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POTLINE OPEN CIRCUIT PROTECTION

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Abstract

A potline open circuit can be a dangerous and catastrophic event. It results in a high power DC arc, which can not extinguish itself unless the conversion substation is tripped. It can escalate into an explosion: the arc energy can injure any operators in the vicinity or can damage not only the equipment in question but potentially anything within proximity. The consequences can include freezing of the potline.

To manage this risk, the potline must be protected against the danger of open circuit fault. A dedicated system is required to provide effective protection: quick tripping of the rectifying groups is triggered when the open circuit trend is detected. In order to avoid inappropriate potline switching off, the protection system settings must always be optimized according to the operating conditions (potline amperage, potline restart after shutdown, number of stopped pots, etc.).

An overview of the potline open circuit phenomena is explained.

Introduction

The opening of an electrical circuit generates an arc. This electric arc will extinguish when the arcing current value becomes zero, however in a DC circuit, an arc can be fed permanently till the power supply is switched off. This phenomenon can be experienced inadvertently in the aluminium potline operation when the high current busbar circuit opens accidently. An electrical arc, if it is not stopped by tripping the conversion substation, can develop as an unsafe, destructive and uncontrolled event. The first rules to avoid such an event are the follow-up and the respect of good operation practices. However, potline open circuit protection remains a must to safely prevent arcs occurring in the high amperage circuit of aluminium smelters.

The theoretical aspects of potline open circuit, the possible causes and the behavior of rectifying groups are presented. Then, a description of the solution offered by AP Technology™ is provided.

Theory of breaking steady-state DC currents

General

The breaking of the current is dependent upon a number of parameters relating to lines and loads:

- An electric circuit is always inductive, and thus breaking the current generates, as soon as the circuit is opened, negative feedback which helps maintain the current. The value of this back-electromotive voltage of the L*di/dt type may be high whatever the value of current (i), until this current is cancelled.
- The resistance of the circuit helps in breaking as long as the current is high, but ceases to be of help when current tends to zero, since the ohmic drop is then negligible.
- The frequency of the current to break, since it is easier to break AC currents with periodic zeros than DC currents.

Figure 1 shows the equivalent electrical scheme of a potline:

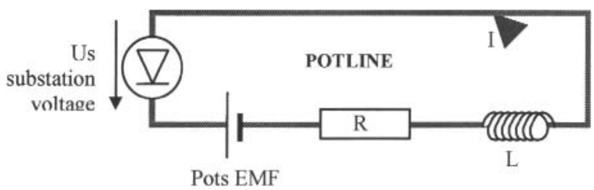

Figure 1: Equivalent electrical scheme of a potline

A potline is a low resistance, high inductance, high voltage, DC current circuit. These characteristics favour the generation of a severe electrical arc in case of an open circuit in the high current busbars.

Electric arc formation conditions

The circuit, always inductive, supplies electrons with sufficient energy to cross the distance in the air: an electric arc forms as soon as an electric circuit opens.

The gas present, normally air, is ionized by these "pioneer" electrons and the resulting plasma will then allow current flow. Even if the circuit is purely resistive, a certain opening distance is necessary to prevent dielectric breakdown. Moreover, any attempt to reduce current rapidly creates a high L*di/dt thus favouring breakdown at any current level.

Electric arc properties [4]

The most striking property of an electric arc is the appearance of an arcing voltage, which has a:

- fixed part, $U_{AC} \approx 20$ to 40 V, that appears on the slightest separation of the contacts,
- variable part, $U_L \approx 50$ to 100 V/cm, when the arc length is stabilized in pressure-temperature balanced conditions,
- total value $Ua = U_{AC} + U_L$.

Several theories have been developed to model the arc voltage (for example Ayrton equation). These theories remain very empirical since all the phenomena that are involved are complex. Note that the magnitude of arcing current does not have any real effect on arcing voltage. This is because the arc "works" with a virtually constant current density (j=i/s).

Secondly it is important to note that an arcing energy is produced: $Wa = \int ua\ ia\ dt$.

Where
- ua is the arcing voltage
- ia is the arcing current.

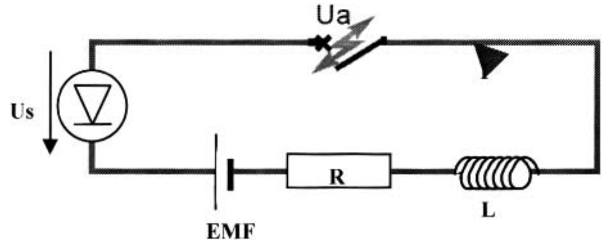

Figure 2: Equivalent electrical scheme of a potline in open circuit condition

Figure 2 shows the electrical scheme of a potline in open circuit condition. For an AP36 potline, the typical values of the parameters are:

- Us = 1500 Vdc (conversion substation DC voltage)
- EMF = 600 Vdc (pots Electro-Motive Force)
- R = 2.25 mOhm (potline circuit resistance)
- L = 1.5 mH (potline inductance)
- Ua = max of arcing voltage

All of these parameters are variable, depending upon the number of pots in circuit.

In DC current, before opening: $i0 = (Us - EMF) / R$
After opening: $Us - EMF - R\ i - L\ di/dt - ua = 0$

When the circuit opens, ua moves towards a maximum value Ua.

Ohm's extended law shows that current can only be forced to "0" if ua becomes greater than E = Us - EMF.
Otherwise, it will move to $i'_0 = (E - Ua) / R$.

Figures 3 show the current and voltage curves as a function of time.

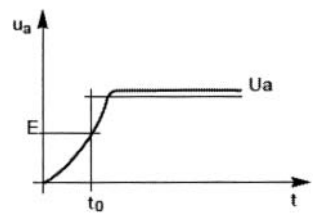

Figure 3a: Arcing voltage curve

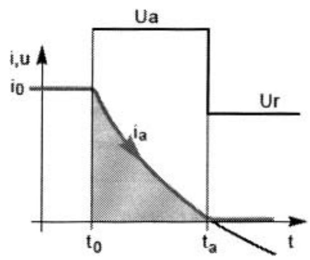

Figure 3b: Arcing current curve

For current breaking purposes, it is easier and sufficiently clear to consider this arcing voltage as a step function, ua = Ua for $t > t_0$, (t_0 = time when ua = E).

Based on the potline values given above, the theory suggests that the electrical arc can stay permanently active unless the potline circuit is opened with a gap greater than 15 to 20 cm.

From an energy perspective, the calculation of the integral:

$Wa = \int ua\ ia\ dt$

gives

$Wa = \int [(us - EMF - R.ia)\ ia]\ dt - \int L\ dia/dt\ ia\ dt$

The first part of the integral depends on the breaking time. It is the power supplied by the conversion substation.

The second integral represents the electromagnetic energy.

$- \int L\ dia/dt\ ia\ dt = ½\ L\ i_0^2 = WL_0$

The power dissipated in the open circuit fault corresponds at least to the electromagnetic energy that is stored in the potline inductance.

For example, in an AP36 potline at 360 kA:
$WL_0 = 1/2\ L\ i_0^2 \approx 100$ MJ.

Description of the phenomenon on the reduction operation side

Various operation incidents can cause the opening of the high current circuit in a potline. This is a very serious incident which is always the result of a gap forming in the circuit.

Possible causes of this condition are:

- Human error during metal tapping (the most frequent cause),
- Tap out, i.e. loss of the molten liquid from a pot leaving the anode completely out of contact with the bath (also one of the most frequent causes),
- Manual raising of anodes out of the bath,
- Decrease in the liquid bath volume due to freezing during a power outage. This leaves the anodes out of bath (the problem might not be immediately obvious until the power is restored),
- Melting of pot busbar through contact with molten bath or metal,
- Multiple separation of all the anode blocks from anode rods (transition joint failure),
- Human error during the handling of the anode raising beam,
- Wrong operation during pot start-up or restart,
- Failure of the short circuiting wedges,
- Breaking of all the cathode bar clads (the connections between collector bars and cathode flexes),
- Maintenance mistake while fixing pot electrical equipment (wrong connection of the jacking motor or contactor for example).

Two examples of open condition causes are shown in Figure 4.

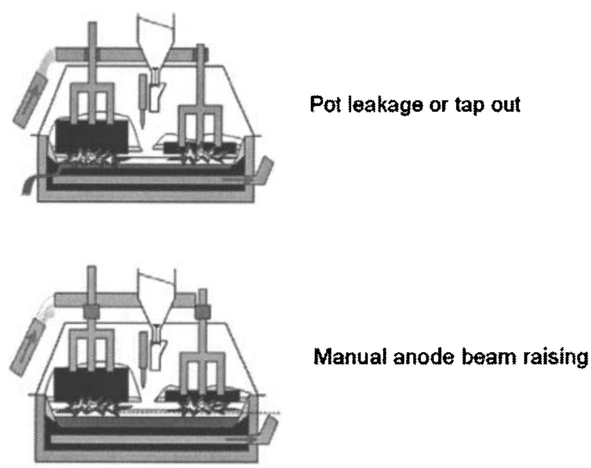

Figure 4: Examples of open circuit possible causes [2]

From a safety perspective, such incidents are very serious situations. In case of manned operation in the vicinity of the incident, the operator can suffer serious burns from the arc.

The consequences of such an incident can be also severe damage because of the energy involved in the arc. The ultimate consequence can be the impossibility of restarting the potline if the damaged busbar circuit can not be repaired and the DC amperage can not be restored in quick enough time.

AP Technology™ specifies "emergency short-circuiting bridges" to be in a position to reconnect the potline circuit when there is partial or total destruction of one or two pot-to-pot busbars. These emergency bridges are connected to the pot circuit busbars upstream and downstream of the damaged zone.

Description of the phenomenon in the DC conversion substation

Consider the case of a DC conversion substation equipped with on-load tap changers, saturable reactors, diode rectifiers and a amperage regulation system.

When the potline circuit tends to open, the potline resistance increases sharply and quickly. The DC substation voltage regulation system intervenes instantaneously to maintain the amperage at its set point value by reducing the voltage drop of the saturable reactors (generally about 30 Vdc to 50 Vdc). Then, the system increases the voltage supplied by tapping up the regulating transformers by 2 (or 3) tap positions (about 2 x 15 Vdc).

The number of consecutive tapping up is usually limited and in any case, the duration of switching between 2 positions is at least 2 to 3 seconds at the quickest.

Then, should the voltage still increase, the operation point (U, I) follows the substation load curve; the amperage drops whereas the voltage increases. Figure 5 shows DC voltage curves of the potline and of the conversion substation as a function of DC amperage.

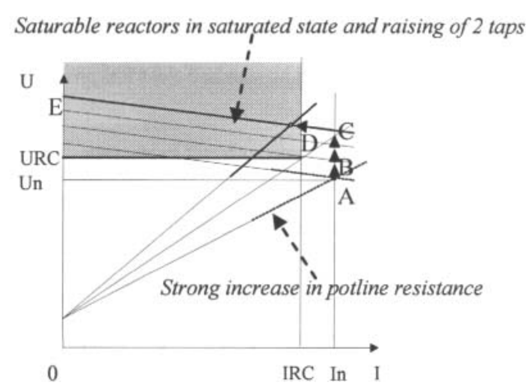

Figure 5: DC voltage curves as a function of the amperage

URC and IRC are open circuit protection system settings (see next paragraph).

The conversion substation will keep on feeding the open circuit arc, but will still operate within its voltage and amperage limits. There is no risk for the conversion substation equipment: no overload, no overcurrent, no overvoltage...

The traditional electrical protections can not detect an open circuit fault, unlike other electrical fault such as a short circuit fault for example.

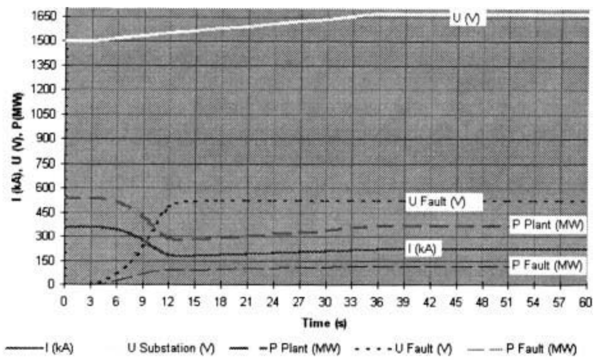

Figure 6: Potline open circuit fault simulation

Figure 6 shows the evolution of the potline voltage, amperage and power after an open circuit fault happened (between time 3 and 6 seconds):

- U Fault: the arc voltage increases (almost as a step function),
- I: the potline amperage decreases, and then increases slightly due to the rectifier units tapping up their output voltage,
- U Substation: the potline voltage increases due to the action of the potline regulation that tends to maintain the potline amperage, and then is stable after the rectifier units can not increase their output voltage,
- P Plant: the smelter DC power decreases because of the amperage drop, and is then almost constant,
- P Fault: the power dissipated in the arc increases and is then permanently fed by the conversion substation and remains constant.

On the conversion substation side, all the electrical parameters are within the capability of the equipment: an open circuit fault is impossible to be detected by standard electrical protection.

Potline open circuit protection

The first rules to avoid such incidents are to follow rigorously good operational practices, such as [3]:

- Written procedures,
- Enforce training about these procedures,
- Respect of the written procedures,
- Systematic operating follow-up of sick or unstable pots,
- Adequate equipment maintenance.

Despite this, the number of cases of potline open circuits is greater than one would imagine. Moreover the frequency of occurrence increases during transition periods of operation (start-up phase, power outage, etc.). So, as a last line of defence, the open circuit protection is required in an aluminium smelter.

To detect an opening circuit trend [1], an automation system (called SURMEC in AP Technology™ package) permanently monitors the potline amperage and voltage. When the normal relationship between the DC amperage and DC voltage is disrupted and is detected as a trend to open circuit fault, the protection system transmits a general tripping command to the conversion substation. The area in grey in the Figure 5 corresponds to the tripping zone.

The protection system settings URC and IRC must be optimized according to the operating conditions:

- potline amperage,
- number of pots in the potline circuit (in operation, in preheating, or short-circuited),
- potline restart after shutdown,
- power supply by a captive power plant or a strong grid,
- etc.

These thresholds must be well engineered to achieve effective protection so that quick tripping of the rectifying groups occurs when the open circuit is detected, while avoiding any inappropriate potline shutdown.

To achieve maximum reliability, the SURMEC cabinet architecture is based on soft and hard protections (i.e. both through a PLC and hardwired relays). The SURMEC system is part of ALPSYS® pot process control system scope of supply, but can also be supplied as stand alone equipment.

Conclusion

An electric arc is generated whenever the potline circuit is accidently opened: it can not extinguish itself unless the conversion substation is tripped. The electrical arc dissipates the inductive energy that is stored in the potline circuit as well as the power supplied by the rectifier units. The phenomenon remains 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 section for example.

AP Technology™ has developed a set of operational best practices to prevent this kind of situation from happening. Moreover, the AP Technology™ package also contains 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 busbar circuit.

For the past few years, Rio Tinto Alcan has been working on ensuring that all of its smelters are equipped with potline open circuit protection. In all the plants, it has been checked and audited that the operations team were well trained with this equipment and that the settings have been correctly fine-tuned.

References

[1] Technical Training & Development - Institut Paul Héroult (TTD-IPH): AP Technology™ module S.2.002, "SURMEC"

[2] Technical Training & Development - Institut Paul Héroult (TTD-IPH): AP Technology™ module S.1.003, "Potline - Electricity"

[3] ALPSYS® Operations manuals

[4] Cahier Technique Schneider Electric no 154 "Breaking techniques"