

## Potline Open Circuit Auto-Adaptive Protection

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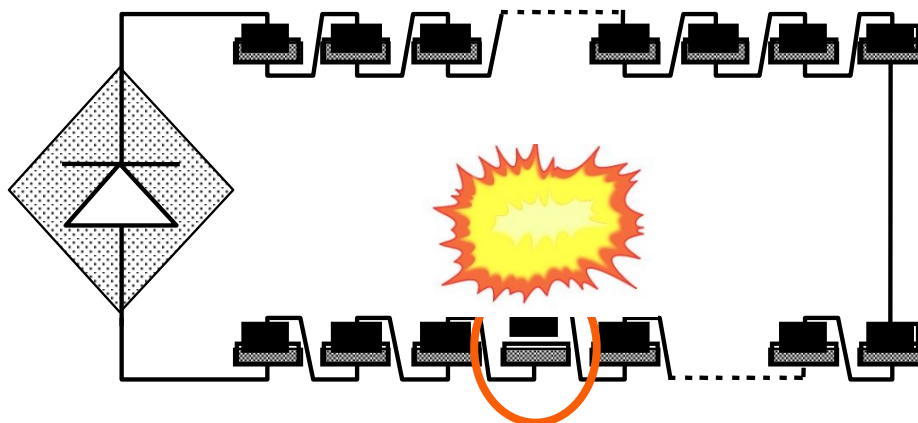
### Abstract

An open circuit event in a potline is always a catastrophic danger, resulting in a high power arcing which feeds itself until the current is cut, degenerating into blast destroying all that is in its vicinity. The consequence can be as bad as freezing the potline. Reducing the risk consists in preventing the occurrence by following the basic rules and best practices during potline operation and maintenance. It consists also in reducing the consequences. Triggering line current tripping by quickly detecting the event is more effective than pushing an emergency-stop or calling the power plant. The protection system settings must be fine-tuned according to the operating conditions of the potline (number of running pots and associated status – normal operation, preheating, starting, ongoing anode effect – number of stopped pots, potline status and set point) and to the conditions of the power contract if any: load shedding, frequency-dependent load adjustment, generating high magnitude of the current variation. At least this last condition requires the settings to be changed frequently and on real-time basis. The theoretical and practical aspects of the open circuit are presented as well as the new auto adaptive protection developed and deployed in Rio Tinto aluminium smelters.

**Keywords:** potline open circuit, open circuit protection, auto-adaptive open circuit protection.

### 1. Introduction

Figure 1 shows the potline circuit. It includes the rectifying units, pots and busbars. As soon as the live potline circuit accidentally begins to open an arc appears in the air gap.



**Figure 1. Potline circuit scheme showing the presence of an open circuit.**

Figure 2 shows the characteristics of a direct current (DC) arc. Air is ionized by pioneer electrons and the resulting plasma allows the current to flow. The expansion of the plasma gas

creates a pressure. The heat and intense light at the point of the arc is called arc flash. Conductive vapors help sustain the arc. The plasma gas is typically directed outward. The power of the arc depends on the current but depends also on the arcing voltage. The arcing voltage has a fixed part, about a few tens of volts, which can be assimilated to a back electromotive force. But, the higher is the arc length, the higher is the arcing voltage, about 80 volts per centimeter. So the arc is extremely powerful. The temperature of the plasma gas is extremely high also: about 15 000 °C at the origin and still 3 000 to 5 000 °C at working distance.

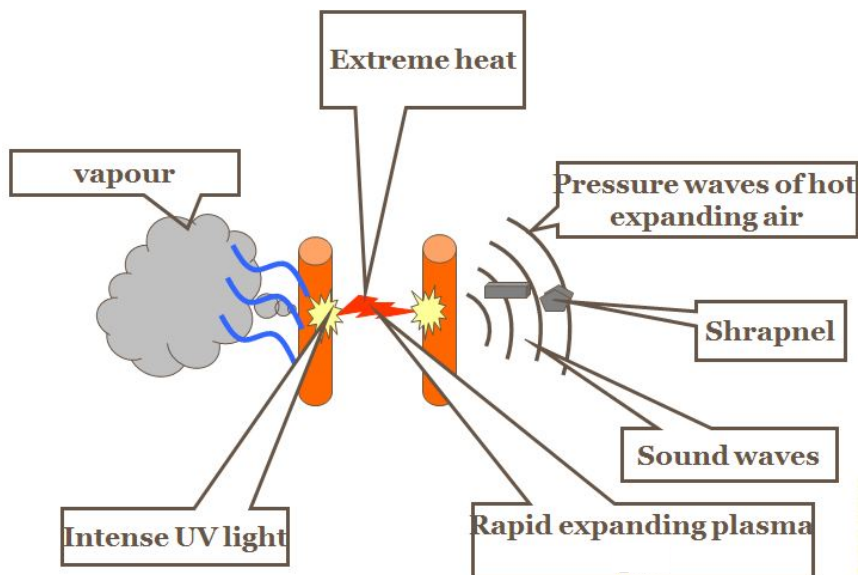


Figure 2. The typical characteristics of a DC arc.

From a safety perspective, such incidents result in very serious situations. In case of manned operation in the vicinity of the incident, the operator can suffer serious burns, damaged eyesight, escalating in some cases to serious injuries or death. The arc blast causes liquid aluminium and pieces to be ejected, equipment to explode. Equipment can be destroyed requiring expensive replacement and repair and causing extensive downtime. If the damaged busbar circuit cannot be repaired and the DC amperage cannot be restored quickly enough, the entire potline can freeze.

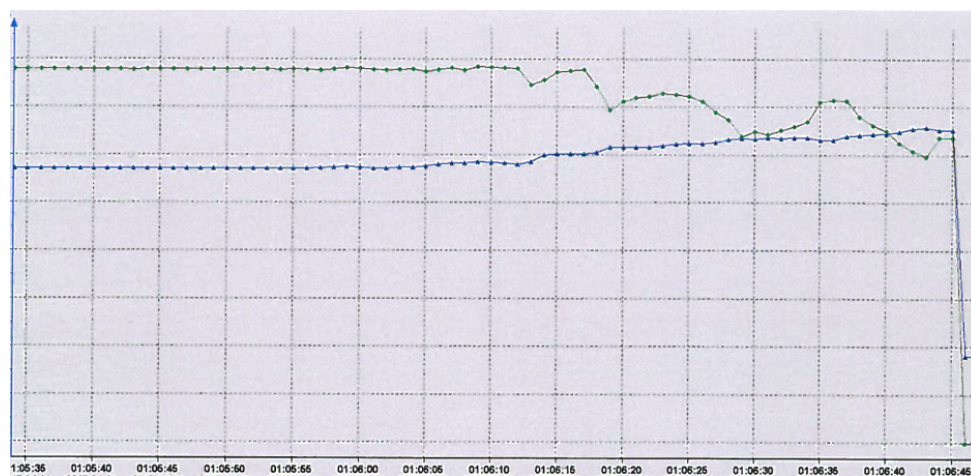


Figure 3. An example of the electrical characteristic of a beginning of open circuit. Green line is potline amperage, blue line is potline voltage.

Figure 3 shows a detailed example of the electrical characteristic of a beginning of an open circuit in its right part. This beginning of open circuit was due to multiple anode clad failures on one pot. The potline voltage (blue line) increased highly while the potline current (green line) decreased a lot. The potline voltage rise in that case was about 150 V before the protection system tripped the potline current while the potline current drop was about 70 kA, about 40 seconds after the beginning of the issue. During this time lap, while the potline voltage increased continuously, the potline current decreased by forming slow oscillations. The potline current rises during those oscillations were caused by the regulation system acting on the tap changers of the regulating transformers of the diode conversion substation. In that case, the open circuit led to the freezing of 80 % of the potline - a catastrophic incident.

A beginning of an open circuit can take much less than a few tens of seconds. The same levels of voltage rise and current drop were observed during a wedge failure but within 10 seconds. In those cases, the first expression of the open circuit was relative to the rise of the resistance of the overheating metal parts and/or the loss of conductors in parallel. The electric arc appeared later after the overheating metal parts had been melted. In other cases, due to other causes, the electric arc appears immediately so that the same levels of voltage rise and current drop are observed within a few seconds.

## 2. Risk Mitigation

In DC this high power arc cannot extinguish itself unless the rectifying units are tripped. Duval et al. [1] showed the inefficiency of the traditional protection systems despite the high power developing in the electric arc. The last resort to mitigate the consequences consists of pushing the emergency stop button or calling the power plant in order to trip the rectifiers. This happens usually when the arcing is taking place for a while. This cannot be considered as an efficient protection to minimize the damages.

The prevention of the causes avoids the occurrence of an open circuit. The main causes that can generate an open circuit are due to the pot (even if it has already happened that a busbar melted because it had been buried beneath a heap of mixed alumina and bath), and there are usually more than 300 pots in a potline. One can list many pot events leading potentially to open circuit situation:

- The tap out, which is the leakage of molten metal (these are among most frequent causes),
- During tapping, anodes could come out of bath by decreasing metal level (this is also one of the most frequent causes),
- During anode beam rising, anodes could also come out of bath.
- Separation of the anode blocks from anode rods (anode clad failures),
- Melting of the pot busbar through contact with molten bath or metal,
- Breaking of all the connections between collectors bars and cathode flexes,
- Failure of the short-circuit pot shutdown wedges,
- An incorrect operation during pot start-up or pot restart,
- A maintenance mistake while fixing pot electrical equipment with a wrong connection of the jacking motor or contactor, for example,
- Etc.

At the first stage, before the open circuit effectively appears, the risk of getting to an open circuit can be reduced by following the basic rules such as good operational practices (as for instance “Think before acting”, the follow-up of sick pots and adequate equipment maintenance), procedures and training.

The last barrier before the open circuit consists of a specific open circuit protection system. The system automatically trips the AC supply of the rectifying units when an open circuit is detected. This detection system is redundant. It monitors potline voltage and current variations.

The expected potline voltage depends on many parameters: the potline current, the number of pots in operation and their expected resistance, the number of pots out of normal operation and their expected resistance (stopped pots, pots in pre-heating ...), the resistances of the busbars, etc. The global representation of the electric scheme of a potline is given in Equation (1).

$$V = E + R_p I \quad (1)$$

where:  $V$  Potline voltage, V  
 $E$  Global back electromotive force (back EMF) of the potline, V  
 $R_p$  Global expected resistance of the potline,  $\Omega$   
 $I$  Potline current, A

The potline current is controlled by a regulation system around a set point. But it can be naturally decreased due to the binding characteristic of the rectifying substation. This one can be represented by Equation (2).

$$V = V_0 - R_s I - V_r \quad (2)$$

where:  $V$  Potline voltage, V  
 $V_0$  Off-load voltage of the rectifying substation on DC side, V  
 $R_s$  Resistance of rectifying substation,  $\Omega$   
 $I$  Potline current, A  
 $V_r$  Reserve voltage in the self-saturating reactors or in the thyristors system, V

$V_0$  is determined by the voltage of the power grid, which is varying around a nominal value, depending on the power grid configuration, and, in diode rectifiers systems, by the position of the tap changer of the regulating transformers of the conversion substation, which depends on the number of pots in operation, the number of rectifying units in operation in parallel and the potline current.

$R_s$  depends only on the number of rectifying units in operation in parallel.

$V_r$  is a fast reserve voltage which is used without delay during anode effect on pots which enables maintaining the potline current around its set point.

In diode rectifiers systems, the maximum value of  $V_r$  is controlled by a regulation system acting on the tap changer of the regulating transformers of the rectifying substation, helping to maintain the reserve voltage around a value fixed by design (in the range of 30 to 60 V) whatever the number of pots in operation. The time constant of this regulation system is deliberately high (several seconds and even a few tens of seconds).

In thyristor rectifiers systems, the maximum value of  $V_r$  depends on the number of pots in operation: In the range of 30 to 60 V for a potline in full operation, in the range of several hundreds of volts for a potline which is in its starting phase.

Figure 4 shows how the DC voltage lines can be represented as a function of the potline DC current and Figure 5 shows the same things but zoomed around the operating point:

- The green line represents the potline normal characteristic described by Equation (1).

- The purple line represents the potline current set point.
- The grey, cyan and dark blue lines represent together the substation electrical characteristic described by Equation (2).
- The dark blue line represents the voltage drop  $V_r$  in the self-saturating reactors (SSR) or in the thyristors system.
- The amber line represents the potline characteristic with a beginning of open circuit consuming the fast reserve voltage in the SSR.
- The dark red line represents the potline characteristic with an open circuit being developed with the result that the current is decreased while the voltage has further increased (which is represented by the cyan line) to such an extent that a significant overvoltage (represented in bright red) needs the system to be tripped.

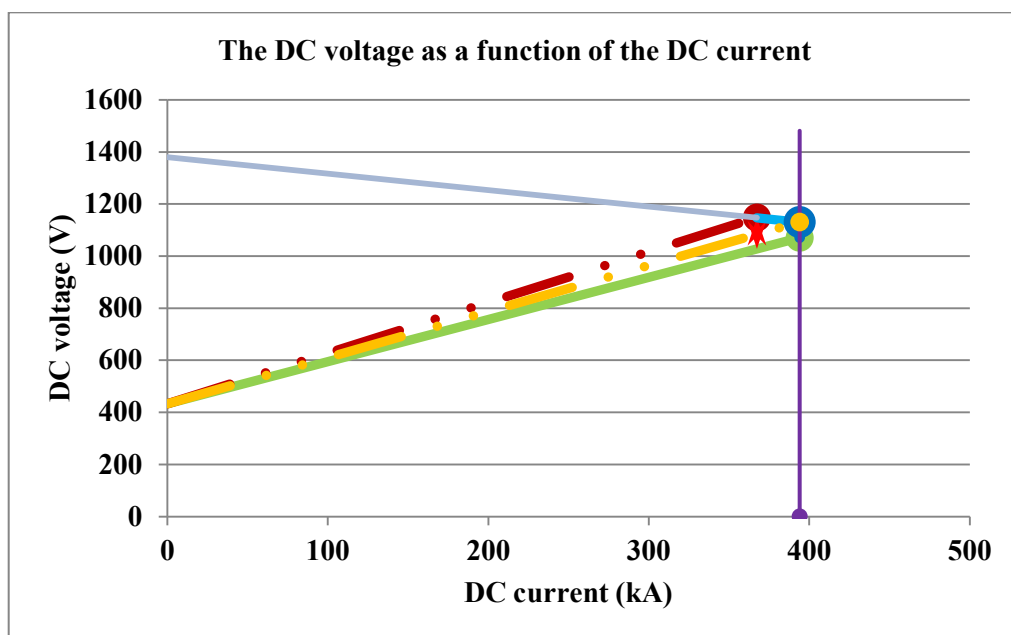


Figure 4. The DC voltage lines as a function of the DC current.

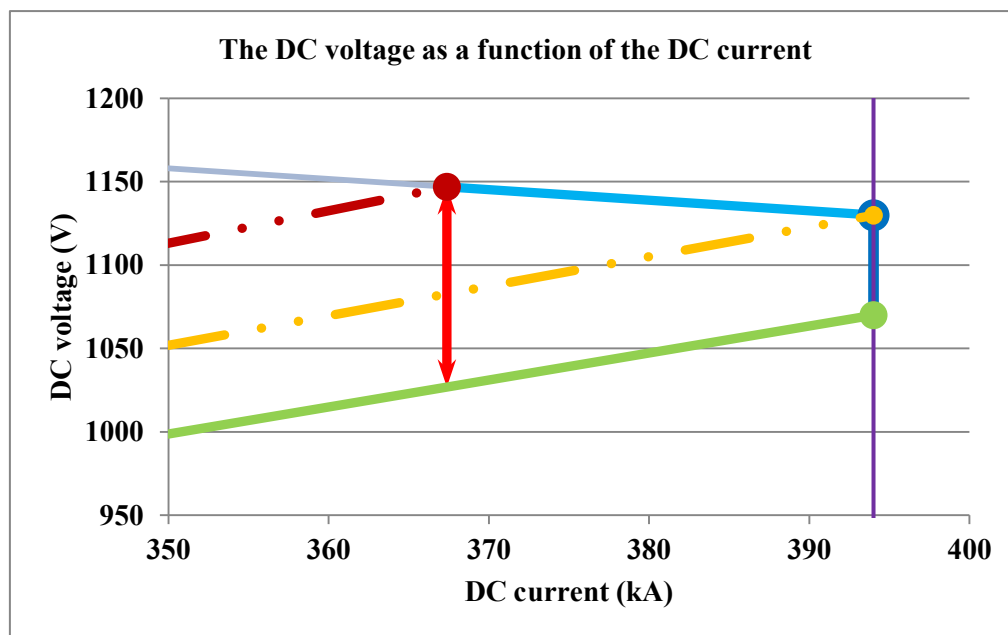


Figure 5. Zoom of Figure 4 around the operating point of the potline.

In these representations the operating point of the potline moves from the green bullet (its normal position) to the blue-amber bullet and then to the dark red bullet.

In a potline being operated at a current set point constant with some exceptions that can be anticipated, the open circuit detection system can use thresholds which only need to be updated from time to time when the number of pots in operation is changed significantly, or when the expected resistance of pots is changed significantly.

### 3. Protection Adaptivity

In Europe and Quebec for instance, load shedding can be required by the power grid operator for application within a short delay. Load shedding means modulating the potline current for an aluminium smelter. Figure 6 shows the result of a load shedding on the current and the voltage of a potline. In that case the potline current was highly modulated, about 90 kA. And the voltage varied by 150 V.

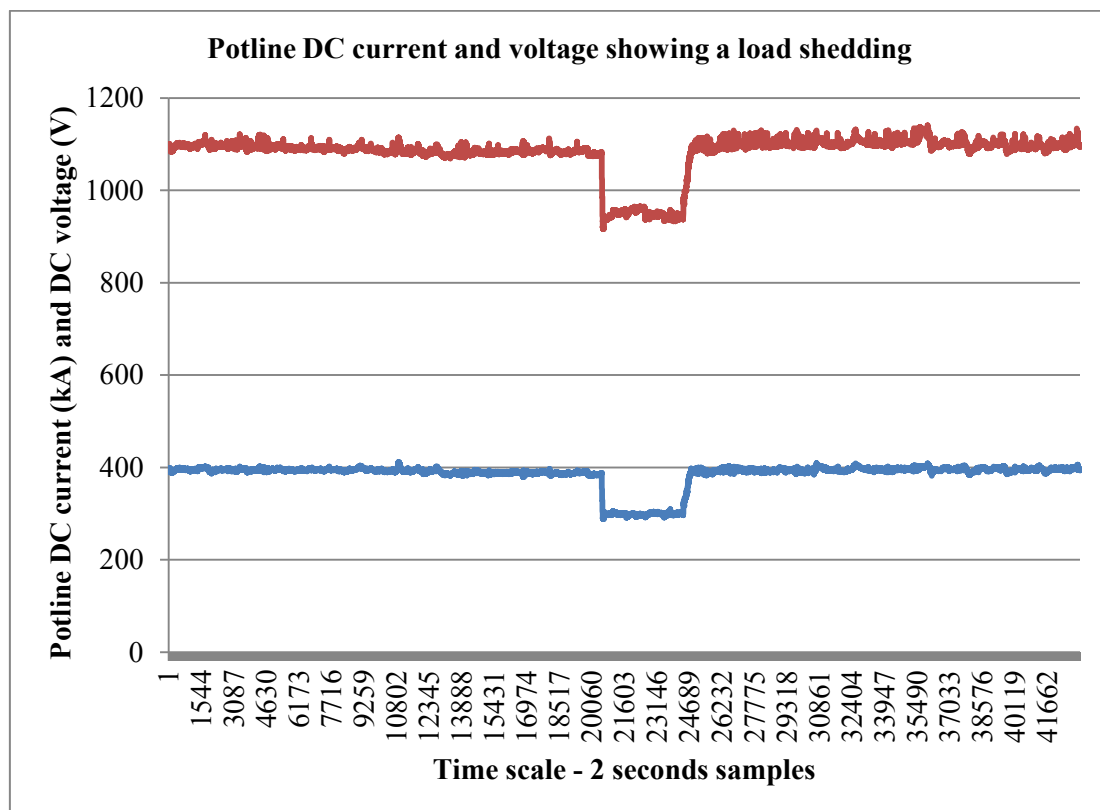
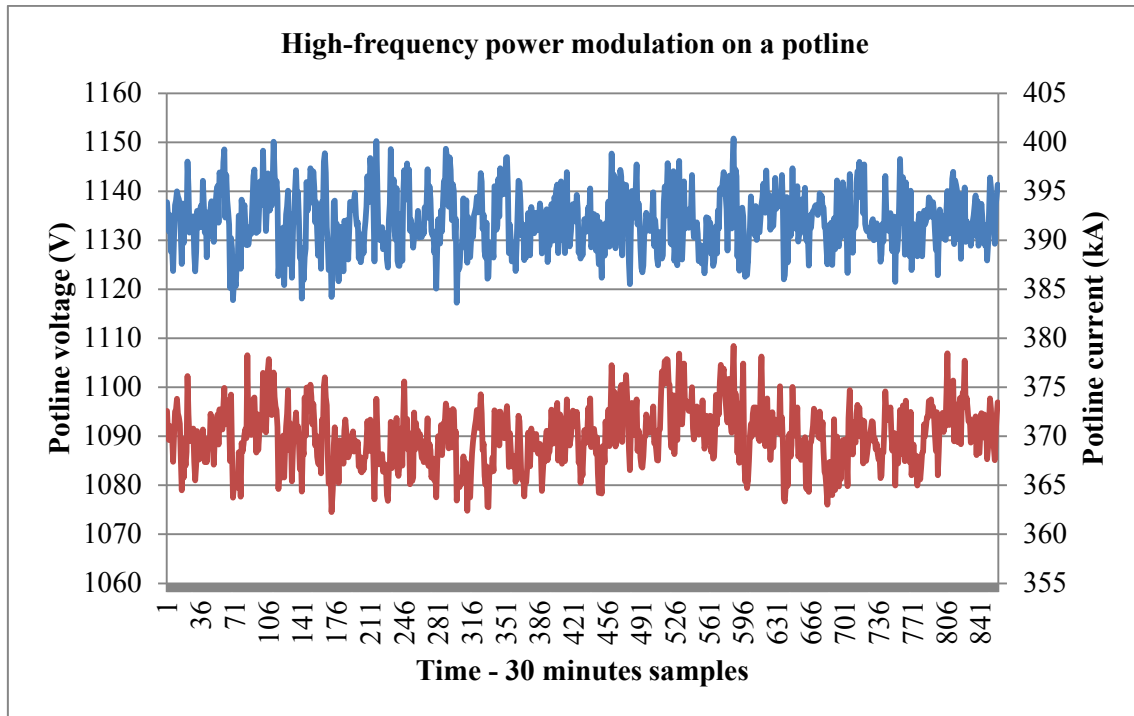
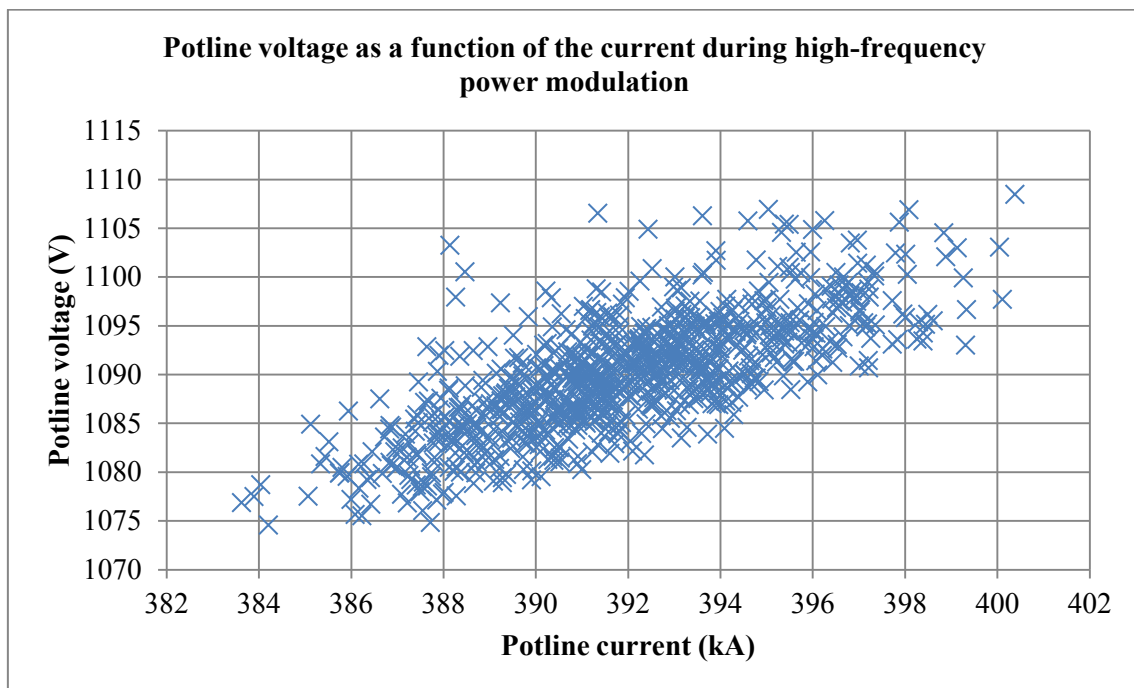


Figure 6. Potline DC current and voltage showing a load shedding.

In Europe, the growth of dispersed and renewable generators (DRG) leads to a need of primary control reserve for stabilizing the power grid at 50 Hz. Lützerath [2] demonstrated the interest for an aluminium smelter to provide primary control power, in other words to be elected as a distributed energy resource (DER). In such a system, energy needs to be balanced. That means that the surplus of energy which is applied during positive power modulation must be compensated with periods of negative power modulation and vice versa. Modulating the power means notably modulating the potline current. Figures 7 and 8 show the result of a high-frequency power modulation on the potline current and voltage. This is an outcome from Dunkerque smelter where this kind of power contract has been in place for some time. In those figures, when eliminating the voltage peaks due to anode effects, the current line, colored in blue, shows 16 kA variations while the potline line, colored in red, shows 30 V variations.



**Figure 7. High-frequency power modulation on a potline.**



**Figure 8. Potline voltage as a function of the current during high-frequency power modulation.**

It is expected that in near future, this kind of power modulation will result in higher variations of the potline current and voltage. Those variations will be in the same range even higher than the thresholds used to detect a trend to open circuit.

Consequently, the open circuit protection system must be adaptive in real time. The Rio Tinto's Aluminium product group developed this evolution in its protection system: The new AP

Technology™ auto-adaptive protection system has been tested in Laterrière smelter and commissioned in Dunkerque smelter. It will be implemented in the other Rio Tinto smelters as soon as possible.

Figure 9 shows the result of the auto-adaptive open circuit protection (amber line) combined to a high-frequency power modulation on potline current and voltage (blue scatter plot).

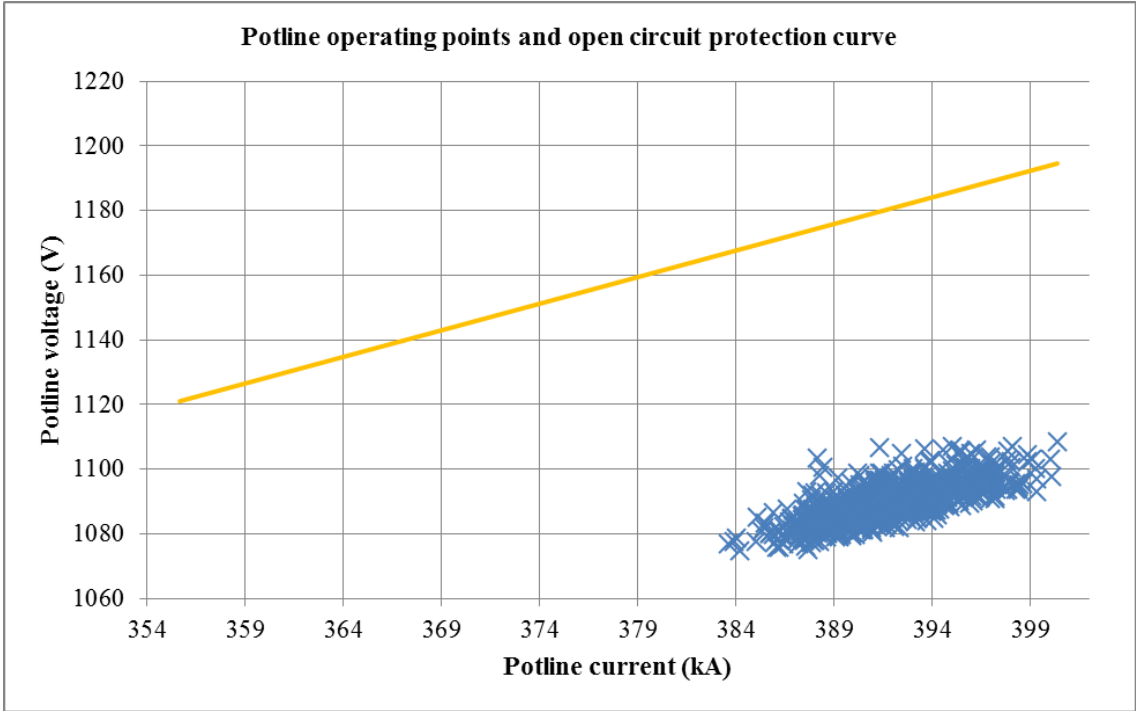


Figure 9. Potline operating points and open circuit protection diagram.

Figures 10 and 11 show the result of the auto-adaptive open circuit protection (amber line) combined to a load shedding on potline (blue scatter plot). No anode effect impacts the protection adaptive settings.

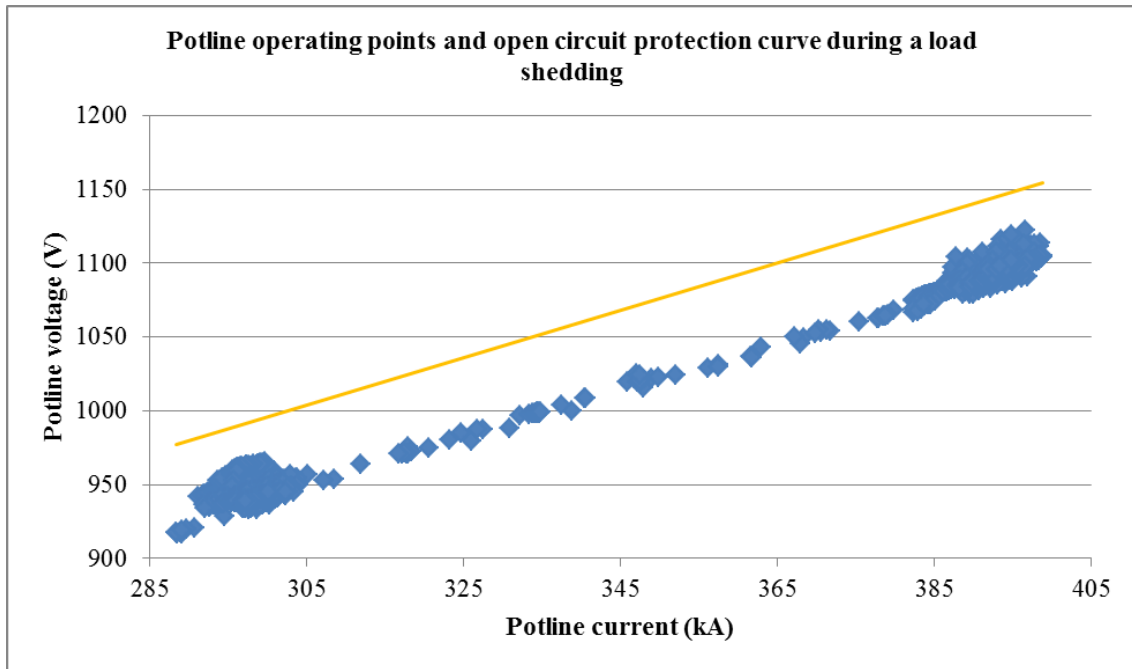


Figure 10. Potline operating points and open circuit protection diagram during a load shedding.

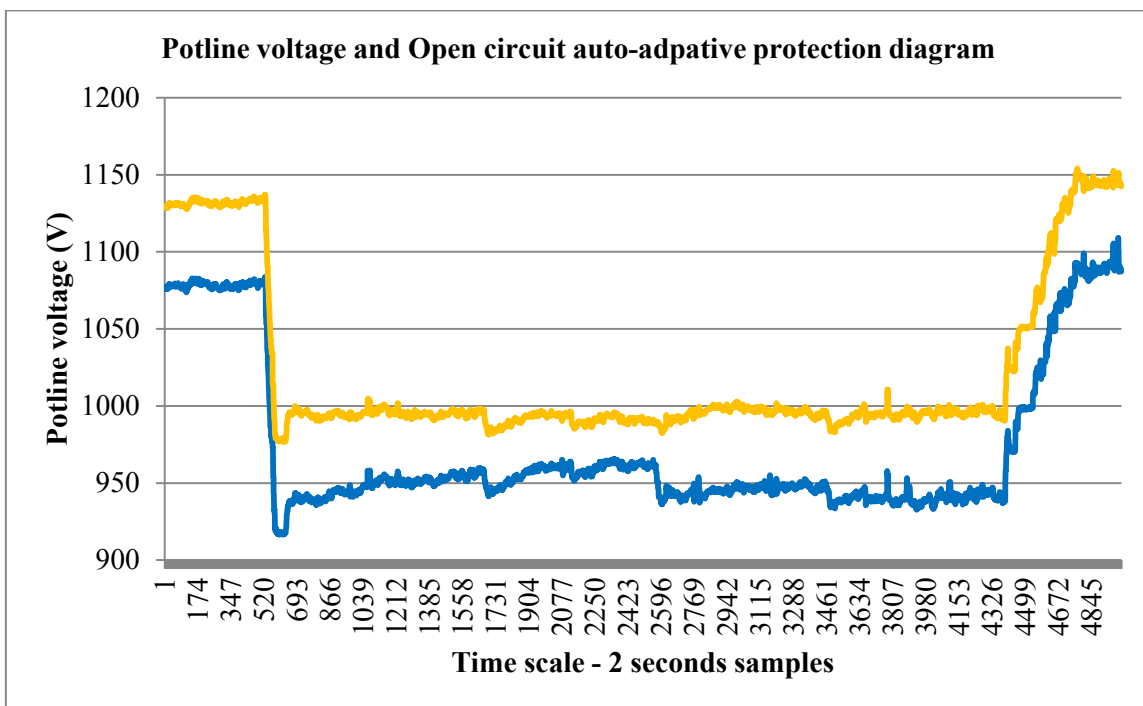


Figure 11. Potline voltage and open circuit auto-adaptive protection diagram.

In those examples, among all the potline variables only the potline current was fluctuating, the other ones (number of pots in operation, expected resistance of pots, etc.) were constant. The AP technology™ auto-adaptive open circuit protection system takes into account any change of those variables.

#### 4. Conclusions

An electric arc is generated whenever the potline circuit is accidentally opened: It cannot extinguish itself unless the conversion substation is tripped. The phenomenon is always dangerous. It can often evolve into a destructive event that may jeopardize the DC amperage supply to the potline for a long duration in case of severe damage of a busbar cross-section for example.

AP Technology™ teams have developed a set of operational best practices to prevent this kind of situation from happening. Moreover, the Rio Tinto has developed a potline open circuit protection in order to detect any open circuit trend as early as possible. The potline open circuit protection is the last barrier against electrical arcing in the potline circuit.

The growth of dispersed and renewable generators requires potline open circuit protection systems to become adaptive, as it is the case for the power grid protection systems. High variations of potline current result from unplanned load shedding and high-frequency power modulation. The unpredictability, the magnitude and the frequency of those variations force the protection systems to be adaptive.

AP Technology™ teams developed an evolution in its protection system so that all the impacting factors, including variations of the potline current, are now taken into account in real time by this new auto-adaptive protection system, which has been now commissioned after qualification tests.

#### 5. References

1. Dominique Duval et al., Potline open circuit protection, *Light Metals* 2012, 913-916.
2. Andreas Lützerath, High frequency power modulation – TRIMET smelters provide primary control power for stabilizing the frequency in the electricity grid, *Light Metals* 2013, 659-662.