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Abstract. The Large Hadron Collider (LHC) operates using superfluid helium provided by eight large refrigeration units (2.4 kW @ 1.8 K each). These units supplied by specialized cryogenic industrial suppliers are composed of serial hydrodynamic cold compressors based on an axial-centrifugal impeller coupled with volumetric warm screw compressors. The process control systems delivered by the suppliers have been installed, commissioned and operated reliably for more than 13 years. However, the implemented process control closed configuration approach limits of the operational diagnostic, and required operational flexibility and adaptability of the cold compressors systems. In the frame of the CERN evolution of process control standards, the LHC cryogenic operational requirements together with the end of electronic components life cycle has motivated an upgrade of the whole process control system.

Through a step-by-step analysis process including the initial operational risk analysis, CERN has conceived and engineered two prototypes with their dedicated functional analysis and process control logic to cover the complete range of system operation. These prototypes have been initially fully tested in an off-line configuration and after that validated in real system operation.

This paper presents the whole process, the successful results obtained and the perspectives for the future deployment during the LHC Long Shut-Down 2 (2019-2020) period.

1. Introduction

The Large Hadron Collider (LHC) operates using superfluid helium making use of eight large refrigeration units (2.4 kW @ 1.8 K each). These eight units have been provided following CERN requirements [1] by two different suppliers (IHI-Linde® and Air Liquide®) using close technologies but presenting differences on the design. Air Liquide® units are based on three serial hydrodynamic Cold Compressors (CCs) coupled with two parallel volumetric warm screw compressors whereas IHI-Linde® solution is composed of four CCs and two serial warm screw compressor. The two solutions were tested in a dedicated test facility at CERN using "pre-series unit" [2] allowing to evaluate the different control strategies proposed by the suppliers [3][4] and an alternative strategy proposed by CERN. These control strategies presented different operational results depending on conditions (pump-down, stability, connection with very low pressure line and standalone) and a combination of those strategies have been successfully used by CERN since then. In 2015, after the first 5 years of operation, the study of the availability for the user aside with the root failure causes analysis has led to important hardware consolidations and upgrades [5].

The different control strategies used are causing different constraints in term of operation that can be improved. On one side, the supplier's control logic is considered as a "black box", it causes significant diagnostic limitations making difficult to fully answer to a particular problem and one of the units in operation was not able to operate at nominal pressure without any clear diagnostic possible. On the other side, the implemented control logic requires too much manual operations that could lead to higher connection time with the very low pressure line. These constraints are a serious difficulty to fulfil the operational flexibility and availability requirements of the cold compressors system. This reason, alongside with the end of electronic components life cycle has motivated an upgrade of the process control system.

2. Current control strategies
The main difficulty with the cold compressors control comes from the serial compressors design (see Figure 1). Each of the compressors needs to keep a reduced speed Nr (equation 1) good enough to pump down depending on its reduced flow Mr (equation 2) and pressure ratio PR (equation 3) without reaching surge/choke lines (respectively the stall and flow saturation lines), those conditions are influenced by the speed of the previous compressor in the series.

$$Nr = \left(\frac{N}{\sqrt{T_{in}}} \right) \cdot \left(\frac{\sqrt{Td_{in}}}{Nd} \right) \tag{1}$$

$$Mr = \left(\dot{m}.\frac{\sqrt{T_{in}}}{P_{in}} \right) \cdot \left(\frac{1}{\dot{m}d}.\frac{Pd_{in}}{\sqrt{Td_{in}}} \right) \tag{2}$$

$$PR = \left(\frac{P_{out}}{P_{in}} \right) \tag{3}$$

Where N is the speed, $\dot{m}$ the mass flow, T_{in} the inlet temperature, P_{in} the inlet pressure and $Nd, Td_{in}, Pd_{in}, Td_{in}$ the corresponding design values.

Surge and choke lines depend on the compressor inputs (flow, temperature and pressure), it represents the maximal and minimal possible speed of the impeller without loosing pumping capacity. Inlet flow, temperature and pressure are subject to fluctuations due to operational and design related reasons. In order to eventually reach the desired pressure, several control strategies are implemented within the different installations.
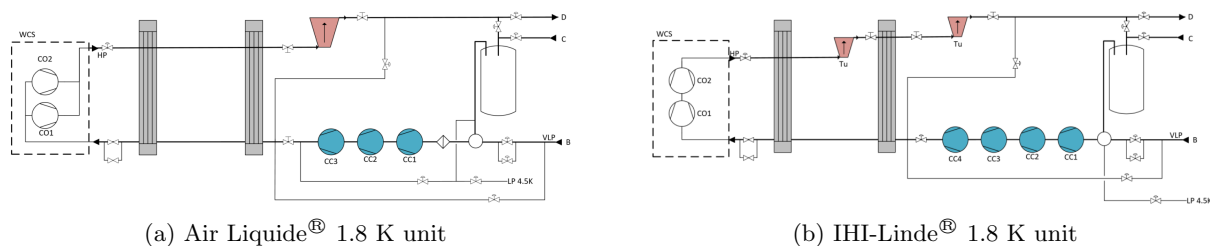

(a) Air Liquide® 1.8 K unit   (b) IHI-Linde® 1.8 K unit

Figure 1. Process flow diagram of the LHC 1.8 K refrigeration units

2.1. Air Liquide® 1.8 K refrigeration units control
The solution currently used in Air Liquide® stations has been developed by CERN and consists in driving the CCs speed by the PR of CC_3 and CC_2 individually and controlling the inlet pressure with CC_1 through PID controllers. Controlling the PR limits the impact of flow fluctuations on the compressor which affect both inlet and outlet compressor pressure. The idea is to use first the CC_3 and start the other ones sequentially to minimize fluctuations between

two CCs, to do this the raise of the different PR setpoints are shifted. The CC_1 is then used to control a precise desired inlet pressure at low pressure, whereas the other ones provide a large pressure ratio especially during transient phases.

Depending on the mass flow, a nominal PR for each CC is calculated using curves provided by the supplier, then depending on a so called *Increment value*, a percentage of nominal PR is determined for each compressor, it is then used as setpoint for the PI controllers (see Figure 2).
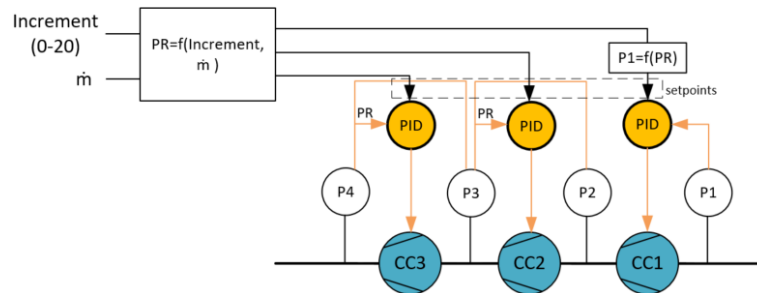

Figure 2. Process control of Air Liquide® units

2.2. IHI-Linde® 1.8 K refrigeration units control
On IHI-Linde® units, two different modes are used, the first one is used during high-pressure (HP) phase (above 90 mbar), and the second one is used in low-pressure (LP) phase. Both calculate Nr values for each of the CCs, the switch between the two modes is handled automatically and then the Nr is used to calculate the corresponding speed (see Figure 3).
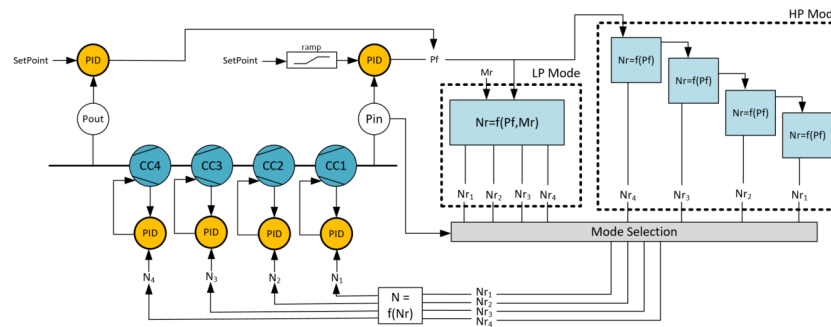

Figure 3. Process control of IHI-Linde® units

2.2.1. High pressure mode   This mode is derivated from the solution developed by CERN and used in Air Liquide® stations. It follows the same principles, starting first CC_4 and then sequentially CC_3, CC_2 and CC_1 but there is no control of individual PR. The inlet pressure PI controller gives a pressure factor (Pf) and a function calculates the Nr to be applied to CC_n and the Pf to be applied to CC_{n-1}.

2.2.2. Low pressure mode   This mode principle is different, in a first time, a PR setpoint is calculated using pressure factor and Mr. Then depending on Mr, a trajectory is chosen from the several possible provided by the supplier [4]. Those trajectories give Nr values for the four CCs and moving from one to another allows to adjust distances from the surge and choke lines.

3. Hardware consolidations

The CCs and their dedicated programmable logic controllers (PLCs) have been commissioned together more than 13 years ago and PLCs reached the end of their life-time cycle. The refrigerator @ 1.8 K is driven by a master PLC using CERN standards (CERN/UNICOS). Since this PLC will be refurbished in the scope of the Long Shutdown 2, it has been decided to integrate the software of the PLC used for CCs in this master PLC. To perform that, a complete reverse engineering of the Cold compressor software has been done and is used as frame to produce the new updated logic. As previously mentioned, the electronic components also reached their end of life cycle, moreover, the removal of one PLC necessitated consequent changes on the electrical installation so it was a good opportunity to review completely the whole installation.

Several hardware interlocks were redundant, moreover most of those interlocks were also present in the PLC as software interlocks, the installation then presented an excessive number of safety features that caused ultimately diagnostic difficulties. Moreover the Variable Frequency Drive (VFD) start cycle was difficult to operate and needed expert intervention to start correctly. For the new design, the *ISO 13850:2015* standard has been used as a reference for safety of machinery and emergency stop function. In the scope of machine protection, only the magnetic bearing levitation loss signal, which is ultimately the risk for the machine is now used as a hardware protection and any other interlock is coming from the PLC as software interlocks.

The simplification of the whole electrical design by removing a PLC and simplifying the interlock chain provide a better diagnostic capacity and improved the global reliability of the installation. This follows previous electrical consolidation initiated in the scope of radiation protection [6].

4. Software improvements

4.1. Common improvements

4.1.1. Warm gas inlet control   Cold compressors in operation are extremely sensitive to incident gas velocity fluctuations on their impeller, which are directly linked to the inlet gas temperature variations and can cause a drift of the compressor working point within its pressure field, eventually getting beyond surge or choke line. In order to control this inlet temperature, the cold compressor stations are equiped with a warm gas inlet (@300K), a control valve driven by a PI controller and a mixing chamber. The setpoint of this PI controller was calculated depending on the actual overall pressure ratio but this led to two main problems.

The first problem is that any fluctuation of the inlet pressure caused a variation of the setpoint and thus a variation of the opening of the valve that fuelled the fluctuations in a vicious cycle. Secondly, using this principle, dead-end situations appear when inlet temperature is not low enough to pump down and pressure is stable, then inlet temperature setpoint is not lowered because pressure doesn't move. In practice, the valve was managed manually most of the time, particularly during a reconnection where the pressure disturbances are frequent but also in the previously described blocking situation.

Setpoint calculation has been changed, instead of using the measured PR, the outlet pressure divided by the ramped input pressure setpoint is now used (ie : the desired PR knowing the output pressure). The use of this linearly decreasing value allows to solve both problems because on one hand, the setpoint is not subject to inlet pressure fluctuations anymore and on the other hand, it controls the temperature depending on desired pressure and then avoid dead-ends.

Tests in situ has shown this new handling very efficient and freed this part of the process from human intervention thus earning significant reliability and reconnection time stability.

4.1.2. Surge detection   When a compressor crosses the surge line, it induces brutal change of pressure and produces strong axial load that could induce an overload stress on the magnetic

bearing system and could eventually damage the compressor. That makes surge detection a crucial feature that will trigger a complete stop of the pumping process.

Analysing previously observed surge trips (see Figure 4), a new detection method has been implemented and successfully tested on site, a trip is triggered when absolute temperature and pressure derivatives are overpassing a certain threshold on all CCs within a certain time window.
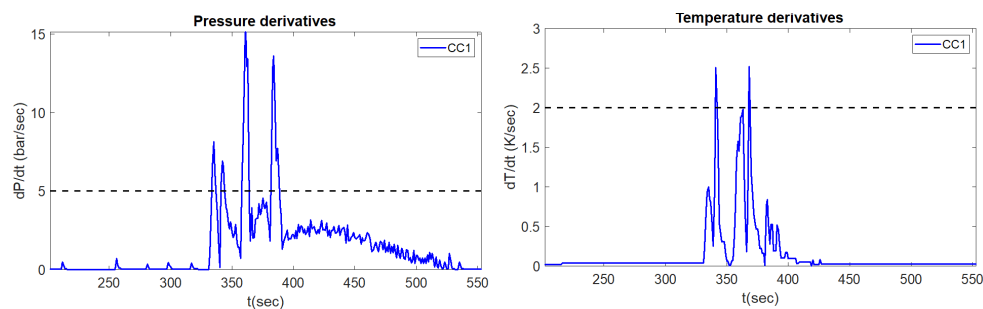

Figure 4. Pressure and temperature derivatives during a surge trip

4.1.3. Outlet pressure mitigation Since cold compressors are coupled to volumetric warm compressors, the maximum pressure at CCs outlet depends on the capacity of the warm compressors that can be overloaded in case of overpressure. The existing control process didn't control this pressure hence an overflow could cause a trip on warm compressors that stops the pumping station.

To solve this issue a PI controller over outlet pressure has been added, its output is used in two different ways on IHI-Linde® and Air Liquide® stations. On IHI-Linde® test station it reduces the output of the global inlet pressure controller (see Figure 3). In the case of Air Liquide® stations, this mitigator reduces the *increment value.*

This allows totally automated control of outlet pressure that was done manually before, it avoids overflows increasing safety for the machines and deleting the potential loss of time linked to a stop of the station.

4.2. Air Liquide® specific improvements

4.2.1. Automatic pressure setpoint handling   As seen in 2.1, an *increment value* determines the respective percentage of nominal PR to apply to each CCs using dedicated curves. For the sake of the process stability, smooth changes on the PR are necessary hence the shape of the *Increment/Percentage of nominal PR* curves [2] (see Figure 5).

First operational problem this solution presented was that the CC_1 had to be operated manually because it was starting to accelerate at too high pressure causing perturbations and eventually trips. This was solved by correcting CC_1's curve, thanks to years of operational experience, an increment value has been determined to start increasing the PR setpoint of the CC_1 without causing perturbations (see CC_1 old and new curves in Figure 5).

Second problem is that cold compressors pumping had to be operated manually modifying the *increment*, a non-unit value from 0 to 20 which is non-meaningful for operators. A solution was found to calculate input pressures for different values of mass flow and *increment*, the obtained curve (Figure 5) is then used to match the necessary *increment value* to reach a desired input pressure depending on current mass flow. This solution is used with a ramped value of desired input pressure and allows to operate in a fully automatic way by just providing the final input pressure wanted.
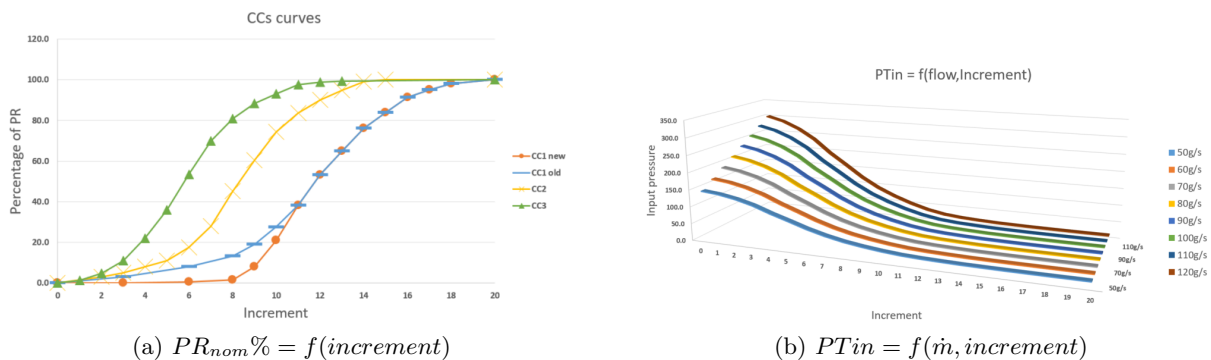
(a) $PR_{nom}\% = f(increment)$ (b) $PTin = f(\dot{m}, increment)$

Figure 5. Increment curves

4.2.2. Control validation using dynamic simulations Due to the operational constraints of the LHC, the allocated time to re-validate such control modifications is very limited and all verifications using the real installations cannot be done properly. In order to cope with these constraints, it was decided to validate these control improvements on an existing dynamic model of the Air Liquide® 1.8 K refrigeration unit. This model was developed during the commissioning phase using the modelling and simulation software EcosimPro and it can be easily coupled to a copy of the control system [7]. The following scenario has been simulated for this validation:

- t=0 hr: The refrigeration unit is in cold-standby with CCs in idle mode at 160 *mbar*.
- t=0.5→1.5 hr: Pumping of the refrigeration unit in stand-alone from 160 *mbar* to 30 *mbar*.
- t=1.5→2 hr: Reconnection of the very low pressure line to the CCs at 30 *mbar*.
- t=2→10 hr: Pumping of the very low pressure line from 30 *mbar* to 16 *mbar*.
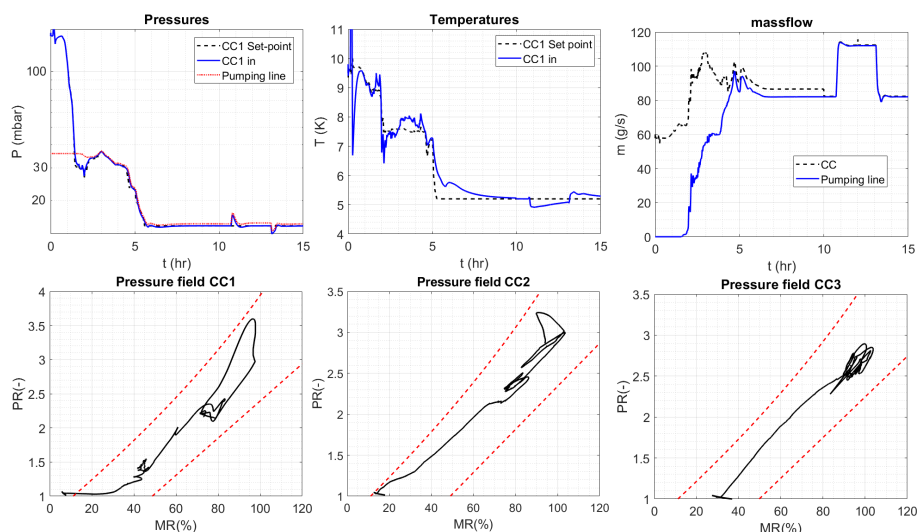- t=10→14 hr: Dynamic response of the CCs during a quench recovery.

Figure 6. Dynamic simulation during the pumping phase and during a quench recovery with an Air Liquide® refrigeration unit

The needed time to perform this sequence is about 15 hours. During the simulations, several issues were identified and corrected at each time in an iterative way to obtain finally the desired results. Five simulations were necessary to complete all validations, representing about 100

hours of operation. As the simulations were performed five times faster than real time, only 15 hours of simulations were necessary, representing a significant time saving without disturbing the LHC operation. The main process values simulated during this sequence are represented on the Figure 6 where we can notice a correct control of pressures and temperatures during transients, staying in the safe areas of CCs, even during strong disturbances such as a quench.

4.3. IHI-Linde® specific improvements
4.3.1. Pumping capacity improvement On one of the four IHI-Linde® unit installed over the LHC, the pumping performances were not optimized and the system was not able to reach the design pressure of 15 mbar but only about 20 mbar. In order to solve this issue, this unit has been the first to be renewed and the new control system has been tested on this one. Analysing the Mr/PR curves of each CCs, an under-exploitation of CC_3 was detected. It has been observed that CC_3 never reached the optimal trajectory on Mr/PR diagram when the other compressors were better positioned in their respective pressure fields. A correction was applied to trajectory curves of CC_3 to provide a slightly higher speed. The on site tests showed a satisfying trajectory for this compressor which improved the pumping capacity of the system.

Moreover, a slight slide between speed setpoint sent by the Variable Frequency Drive (VFD) and measured value has motivated the adding of a closed loop control of the motors' speed.

Those corrections solved the pumping issue and the design pressure has been reached by the new control system.

4.3.2. Temperatures re-calculation In IHI-Linde® cold compressor units, it is necessary to have consistent temperatures to calculate the speed from Nr value. The units are equipped with several temperature sensors distributed along the serial compressors, those sensors are not 100% reliable, they can break or produce spikes. So in order to avoid a wrong speed calculation that could lead to stop the pumping or even damage the compressors, a re-calculation of the temperatures has been developed by Linde.

It consists in, first determining a temperature ratio TR for each compressor depending on its PR, Mr and isentropic efficiency (η), then using those pressure ratio and the temperature sensors values to re-calculate the inlet temperature T_0. When T_0 is known along with the respective TR of each compressor, every temperature can be found easily one after the other ($T_1 = T_0.TR_1$, $T_2 = T_1.TR_2$, etc). In order to be free from spike sensitivity, the value of this re-calculated inlet temperature is smoothed. The used η values are theoretical values provided by IHI-Linde® and depend on the total PR and chosen trajectory which allows not to rely on temperature sensors. This solution provides consistent temperatures but it has limits due to the use of all temperature sensors in the calculation even the broken ones.

The function has been extended so that any broken sensor is removed from the calculation of the inlet temperature and then doesn't affect the result. The calculation can then be made using only one working sensor, the more sensors available the better would be the calculation. Those changes improved the accuracy of the calculation enhancing the global reliability of the system.

4.3.3. Results The final control system for IHI-Linde® station has been deployed after quality insurance validation then intensively tested on site (around 10 days of test), adjustments of the control process have been added during those tests. Since then it has been used on production for the LHC normal operation for more than a month presenting satisfying stability on steady state conditions and good performance for reconnection. The differences between setpoints and measured values for both temperature and pressure that can bee seen in Figure 7, can be explained by the constant adding of liquid helium in the magnets during their cool down phase. On steady state phase, a pressure of around 16 mbar has been reached with a temperature of

4.8 K which represents nominal operational conditions. It can be noted that CC_2 and CC_3 theoretical surge lines have been crossed without consequences on pressure, it shows that those lines don't represent exactly the reality (because of measurements imprecision), new detection method allows to trigger real consequences of a surge.
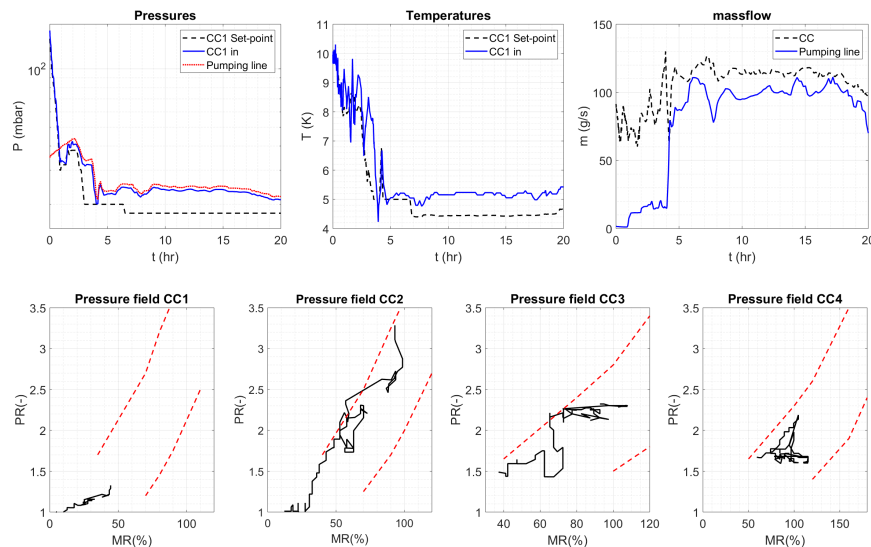

Figure 7. Measurements dring pumping phase on LHC for the IHI-Linde® refrigeration unit using new logic (October 2018)

5. Conclusion

In the scope of LHC long shut-down, several hardware and software modifications have been initiated on both CCs unit types. On the hardware part, the simplification of the control and electricity architecture gives a better global reliability of the system. On the software part, the reverse engineering and rewriting of the control logic using CERN standards give the possibility to better diagnose specific problems and have allowed to initiate new features and improvements. Those changes aim at improving machine protection (surge detection) and automatize numbers of manual operations and thus improve significantly the global reliability of the process along with the standardization of the reconnection time. The two prototypes created for both units types have been intensively tested on site for IHI-Linde® unit, on simulation for Air Liquide® and present satisfying results. These consolidations will be implemented to all units during Long Shutdown 2.

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