- a complete line shutdown;
- putting cells to sleep;
- line amperage modulation.

Line Shutdown

Every smelter will have experience with compelte shutdowns for short periods, either for cutting cells in and out or by unintentional actions or rectifier failures. It is a viable option to overcome short periods with extremely high power costs, but the time frame is very short. Stam and Schaafsma reported that based on experience the maximum time for their cell, a 140 kA end-to-end technology, to have no current should be 2 hours for manageable, repeatable current interruptions[3]. This limited shutdown period is due to the heat loss incurred due to the complete loss of power to the cell.

A total shutdown event, which occurred at the now idled VAW Töging smelter in Germany, was retrospectively modelled by Dupuis et al[5]. A 3 hour shutdown of a 240 kA potline was preceeded by 4 hours of "pre-heating" and followed by 8 hours of "re-heating". They point out that during the shutdown no more power is generated within the cell, but that heat convection on the outside remains almost unchanged, causing rapid cooling. Furthermore, major changes in the heat transfer to the ledge occur, due to the flattened metal pad. Zones with high heat transfer during normal operation changed to become zones with low heat transfer. This typically happens in the middle of the side and end walls. In the cell corners the opposite happens: previously zones with low heat transfer, the local heat transfer increases after the shutdown.

Sleeping Cells

The practice of putting cells to "sleep" was also successfully put into practice by Aluminium Delfzijl and was devised as an adaptive strategy which allows major energy reductions to be made over a longer period of time[3]. The strategy involved reducing the current from approximately 140 kA to 100 kA with appropriate voltage compensation on two thirds of the pots while the remaining one third of the pots had a voltage reduction down to 3 Volt. The goal for the sleeping cells was to lower the current efficiency to close to zero to ensure that the energy input into the cell was only used for heat generation to prevent excessive cooling during the modulation periods. Reduction of the voltage to 3 Volt for one third of the cells allowed the voltage in the remaining cells to be increased while keeping to the energy reduction targets.

Amperage Modulation

The third option, which is more widely used and reported as in the cases of the brazilian smelters, is the reduction in the line current by a predetermined value during the peak power periods. This method of power modulation allows greater flexibility, because the modulation period can be longer than that of a complete line shutdown.

First trials at the Alcanbrasil smelters had started as early as 1987 and were based on the experience of Nippon Light Metals at their Kambara smelter. The story is surprisingly similar to today's story in Western-Europe: after the implementation of a variable tariff in Brazil, power prices during peak hours sky-rocketed and forced the smelters to reduce their power consumption in some potlines by up to 30% during 3 hours each working day. Two ways of modulating were reported: one line was operated with lower amperage during peak hours and a higher amperage during the off-peak hours to compensate for the reduced heat input. Another potline was operated with voltage compensation during the low amperage periods. In both cases, reportedly no loss in current efficiency occurred, with only small production losses due to lower average amperages[4].

Another smelter with long term experience with power modulation is the brazilian Valesul smelter[6]. Starting in 1985, after the introduction of the variable power tariff, the 160 kA prebake potline was modulated by 4%. However, as the LME prices came down dramatically, in 1993 power modulation was increased to approximately 50%.

Other brazilian smelters that have reported some forms of power modulation are Albras[2], during the 2001 energy crisis in Brazil and Poços de Caldas, after a rectifier crash in 2003[7]. Also Hydro's Karmøy plant was forced to significantly reduced its power consumption during the winter of 2002/2003 for a four month period, due to the low water levels in the lakes of the hydro power stations[8]. In their paper discussing smelter economics, Richards and Forberg refer to Alcoa's Eastalco smelter using a strategy called "Peak Shaving" in order to avoid extreme power prices during some peak hours[9]. The energy deficit was always compensated within 24 hours, either by increasing the heat input before the peak period or by catching up.

The only alternative to power modulation is to shutdown a number of cells completely, but this is costly, more permanent and makes a smelter less flexible to use cheap hours. New Zealand's Tiwai Point smelter has been regularly reporting partial shutdowns for the last years, due to energy shortages. A 5% deviation from the cell heat balance was given as an indication of when to start taking cells out of circuit[10]. Ultimately, the most economic way of dealing with power shortages and/or excessive power prices will depend on each smelter's strategy and what kind of performances it can achieve using power modulation. Negative effects on current efficiency, energy consumption, anode effect frequency and cell life have to minimized, but have to be taken into the equation.

Considerations with Amperage Modulation

Two extreme cases of amperage modulation can be distinguished:

1.- In the first case, no voltage adjustments are made during the low amperage phase. Essentially, the anode-to-cathode distance (ACD) is kept constant and the voltage is allowed to float with the amperage. This scenario has the strongest economic effect, as the reduction in power is the largest, but it also has the most severe effect on the cell heat balance. As the cell will start to cool, ACD adjustments will be made by the cell control system.

2.- On the other side of the spectrum is the "constant heat balance" scenario. In this case, the reduced heat input due to the lower amperage is compensated by a voltage increase. This scenario has the least impact on the cells, as the cell is kept in heat balance. The main difference between the low and the high amperage period will arise from the changes in the magnetic field and its consequences on the metal pad heave.

Of course all variations in between the two cases are possible, whereby part of the heat deficit is compensated by voltage. Determining which scenario gives the best economic result will depend on the actual price profile on the power exchange and on what is considered manageable by the smelter. For judging this, a clear understanding of the impact on the cell performance and cell operations is needed.

Bath & Liquidus Temperature

Cyclic changes in the line current will create greater fluctuations to bath and liquidus temperatures in the cell. During periods of current decrease, bath temperature and superheat will drop, resulting in the bath freezing as either side ledge or as ridge or sludge on the cathode surface.

The degree of cooling is a direct function of the change in energy input into the cell. Figure 2 shows a typical cooling curve for a TRIMET EPT-14 cell undergoing a 20 kA reduction (167 kA to 147 kA), with a 200 mV voltage compensation for a 24 hour period. It was found that cooling was linear in respect to time (Figure 3) and over 24 hours the average decrease in temperature was found to be 17.3°C with a range of 13.5 to 20.7°C. This equates to an average cooling rate of 0.0046°C/kWh. This rate is of notable importance when making adjustments to the control system inputs; this however will be discussed a later section.

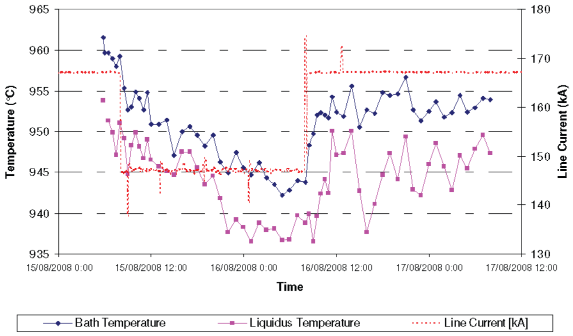

Figure 2: Typical cooling curve for an EPT-14 cell undergoing 20 kA reduction for 24 hours with 200 mV voltage compensation.

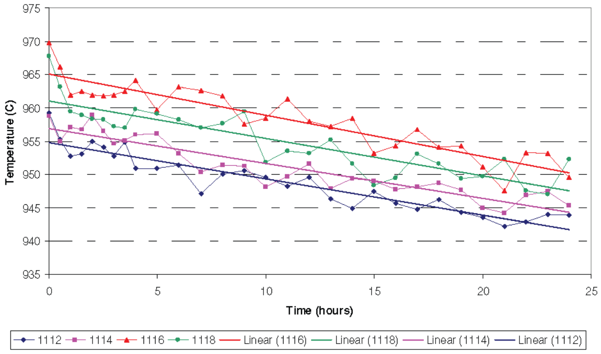

Figure 3: Linear decrease in temperature for an EPT-14 cells undergoing 20 kA reduction for 24 hours with 200 mV voltage compensation.

The actual decrease in the bath cooling and heating can be regulated by voltage compensation during the cooling periods. However, the degree of compensation will need to be such to still ensure target energy savings are still achieved. Increases in current and/or voltage in off-peaks times are also means for reducing the impact of cooling in low current periods. This strategy will result in surplus energy input to the cells in cheap power periods, increasing the cell temperature and thus creating an energy buffer before the cooling period.

Ledge Dynamics

A reduction in heat generation and subsequent bath temperature reduction due to current decrease will naturally cause the bath to freeze. Most likely this will result in either an increase in the thickness of the side ledge or the formation of freeze or ridge on the cathode surface. The build up of ledge and bottom freeze essentially reduces the volume in the cell which the metal and bath can occupy, thus causing the bath and metal heights to increase. Dramatic changes in bath height can be problematic as it can lead to stub wash which can result in poor metal quality.

The formation of ledge can have considerable effects on the bath volume, height and chemistry. Figure 4 shows the typical reduction in the bath mass over time for the same cell and conditions shown in Figure 2. It was found that on average 787 kg of bath would freeze over the 24 hour period. In these trials it was most likely that the majority of the freeze was in the form of side ledge as there did not seem to be any increase in noise as one would expect if significant bottom freezing was taking place.

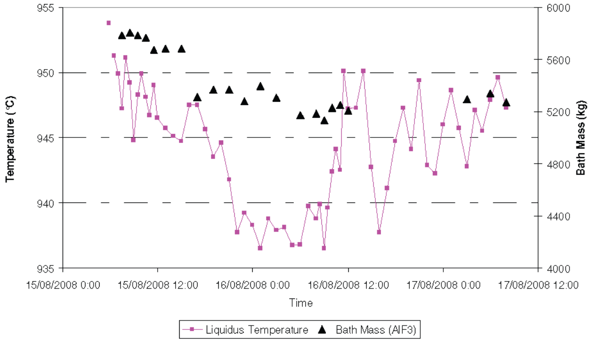

Figure 4: Typical bath mass curve for an EPT-14 cell undergoing 20 kA reduction for 24 hours with 200 mV voltage compensation.

Of more significant interest was the recovery of the cells once the 20 kA was re-established (going back to 167 kA from 147 kA). For all cells the rate of freezing was much higher than the rate of melting. The mass melted back into the bath 24 hours after re-establishing the current was found on average to be only 305 kg. This is much lower than the mass originally frozen. These results indicate that continual cycling of the current could lead to a continual build up of ledge on the sidewall and the cathode which could affect current distribution and alumina dissolution in the long term.

Although the melting rate was found to be slower than the freezing rate in the above mentioned example, current increases on cells running at steady state showed a much faster rate of melting. Figure 5 and 6 show the temperature and bath mass increase for a 10 kA increase for 10 hours. The results essentially show the reverse dynamics to what was observed in the previous example with the rate of melting in this case being faster than the rate of freezing. These results indicate that the rate of melting and freezing is a function of recent modulation history, with it seeming there is a lag in the cells response to the turn around between modulation periods.

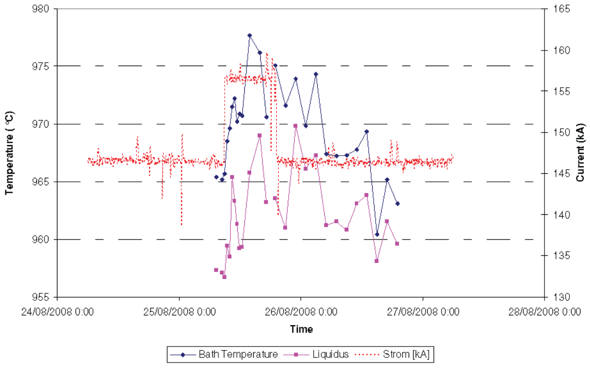

Figure 5: Bath and liquidus temperature for a cell undergoing 10 kA increase for 10 hours

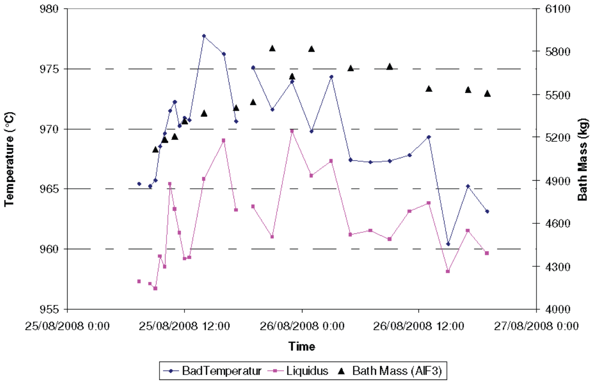

Figure 6: Temperature and bath mass for a cell undergoing a 10 kA increase for 10 hours.

Trials conducted at TRIMET Essen showed limited change in bath height over time, indicating that its control was not a large concern under the current modulation strategies employed and trialed.

Bath Chemistry

Cryolite is the dominate constituent of ledge and therefore freezing will result in increasing excess AlF_3 levels in the bath which will then in turn result in decreasing liquidus temperatures. Figure 7 highlights the increasing bath acidity as the freezing of cryolite takes place. This leads to an increasing bath resistivity and to a lower alumina solubility. The results above correlate well with the decreasing bath mass and show that the recovery of bath chemistry is also much slower than expected. This is a direct function of the freezing and melting dynamics of the cell.

This resistance increase is due to a coupling between the decrease in the bath conductivity due to the increasing excess AlF_3 content and also the possible deposition of sludge on the surface of the cathode. The risk of sludge formation is increased due to the lower superheat, the lower bath volume, as well as the increasing acidity of the bath. In significant cooling periods care should be taken with the limits imposed by the resistance control bands. Upper control bands should be increased to accommodate the resistance increase due to due to cooling. The effect of the bath cooling, resulting in chemistry changes and subsequent changes in the bath resistivity is shown in Figure 8.

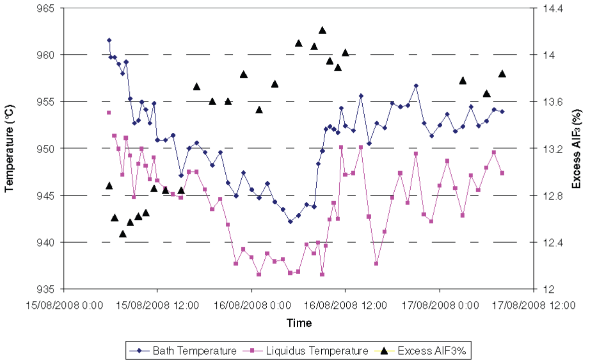

Figure 7: Typical bath mass curve for an EPT-14 cell undergoing 20 kA reduction for 24 hours with 200 mV voltage compensation.

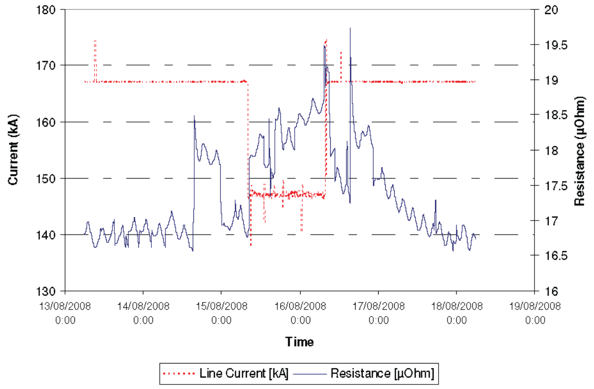

Figure 8: Resistance trace for an EPT-14 cell undergoing 20 kA reduction for 24 hours with 200 mV voltage compensation.

Alumina Feeding & Anode Effect Frequency

Alumina feed should be adjusted to reduce the chance of sludging and anode effects in the cell when changing between line current levels. In most cases it is ideal practice to reduce the nominal feed in the cell in accordance with the reduction in the current.

Further consideration will also have to be made to adjusting the feeding pattern to compensate for the reduced superheat, bath temperature and bath volume in the cell. These three effects are due to the bath cooling and all will hinder the dissolution of alumina. If feeding patterns are not adjusted accordingly, sludge levels will increase and can result in instability. Care should also be taken into monitoring the deposition of permanent crystalline alpha alumina on the surface of the cathode, which is difficult to dissolve and will grow over time. Growth of this layer will decrease cathode performance.

Figure 9 shows the results of trials on EPT-14 cells at TRIMET. In these trials the feed was adjusted solely for changes in current with no additional compensation for superheat etc. The data shows that long under feed times were often found when the cell superheat was below 5°C. This was likely due to back feeding due to sludge formation. This is consistent with theory as superheat is one of the forces driving alumina dissolution in the cell. Figure 8 shows that there is a significant decrease in the superheat of the cell directly after current is reduced. In this period it is critical to ensure accurate feeding rates and sufficient superheat to ensure limited degrees of sludging. More work will be needed in this area to reduce the chance of sludging.

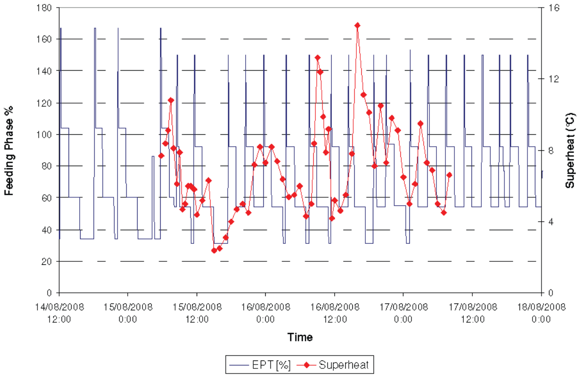

Figure 9: Feeding pattern and superheat for an EPT-14 cell undergoing 20 kA reduction for 24 hours with 200 mV voltage compensation.

Although anode effects can occur during low current modulation periods due to inadequate feeding and dissolution problems due to the cell cooling. It has been found that more concern is placed on the period just after power modulation when current is restored. Both Valesul and Alcoa reported increases in anode effect frequency (in some cases 5-10x greater) directly after the modulation periods[6, 9]. This is due to inadequate bath temperature, superheat and bath volume which all results in lower alumina solubility. This in conjunction with increased current will increase anode effects frequency. Anode effects after low current power modulation periods are undesirable as they consume a considerable amount of energy that is required to be used to heat up the cell and melt the ledge. Trials at TRIMET Essen to date have not resulted in a dramatic increase in anode effects directly after the restoration of current as those seen by others. Only in some cases anode effects have been observed, however their frequency has not led to considerable concern.

Effect on Cell Operations

Operations that will have significant impacts on the heat balance of the cell should be kept to the absolute minimum in low current periods. These mainly include anode changing and metal tapping. Both these practices cause significant heat loss from the cell which will accelerate the cooling effect that will already exist in the power modulation period. Figure 10 shows the effect of an anode change during a low current modulation period. In this case, cells showed a significant sudden change in temperature with the decrease in the range of 8 to 12°C. Ideally operations should be moved to times well clear of the modulation periods however, distribution of operations in the ideal way will depend on the actual modulation profile and how often the profile changes.

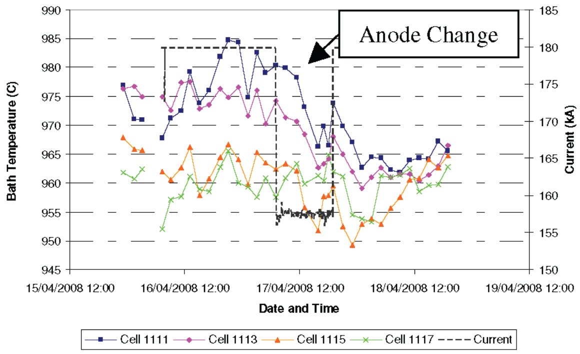

Figure 10: Effect of anode change during a 12 hour, 22.5 kA reduction power modulation

Dealing with Power Modulation

As was shown in the previous chapter, power modulation requires a different approach to cell control. Traditionally, control systems implicitly or explicitly assume (near) constant amperage and variable voltage to adjust the power input into to cell. Measurements usually are taken according to set schedules, which distribute the measurements in such a way as to best reflect the general state of the cell. When large amperage swings are made, a voltage-based control is no longer viable, as it will react to false triggers. Therefore a purely energy-based control is needed.

TRIMET Essen uses the Alusuisse Alesa "Blue Box" control system with the so-called "9-Box" model for heat and mass balance control[11]. At the core of the 9-Box model is the superheat measurement. Various trials at TRIMET showed that there are a number of areas in both the Blue Box and the 9-Box control system that require modification and automation.

One of the problems highlighted was the need for new procedures to deal with line current changes. As shown by Figure 11, large voltage swings occurred when current was lowered and raised, because the standard practice of making parameter changes (line current set point and voltage set points). Especially the reaction after increasing the current had a strong impact: the cell voltage spiked more than 400 mV above the target voltage and decreased in small steps, leading to a much higher energy input than desired. Ideally, after making large amperage steps, the control system should be allowed to have faster beam movements, similar to those that are typical during and after metal tapping. However, a small change in the manual sequence of changing these set points reduced the problem to an acceptable level (Figure 12) for the time being.

The changing amperage also posed problems for the 9-Box, as it does not account for this. As the cells are going through continuous cycles of heating and cooling – much stronger than usual, depending on the way of modulating – the system might act on temperatures that poorly reflect the average operational state of the cells. For example, a bath temperature of 980ºC might be perfectly natural at the end of a high-amperage period, especially if the "ACD-constant" scenario was used. Without proper information the 9-Box might act with increased AlF_3 addition and/or ACD squeezing. Therefore, rather than assuming constant amperage and then adjusting voltage based on measurement, the thermal regulation of the cells should be based on an "energy counter" that keeps track of the expected state of the cell. The modulation history needs to be taken into account for this and accurate knowledge about the cell dynamics are a prerequiste to develop such a modulation module.

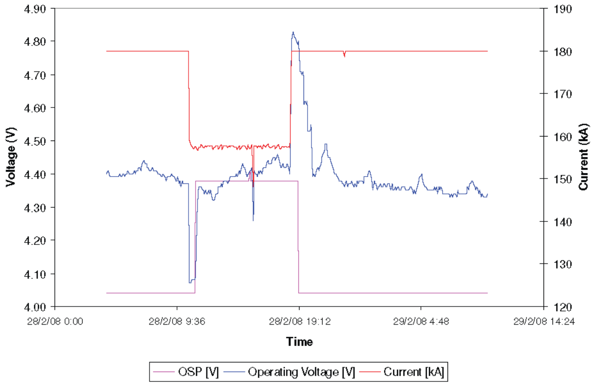

Figure 11: Large voltage swings due to incorrect parameter changing procedures during current transitions.

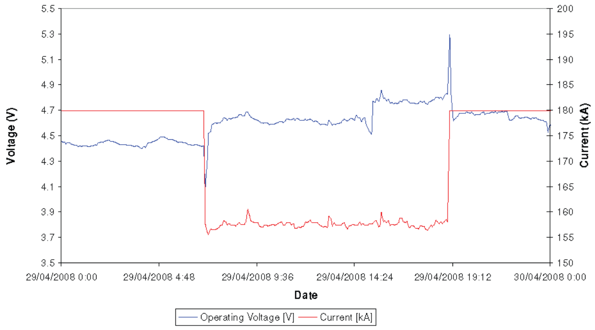

Figure 12: Voltage trace with corrected parameter changing procedures during current transitions.

Other measurements that might be strongly clouded by power modulation are all voltage measurements. As measurements like clamp drops, stub-to-carbon drops and cathode voltage drops are all ohmic, all these measurements need time stamps in order to be put into context. Operators that measure for example anodic current distributions based on voltage drops will need to be trained accordingly.

Outlook for TRIMET Essen

Currently, TRIMET Essen is operating two potlines routinely on a day/night rhythm power modulation strategy. However, as the smelter is building its toolbox for various scenarios it is now operating a small group of trial cells with a more aggresive modulation strategy involving multiple changes in amperage per day (Figure 13).

Furthermore, TRIMET Essen and the Light Metals Research Centre are working towards developing a power modulation module for the control system. This module will not only automate many of the parameter changes that to date have to be done manually, but which will also include an energy-based approach will allow a range of modulation scenarios. Only this way the smelter will be flexible enough to maximize the benefits from power modulation, while minimizing the negative impact it might have.

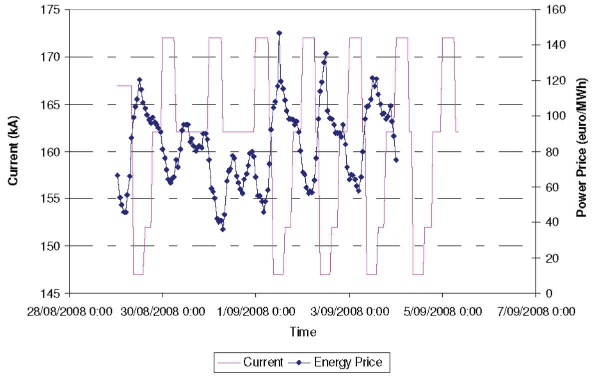

Figure 13: Multiple daily current change strategy based on hourly power price

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