

Protection Against Open Circuit in ALPSYS Pot Control System

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Abstract

To the question "What is the most important feature of a pot process control system in a smelter", many will talk about current efficiency, energy consumption or will talk about how the system helps manage the potline. For us, this is not the best answer. The most important feature of a pot process control system (PCS) is safety. Safety for people who work all day long beside pots (pots generating up to 1 to 2 MW power) and safety for equipment, to ensure continuity of the smelter activity. There are many risks in a potline, and the most important risk the process control system has to manage is an open circuit.

Safety features have been an important part of ALPSYS right from the start. 30 years ago, when pre-version of ALPSYS was under development, open circuit protection was already part of the system. Over the years, many improvements have been made to this protection, either by improving the existing protection, or by developing new ideas. Several open circuits or near open circuits happened in plants over past years. All were analyzed to identify the root cause and propose a solution or a mitigation. This article describes different types of open circuit protections encountered in existing plants and discusses the advantages and disadvantages of each type.

Keywords: Safety in potline operation, Pot control system, ALPSYS, Aluminium reduction supervision system, Open circuit protection.

1. Potline Protection

Potline protection against open circuit is not done by the PCS; it is managed by the substation. The substation monitors in real time the potline voltage and the potline current. During an open circuit, the potline voltage increases until the substation reaches its maximum power limit. Then the potline current decreases significantly. An open circuit is then detected when the potline voltage is high, and the potline current is low. Upon detection, the substation immediately cuts the power to the potline to stop the incident. An example is given in Figure 1. This is probably the oldest and the most standard open circuit protection. It is very effective, but it has some disadvantages. Its main weakness is its inability to make the difference between several anode effects (AE) happening simultaneously and an open circuit happening on one pot. At the beginning of the phenomenon, as seen from the substation, both give the same result: Potline voltage increases rapidly, and potline current is maintained at its setpoint as much as possible by substation rectifier regulation.

The potline open circuit protection efficiency is based on the proper adjustment of the protection thresholds. But they require a precise adjustment. If the thresholds are too restrictive, the potline will trip when several AE happen simultaneously. Multiple AE occurs regularly during a difficult restart after a potline shutdown, and a badly adjusted substation protection can repeatedly trip the substation during the restart. If the thresholds are not restrictive enough, an open circuit will be detected too late, when a lot of damage has been done to the pot or the potline circuit, with a very high risk for people around the pot.

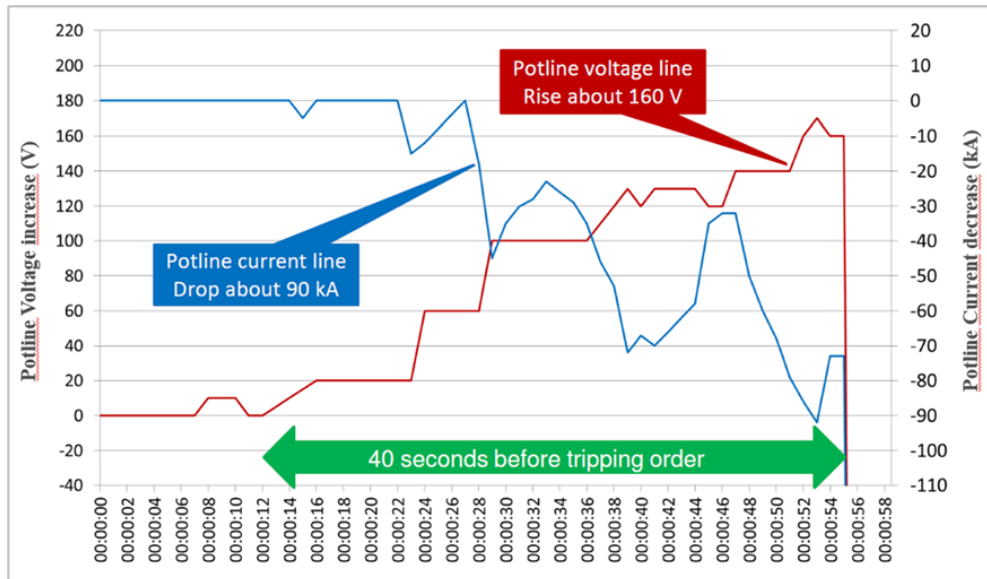


Figure 1. Example of potline current and voltage at the beginning of an open circuit.

Another difficulty of a potline open circuit protection is that it needs to be regularly adjusted to what happens in the potline. Ideally, each time a pot is stopped or is going in preheating, each time the potline resistance setpoint is changed, the protection thresholds should be adjusted to ensure that the protection thresholds are not too high or too low.

Several improvements have been done and are still ongoing to improve the potline protection:

- A new algorithm has been developed in the substation protection system (the so called SURMEC) to adapt automatically the thresholds during a potline start-up [2].
- ALPSYS and the SURMEC are exchanging information so the SURMEC can adjust its protection in real time to what happens in the potline.

Despite these improvements, there are still some limits to what can be done from the substation point of view. It was clearly demonstrated by an open circuit that happened a few years ago with substation thresholds correctly adjusted. From the data recovered from this incident, we were able to get information about the pot voltage during the incident, the pot voltage was:

- Above 30 V for almost 2 minutes,
- Above 60 V for 63 seconds,
- During the incident, despite the substation tripping in less than 2 minutes, the power input to the pot was 16 times the normal power: at this rate, the total energy consumption for one hour is injected in the pot in only 4 minutes.

Whatever the improvements in substation, the results will always be limited from the potline point of view. An even more efficient protection can be achieved by building a protection at pot level. Table 2 shows an example of pot voltage during an open circuit.

2. Pot Protection

There are several categories of risks leading to an open circuit situation, and they need be addressed differently:

- Equipment fault,
- Human mistakes,
- Unexpected pot behavior,
- Pot fault.

Table 1. Example of pot voltage distribution during an open circuit.

Pot voltage (V)	Time (s)
30-40	19
40-50	11
50-55	7
55-60	4
>60	63
TOTAL	104

2.1 Protection Against Equipment Fault

The risk of an equipment failure was also integrated in ALPSYS right from the very beginning. This risk refers to any failure of the electrical equipment associated with the pot microcomputer (Potmicro). It includes for example:

- The anode beam movement motor contactors,
- The anode beam movement motor power source,
- The push buttons or selectors used by the operator (such as, the automatic / manual anode beam movement mode selector).

It also includes problems that could happen with the Potmicro parametrization. A badly set parameter is also a problem that can lead to anode beam movement issues. A large set of parameters is used to adjust the anode beam movement. If one of them is set to a wrong value, it can lead to issues with the anode beam.

The consequences of these cases can be summarized in the following main failure modes:

- A contactor does not open on command,
- A contactor does not close on demand,
- An order is given with a too long duration,
- The motor does not move during an order.

Mitigating this risk is based on sensors to get the status of the important pieces of electrical equipment, and on software functions to monitor its proper functioning. Based on the sensors, the Potmicro can detect faults, but it also needs a way to act when a fault is detected. This is done generally by integrating a component, a circuit breaker or a contactor, that the Potmicro can use to physically stop the power to the anode beam. By opening this component, the power to the anode beam is effectively cut, stopping any movement even if the fault is still ongoing.

2.2 Existing Protections

There is a large variety of sensors and protections that can be found depending on the pot technology for this purpose:

2.2.1 Contactors Feedback Information (Figure 2)

- This protection is used to detect a faulty contactor, whether it does not close on command, or it does not open on command.
- The contactor positions (open or closed) is sent to the Potmicro.

- Ideally, there should be one input for the upward contactor and one input for the downward contactor but sometimes there is only one for both directions.
- If the Potmicro is giving an order and the corresponding contactor is not closing, then the Potmicro detects a contactor fault.
- Inversely, if the Potmicro is not giving an order and the corresponding contactor is not opened, then the Potmicro detects a contactor fault.
- Upon detection of a fault, the Potmicro immediately stops the power to the anode beam.
- It is a software protection based on I/O.

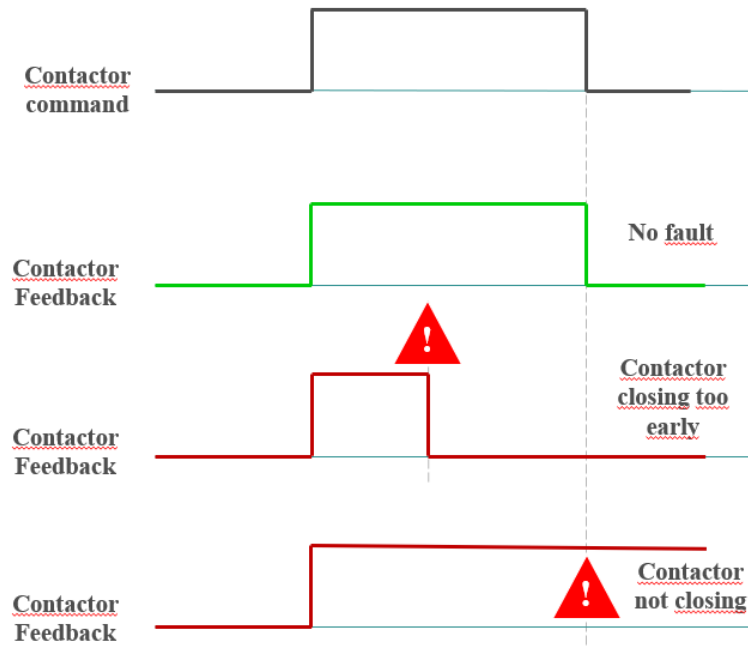


Figure 2. Contactor feedback logic.

Contactors feedback is one of the most important features to protect a pot against a circuit opening. Having a contactor stuck either in the open or in the close position is a common failure and this protection is highly effective against it. It can react in less than a second to a failure, effectively limiting an uncontrolled order to less than a second. It works by comparing the contactor status (open or close) to the order requested by the Potmicro. So, this protection is aimed to check that the motor activation matches the order calculated by the Potmicro. It is not a protection if a wrong order is given by the Potmicro. This protection is complemented by software functions that monitor the orders duration and can detect and stop anode beam movement if a too long order is given by the Potmicro. So, the contactor feedback solution is including a software timer switch.

2.2.2 Anode Beam Position Limit Switches

- This protection is used to detect an anode beam which is too high or too low.
- Position switches are installed on the anode beam and connected to the Potmicro.
- There is one input for the high limit and one input for the low limit.
- A fault is detected when one of the limit switches is activated.
- Upon detection of a fault, the Potmicro immediately stops giving orders in the direction corresponding to the limit reached.
- It is a software protection based on I/O.

Anode beam position limit switches are an anode beam protection, and not an open circuit protection. The anode beam can be damaged if it has reached a limit position and the Potmicro keeps trying to move it while the limit is exceeded. It however cannot protect against an anode beam movement failure happening when the anode beam is far from its limits. It cannot be considered as a good protection against open circuit.

2.2.3 Timer Switch (Figure 3)

- A timer switch is used to detect if an abnormally long order is given to the anode beam.
- It is an electrical component connected to the anode beam power line, that triggers an output when the motor is powered for a higher duration than a preset time limit.
- The timer output can be read by the Potmicro to declare a too long order fault. It will then stop any orders given to the anode beam.
- The electrical cabinet can also be designed for the timer switch to directly stop the power to the anode beam, independently from the Potmicro.
- Depending on the electrical cabinet, it can be either a software protection based on I/O, or a purely electrical protection.



Figure 3. Timer switch logic.

The timer switch is an important and very effective protection against open circuit. This protection is triggered when an order is too long (for example for more than 7 seconds for an AP technology pot), so when it reacts, the order has already been given. It is a rather slow protection. One of its strong advantages is that it does not depend on the Potmicro to function. Even if a Potmicro is not responding correctly, this protection is effective. If the pot is not equipped with a timer switch, it is replaced by a software timer which does the same function. The only difference is that a software timer switch is not totally immune to software glitches. An external timer switch brings a better level of safety.

2.2.4 Anode Beam Position Encoder

- An anode beam position encoder can be used to send the anode beam position to the Potmicro.
- The anode beam position is read in real time by the Potmicro and a wide range of detection can be performed.
- All faults detection described above can be detected using an anode beam position sensor.
- It is a software protection based on I/O.

Anode beam position encoder is taking the problem from a completely different point of view, which enables it to perform a lot of monitoring, by comparing the orders given to the corresponding anode beam movements. A contactor stuck closed is detected because there is a movement while no order is given. A contactor stuck opened is detected because there is no

movement when an order is given. It can of course also monitor anode beam positions limits. However, to function properly, a big enough change of the anode beam position is required. It cannot react for very short duration orders. It is a rather slow protection. Furthermore, it needs a lot of software functions to work, with more complex algorithms.

All these protections are highly effective, but they do not protect against the same risks. In existing plants, there is a wide range of protections installed depending on the pot technology. Anode beam position encoder is uncommon, mainly because of the rather high cost associated with this solution. Limit switches are more common but not widely used. The most common are the contactor feedback and/or the timer switch; very often, only one of these two is available.

2.2.5 The Maintenance Issue vs Fail Safe

In designing an open circuit protection, the most important question is, of course, to ensure that the protection can detect the maximum of possible cases. But no less important is the question of the maintenance of the protection.

For protections based on sensors, it is of the utmost importance to be able to check regularly that the sensor is properly functioning. The best solution is to be able to test automatically and frequently the sensors. For example, in ALPSYS, on pots with contactor feedback, the feedback is automatically checked every hour. A failure would then be reported within the hour.

If no automatic testing is possible, then it must be done manually. Manual maintenance of a high number of sensors is a very time-consuming action. The risk is then that it is done rarely, if ever.

Regarding maintenance, the existing solutions vary greatly:

- The contactor feedback can easily be checked automatically. It is, in fact, not absolutely needed because it is a fail-safe solution; an alarm is raised if the feedback does not work. In case of a contactor feedback failure, the first order after the failure will raise an alarm.
- On the opposite, the limit switches are probably the worst solution regarding maintenance. They cannot be tested automatically as this would call for raising or lowering the anode beam automatically to its limits. It could be manually done during anode beam raising operations, but it would be a risky operation. So, maintenance relies only on manual checking. In addition to that, they are very rarely used (meaning that an anode beam very rarely goes to a limit) so the risk that it does not work when required is very high.
- The problem is almost the same for timer switches. They cannot be automatically checked.
- Anode beam position sensors present a different problem. They are very easily checked automatically. As for the contactor feedback, it is also a kind of fail-safe solution because the monitoring functions associated with the position sensors will trigger an alarm in case of failure. The drawback of anode beam position sensors is that it could be more difficult to replace a faulty sensor because it is installed on the pot instead of inside a cabinet. When designing this solution, great care should be taken to make it very easy to replace a sensor.

When designing an open circuit protection solution, it is very important to consider the maintenance. If very frequent checking is not possible, then another solution should be considered. And of course, automatic checking is better than manual checking as it is the only way to ensure the continuity of the checking.

2.2.6 Contactor Feedback vs Timer Switch

The rationale behind having either contactor feedback or timer switch is that one of these protections, alone, is sufficient to mitigate the open circuit risk. And this is because the risk

considered is the risk of a stuck contactor. This risk is indeed efficiently mitigated by only one of these two protections, but there are other risks to consider, and those risks are not covered equally by both protections.

This is clearly demonstrated by an open circuit that happened in a smelter in the recent past. Protection was done by a timer switch only (no contactor feedback). Due to an electrical fault in the pot control cabinet, there was a problem in the anode beam movements requested by the Potmicro; all up orders were carried out correctly, but no down order was ever done. Without feedback, the faulty down orders were not detected so no alarm was raised. All up orders were done correctly, with a normal duration, so no alarm was raised during up orders. Soon after the failure, an anode effect happened and, because there was no alarm, the Potmicro proceeded to treat the pot normally. During the squelching sequence, long down orders were given, followed by long up orders. With only the up orders effectively done, the pot ended up raising the anodes until an open circuit happened.

This clearly shows that a timer switch, alone, is not adequate for avoiding open circuit.

2.2.7 In ALPSYS

Today, all these protections are available in ALPSYS so it can be configured to run on an existing system without the need to change the electrical cabinet.

The contactor feedback solution is very efficient. With this solution, in the above case an alarm would have been raised at the first down order given by the Potmicro and the open circuit would not have happened. Contactor feedback alone is however not sufficient. It removes effectively most of the risks, but some cases still exist (discussed below). They are less frequent than contactor blockages, but they still can lead to open circuit incidents. The most efficient protection calls for both protections used simultaneously.

Our standard (for a new plant for example) is built on the contactor feedback solution. It does not use limit switches mainly because limit switches do not protect against open circuit, and because of the maintenance issue. It also does not use an external timer switch because this function is available in the software. We are today considering modifying our standard to include an external timer switch as it will improve safety by creating a timer protection independent from the Potmicro software.

2.3 Protection Against Human Mistakes

Many different mistakes are possible with a pot control system, but only a very limited number can lead to an open circuit incident.

The most common risk related to human mistake is the risk created when tapping the metal from the pot without the corresponding procedure running at the Potmicro. This could happen in two situations:

- The operator forgets to launch the procedure at the Potmicro when he starts tapping the metal.
- The procedure is launched by the operator when he starts tapping the metal, but the procedure is stopped during the operation (generally due a fault detected by the Potmicro).

In this situation, the metal in the pot is lowered during the operation, but the Potmicro is not moving the anode beam. This can result in an open circuit, particularly if the bath height is low.

This risk has been considered for a long time, but mitigations were relying solely on operation practices. During the operation, the operator is supposed to check visually and regularly the pot resistance. If the pot resistance is deviating from the pot target, the operator is supposed to stop the metal tapping and deal with the problem before restarting the operation.

The problem with this, is that it does not consider that mistakes happen. In a modern potline, around 10 000 metal tapping operations are performed every year. With so many manual operations, it is impossible to guarantee that all of them are done perfectly. A common practice in potline is to start tapping the metal before launching the procedure at the Potmicro. We believe that this practice is increasing the risk as any disturbance arising in between (before launching the procedure) could distract the operator and make him forget to launch the procedure. Mistakes happen and it is important to keep trying to avoid all mistakes by training and enforcing standard practices, but we should also consider that mistakes will happen anyway. Protections should be built into the system against this risk.

Protections can be built with two different objectives:

- Either remove completely the risk, i.e., make it impossible to tap the metal if the procedure is not launched at the Potmicro.
- Or detect the problem when it happens and act.

Removing the risk has been achieved by creating an interlock between the pot tending assembly (PTA) and ALPSYS. For every metal tapping operation, a direct communication is established between the PTA and the Potmicro, and metal tapping from the PTA is conditioned to an authorization delivered regularly by the Potmicro.

With this protection:

- The PTA refuses to start tapping the metal if the metal tapping procedure is not running in the Potmicro,
- During the operation, the PTA immediately stops metal tapping if, for any reason, the Potmicro procedure is stopped. For example: if anode movement failure is detected during metal tapping, the metal tapping operation must be stopped immediately.

Metal tapping interlock requires some infrastructure to work:

- An Ethernet communication between all Potmicros and all metal tapping equipment,
- A way for the PTA to identify the pot number in order to identify the Potmicro to communicate with.

While easy to install when building a new smelter, this infrastructure could be difficult and costly to install in an existing potline, thus slowing down the deployment of this solution in all smelters.

For smelters which decide not to go for an interlock, another option is to install a metal tapping detection function. This is a software function installed in the Potmicro. It is a real time monitoring function which is looking for a pattern specific to this risk. As soon as the Potmicro detects that a metal tapping operation is in progress (Figure 4), an alarm is raised to warn the operator. The issue is then dealt with easily by the operator, either by launching the metal tapping procedure in the Potmicro or by stopping the PTA. It is also possible for the Potmicro to automatically launch the metal tapping operation when the alarm is raised, without the need for an operator intervention.

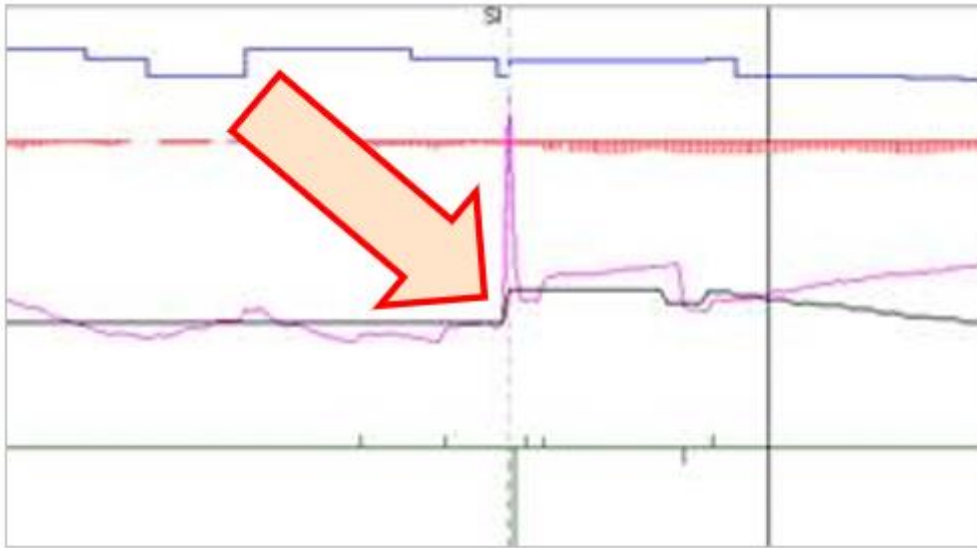


Figure 4. Example of a metal tapping operation triggered automatically.

This option is available, and it looks promising, but it needs to be considered with care. If the procedure is launched automatically, there is a risk that operators will rely on it to launch the operation for them. It is important to understand that this protection is based on the Potmicro identifying a pattern on the pot. This kind of protection is very effective when the pot follows the pattern, but if the pot deviates from the pattern, the detection may not work in some cases. The metal tapping could be discontinued, the ladle could be leaking, bath could be tapped along with the metal, the pot could be unstable, etc. Several things could disturb the pattern and make it difficult for the Potmicro to identify it. While the detection is very efficient with a very high rate of positive detection, it may miss some cases. In a smelter where this protection is installed, it is very important to continue enforcing standard practices.

This protection is less effective than the PTA interlock, but it is generally a lot easier to install as it only requires updating the Potmicro software.

2.4 Protection Against the Unknown or the Unexpected

The protections previously discussed were about cases where we know what happens in the pot; a specific scenario is described, and the system is designed to deal with it. Unfortunately, this approach is not always applicable. With the limited number of sensors available in a pot, some phenomena can happen in the pot with the Potmicro not able to detect exactly what is happening.

A first possible scenario is if the anode beam cannot move for another reason than an electrical fault, for example if an anode touches the bottom. When the Potmicro gives down orders, no electrical fault is detected but the anode beam is not moving, and the pot resistance cannot be adjusted.

Another scenario is when the pot resistance overreacts to an anode beam movement. This could lead to some unusual behavior:

- “Zipper” pots:
 - Up and down orders are done in a quick succession, that could be ongoing for hours
- Long up movement during metal tapping (Figure 5)
 - During the metal tapping operation, a lot of up orders are given even though metal is tapped. On one occasion, the anode beam went up during a total of almost 30 s!



Figure 5. Example of very long up orders during metal tapping.

Although it may be quite spectacular, there is generally no open circuit risk because the pot resistance is globally maintained close to the target.

A more dangerous scenario is if the pot resistance does not react, or not enough, to an anode beam order. In the past, we have witnessed several cases that lead to this situation:

- The first case is linked with pot instability. The waves in the metal due to the instability can sometimes be strong enough for the metal to touch the anodes. The resulting short-circuits, even if very short, significantly bring the pot resistance down. If it happens repeatedly and regularly, the pot resistance stays low even if the Potmicro raises the anode beam.
- The second case happened because of mistakes in setting the PCS system parameters. The parameter used to detect a potline shutdown was set too high. During a potline shutdown, some pots did not detect the shutdown, so the Potmicro kept adjusting the pot resistance (Figure 6). Because of the low pot voltage, the Potmicro gave numerous up orders during the potline shutdown. As a result, several pots had anodes almost out of the bath when the potline was about to be restarted.

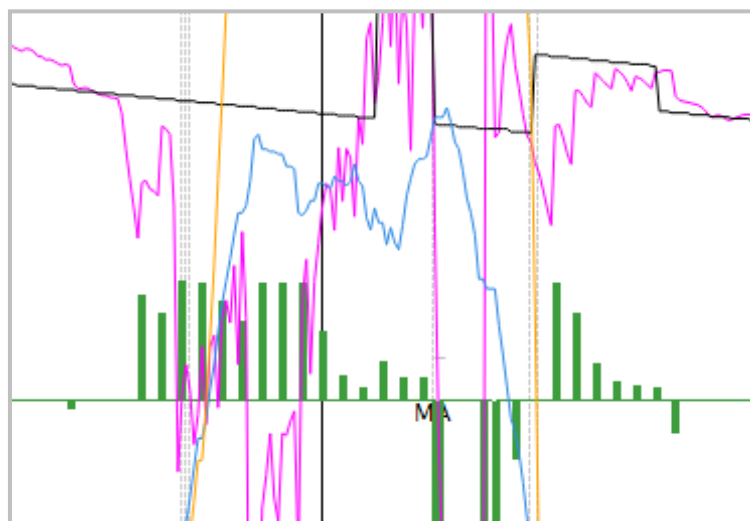


Figure 6. Example of low pot resistance (magenta curve) despite numerous up orders (green bars).

It is obviously impossible for the Potmicro to detect these problems. It is however possible to detect the consequences. If you cannot identify the root cause of the problem, you can always try to treat the symptoms. Here, the symptoms are having the pot resistance not going up despite numerous up orders.

A protection is based on monitoring the number and the total duration of orders given by the Potmicro.

A fault is declared if too many orders are given in the same direction over a preset period, or if the duration of all orders given during this time is too high. In order to be efficient and cover many different cases, this protection is multiple:

- A first lowly critical detection is based on a short time window, and is used to only trigger an alarm. This is just an indication that something is wrong, but it could be a normal situation due, for example, to some instability or to some ongoing operation on the pot.
- A highly critical detection is based on a long-time window (around 6 to 8 hours). This is a strong indication of an open circuit risk happening, so it triggers an alarm and stops any anode beam movement order.
- Another critical detection is specifically done during metal tapping operation. It can indicate, for example, that the anode beam is stuck for a mechanical reason (like anode touching the lining).

Many protections have been installed, and more may come, but it is important to understand that the efficiency of this kind of protection is limited because it is based on pattern recognition. If protections parameters are adjusted to guarantee detecting 100 % of cases, then false detections will occur, and, if too many false alarms are triggered, people will stop responding to it. This can be observed in many situations.

Despite it not being 100 % efficient, it remains a very good protection. Only based on software, it is a very low-cost protection that can save a potline.

2.5 The Last Defense

As discussed above, all the protections integrated in the system, although very efficient, cannot guarantee a 100 % success rate of open circuit detection. The reason is that there are limits to what the protections can detect. For example, an open circuit failure can sometimes be very quick. If the protection does not rely on a sensor (like a contactor failure), then the system may not have enough time to detect the issue.

A anode clad failure, a pot short-circuit wedge failure, a pot tap-out are all examples of these failures:

- The failure cannot be directly detected by the Potmicro, only the consequences are visible to the Potmicro.
- It may unfold in a very short time frame so all protections based on orders duration monitoring may not be able to react.

Detecting the event is then a major challenge. Some faults may be detected with additional sensors. Clad failures, for example, can be detected if the Potmicro has access to real time anode current distribution, but this is costly.

If it is impossible to detect the fault itself, then it is impossible to totally prevent the open circuit. Another option is then to try to detect the open circuit as soon as possible, to reduce consequences

as much as possible. As discussed before, potline protection is very effective but may be slow to react because the open circuit pot is “hidden” in a lot of other pots. To improve effectiveness, we need to move this protection to the Potmicro itself.

The problem then can be stated as the following: How can a Potmicro make the difference between an anode effect and an open circuit? Studies have been done on this subject and the preliminary conclusions are that it seems possible to create a detection in each Potmicro, with the objective for the Potmicro to send a shutdown order to the substation upon detection.

The second question is: Is it possible to detect an open circuit before the substation, enough in advance to make a difference? The results of our preliminary studies, when applied to the open circuit case discussed previously, show that the open circuit duration would have been divided by 3, and the total power consumed during the open circuit would have been divided by 4. We can confidently assume that this will result in a significant reduction of the consequences for people and equipment.

Additional work and tests are still necessary to integrate this kind of protection in ALPSYS, but it looks very promising.

3. Conclusions

Contactor feedback or anode beam position feedback is a must. Having a timer switch and no contactor feedback is not enough to prevent open circuits. Each smelter not having it should be looking into installing it.

Depending on pot technology, the maintenance can have a very significant impact on open circuit detection efficiency. For a smelter relying on non-fail-safe protections, a very strict maintenance policy needs to be enforced to maintain the risk at an acceptable level.

Always consider risk that could be created by the mitigation actions (people should not rely on risk protection to do the job). A high level of training to open circuit protections should be maintained for operators in a potline.

Regarding ALPSYS development, several evolutions have been implemented in different smelters and other improvements are under study to develop protections with the objective to greatly reduce the occurrence and the consequences of an open circuit.

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