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Overview of different control strategies for a typical cryogenic warm compressor station at CERN

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Abstract. Helium cryogenic systems are extensively used at CERN under several configurations for accelerators and detectors. The Warm Compressor Station (WCS) is the primary component of the helium cryogenic systems. The basic controls structure mainly depends on the bypass, charge and discharge valves configuration ensuring the nominal flow and compression ratio. This paper presents three studied methods for the WCS process control systems covering all transient and operational requirements: the proportional-integral-derivative (PID) control approach, the Fuzzy Logic Control approach (FLC) and the Internal Model Control approach (IMC). The paper emphasizes on simulation results of the different control strategies using Ecosimpro software associated to the CERN CryoLib library. Advantages and limitations of each method are presented.

1. Introduction
The Warm Compressor Station (WCS) is one of the main components of the cryogenic systems used at CERN [1]. Its optimal functioning depends on many factors [2] including the right choice of the control methods and their tuning. The WCS can be found in various experiments, buildings and facilities under different configurations, capacities and constraints, thus a centralized study of the control methods is interesting for CERN's cryogenics group.

Different studies have been made over advanced control methods in many applications. Normally the non-classical method is compared with the proportional-integral-derivative (PID) approach to show its improvements. This study compares two advanced control methods and discusses their advantages applied to WCS. The chosen methods are the Internal Model Control (IMC)[3] [4] and the PID-like Fuzzy Logic Control (FLC) [5]. After an introduction about the compressor station used for these studies and the hypotheses made, the criteria to compare the control methods are presented with the results obtained in simulation.

2. Compressor Station
There are many different configurations for a compressor station used according to the flow and pressure needed for the cryogenic system. All of them share the same basic structure, which is composed of one or more compressors, a buffer system and some control valves, as shown in Figure 1.
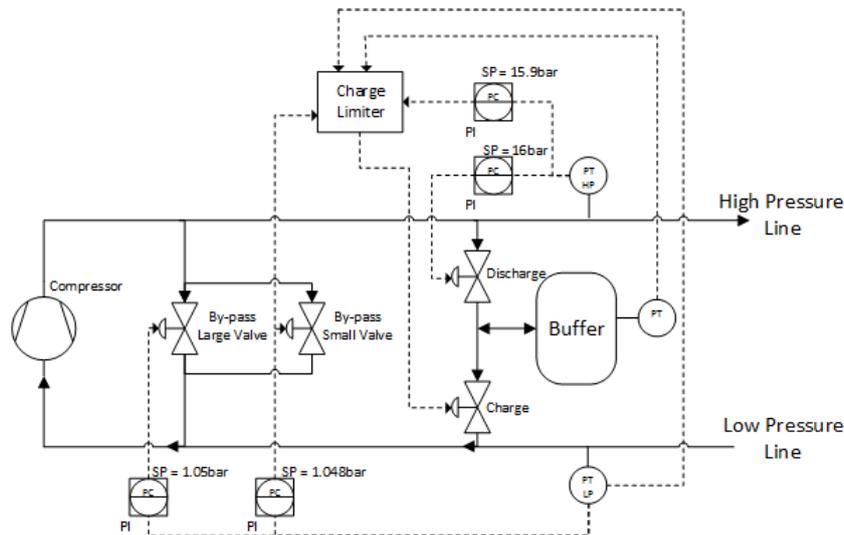
Figure 1. Overview of the PI control approach

The Bypass Valves allow the pressure control of the low pressure (LP) line. It is composed of a large and a small valve in parallel, making it possible to control even big quantities of gas with precision.

Two other valves called charge and discharge control the high pressure (HP) line. If the pressure in the HP line is below a given set-point (SP), the station will charge LP giving more gas for the input of the compressors and thus, raising the pressure in the HP line. On the other hand, if this pressure is too high, the discharge valve opens in order to store some of the gas in the buffer. These two valves must never be open simultaneously.

3. Operational Constraints and Hypothesis
For the purpose of being able to compare the performance of all the different configurations, it is important to first determine some compressor station specifications independently of the control techniques to be tested.

(i) The compressor station is composed of a LP line and a HP line. Even though, there are some configurations of compression station that also have a Medium Pressure Line. Those cases, can be treated as an extrapolation of the one discussed in this study, where there are more levels of compression and thus, better control on the valves to regulate the required different pressure values.

(ii) The regulation methods created must be able to operate in two different modes:
- **Regulation**: The closed loop controller output signal is driven by the control method applied.
- **Output Positioning**: The control loop is bypassed and the output signal is assigned to a desired value (Auto or Manual position request).

4. Performance and Robustness Criteria
The conception of the control system can be generally divided into two categories, the performance specifications and the robustness specifications. The performance specification describes the desired response of the nominal system to command the inputs. The robustness specification limits the degradation in performance, due to systems variations and disturbances [6]. The evaluation of the control system must be done by selecting the most relevant criteria

for each case[7]. The specification followed for the conception and comparison of the control methods are:

(i) The set-point of the LP line (**LP**) is always constant, thus the goal of the control in this line is to **reject disturbances**, regardless of other constraints.

(ii) **Prevent the pressure in the LP line from reaching high values**. Given that the compressors operate in a volumetric principle they might not work properly if the input pressure reaches **0.2 bar over the operational set-point**.

(iii) The pressure in the LP line is also extremely important for the Phase Separator in the Cold Box and for the good functioning of the turbines in the Cold Box. Hence, **the control implemented on the LP line must be faster than the one applied to the HP line** to ensure the regulation priority between the lines.

(iv) **The HP might be subject to set-point changes**. Hence, the control system must perform well when facing this kind of variation.

(v) It is preferable to **keep the discharge and the Bypass Valves closed as much as possible**. That is because their opening is considered a waste of energy. Even though the four previous criteria have priority over this one.

In addition, there are still some criteria concerning the structure and resources used by the controllers:

(i) **The implementation on the PLC**: The controller developed must be feasible and should not be excessively demanding to the PLC processing.

(ii) **The maintenance procedure**: If the control method is complicated to understand it is not going to be usable in a real application. Any operator might be able to understand and change the parameters of the controllers and correct anomalies when required.

5. WCS Control Methods

In this paper, the application of three different control methods is discussed. The first one is the classical approach with PI controllers that is going to be a reference for those two advanced methods applied: Fuzzy Logic Control (FLC) and Internal Model Control (IMC).

5.1. PI Control Approach

The PID controllers are the most common solution for industrial control systems. It is possible to find different PID configurations for a multiple-input multiple-output (MIMO) system like a compressor station. A configuration with four PI controllers acting on the four valves, as shown in Figure 1, to control the HP and the LP has been chosen. In order to minimize the coupling between the controllers, several techniques are used:

• The HP set-points, for both the charge and the discharge valves as they are antagonist actuators, are slightly different in order to avoid the opening of the valves at the same time.

• The LP set-points for the small and the large Bypass Valves are slightly different so that the small valve is used first and the large valve is used only if the flow through the small valve is not sufficient.

• When an important charging occurs to maintain the HP, it can disturb significantly the LP as an undesired effect. To prevent this effect, a charge limiter is installed on the PI controller output controlling the charge valve (PC189) to limit the valve opening in case of too high LP. This limiter works as follows : if the small bypass valve is below 12 %, the charge valve maximum opening is limited as a function of the buffer pressure. If the LP value is above 1.12 *bar*, the charge valve maximum opening is reduced by 1 %/*sec*. In the end if the LP falls below 1.1 *bar*, the charge valve maximum opening is increased by 1 %/*sec*.
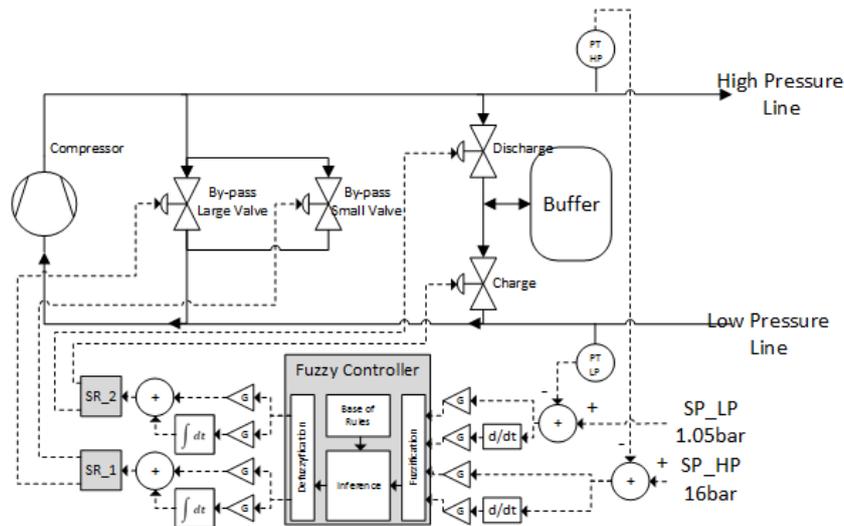
Figure 2. Overview of the PID-Like Fuzzy Logic Control approach

5.2. Fuzzy Logic Control Approach

The FLC method employed for this application is a PID-like FLC, developed as an adaptation of the method PI/PD-like FLC presented by [8] with the analysis made by [9] over the PID-like FLC configuration. The system overview can be found in the Figure 2.

The controller calculates the error between the measured value and the set-point of both lines and their derivative errors. The outputs of the fuzzy logic are the opening of the Bypass sub-system and the opening of the Charge/Discharge sub-system. Each output is divided into a direct component (for a fast control action) and an integrated component (to treat the steady-error), before being superposed again, thus defining the FLC as a PID-like. Hence, even though the overall solution measures two pressures to control four valves, the fuzzy logic in the core controller has **four inputs and two outputs**.

The control signal of each sub-system passes through a Split Range (SR) logic to split the position request to the four valves.

As explained by [10], the fuzzy logic implemented is called normalized, because all of the universes of discourse (that is the domain in the x-axis of the membership functions) are equal to $[-1, 1]$. The gains (G) shown in Figure 2 are needed to scale between the normalized universe of discourse and the real one. The use of the normalized fuzzy logic is very useful to the maintenance of the controller. It allows the operator to dramatically change the behavior of the system just by adjusting the gains, without the need to access the fuzzy logic. This is done by understanding the function of each gain, and adjusting it through the questionings: What should be in_{max} in order to generate the out_{max}? And what should this out_{max} be? Questions that the operators can easily answer. There are also methodical ways to do so, such as the application of the Linear Quadratic Regulator (LQR) gains [10].

The membership functions (MFs) employed for this problem are described in a normalized universe of discourse in the Figure 3.

The output memberships are singletons, so the **Sugeno Constant Inference System** is used. The meaning of the MF names are $[NL, NS, Z, PS, PL] =$ [Negative Large, Negative Small, Zero, Positive Small, Positive Large].

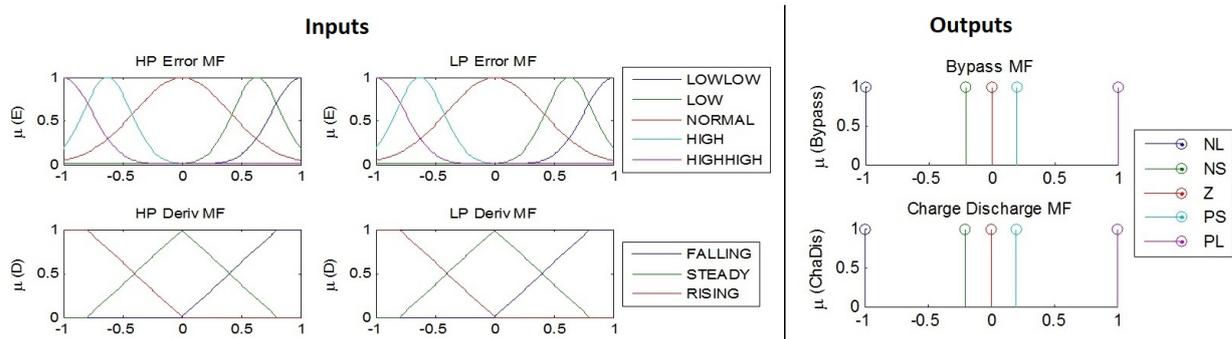The base of rules of this system is composed of 16 rules, as shown in the table 5.2.

Figure 3. Normalized membership functions used for the Fuzzification.

Table 1. Base of Rules

Bypass Opening					
Deriv\LP	LowLow	Low	Normal	High	HighHigh
Falling			PS		
Steady	PL	PS	Z	NS	NL
Rising			NS		
Charge/Discharge Opening					
Deriv\HP	LowLow	Low	Normal	High	HighHigh
Falling			PS		
Steady	PL	PS	Z	NS	NL
Rising			NS		
Charge/Discharge - Given the LP overloaded					
HP\LP	LowLow	Low	Normal	High	HighHigh
HighHigh	NL	NS	-	-	-

5.3. Internal Model Control Approach

The Internal Model Control (IMC) is based on finding a mathematical model of the process to improve the traditional PI approach. As shown in Figure 4, a solution with three IMC blocks is implemented as explained in [11], with a feed-forward control included in the low pressure control to avoid significant LP overshoot in case of charging. A pretty simple linear model can be found for such a compression station using a few reasonable approximations that take into account only the main volumes and compressor flows as input data[12].

6. EcosimPro Test Protocol

Every configuration passed through the same set of tests. The simulations were implemented in the software EcosimPro 5.6.1 using the cryogenic library CRYOLIB [13] in an Intel Core i7-6700 CPU @ 3.4 GHz with 8.0GB RAM. The model of the compression station consists in 560 algebraic equations and 74 differential algebraic equations and the cold box is simply approximated by an equivalent volume requesting a certain mass flow.

The test sequence is composed of disturbances and transitions present in the normal functioning of a compression station. Some of them are even simulated with an additional intensity, to better test the robustness of the control methods and assure a good performance in the real application. The sequence test consist of the following steps:

(i) From a stable initial state, the first dynamic induced in the system is a positive **step in the SP of the HP line**. Due to consequent opening of the charge valve, the LP line might
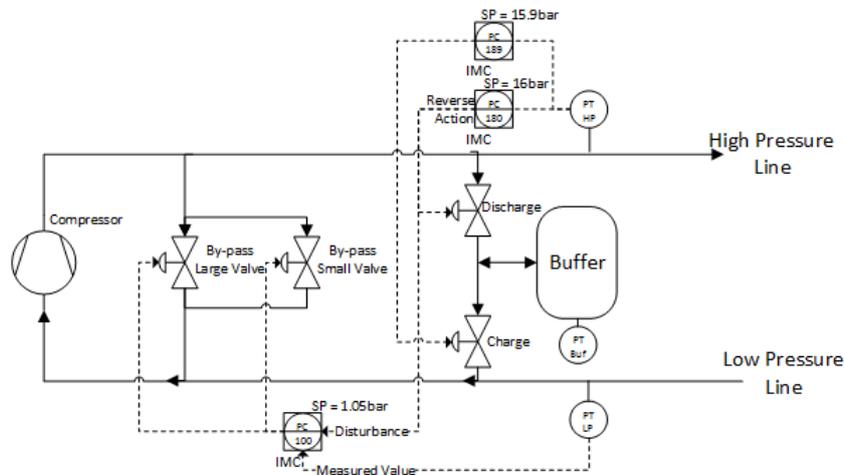
Figure 4. Overview of the Internal Model Control approach

show a reaction, which the control system must keep as small as possible to maintain the LP on its SP, while keeping the approximation of the HP to the new SP as fast as possible.

(ii) In a second moment, the inlet and outlet valves are opened, **connecting the compression station to the Cold Box**. This might reduce the pressure in both lines, letting the control system drive them to their SP.

(iii) Next, the **turbines in the Cold Box are turned on**. Which might cause oscillatory disturbances in both lines with which the controller has to deal.

(iv) The **turbines turn off**.

(v) The LP receives a **sudden input of gas** coming from the Cold Box. This disturbance reproduces the effect of a quench (resistive transition of the superconducting magnets) in the client [14].

(vi) The **SP of the HP receives a negative step**, equivalent to the first disturbance applied. Nevertheless, in this case, the step is being applied while the Cold Box is still connected, thus the system should behave differently.

7. Simulation Results and Discussion

Many simulations were made to compare the differences between the control methods. In this section simulations with and without delay are shown to highlight the most important analysis.

The choice of the PI parameters is based on the Åström-Hägglund [15] tuning rules and adjustments were made to follow the robustness criteria (section 4). This approach requires to adapt the parameters after the connection to the Cold Box, given the consequent change on the system behavior.

The calibration of the fuzzy solution is made only by the adjustment of the gains, as explained in the section 5.2.

The IMC controller takes as inputs the volumes and flows of compressors for the modeling parts and there is a tuning parameter λ to adjust the desired time constant of the closed loop. Note that the model volumes can evolve over time according to the connection of the coldbox that makes a significant change of volume and thus on the dynamics.

The results collected by the simulations are shown in Figure 5. Set-points are represented in a dashed-black line. The pressures of the system controlled by the PI approach, the IMC and the FLC are respectively represented in yellow, blue and red.
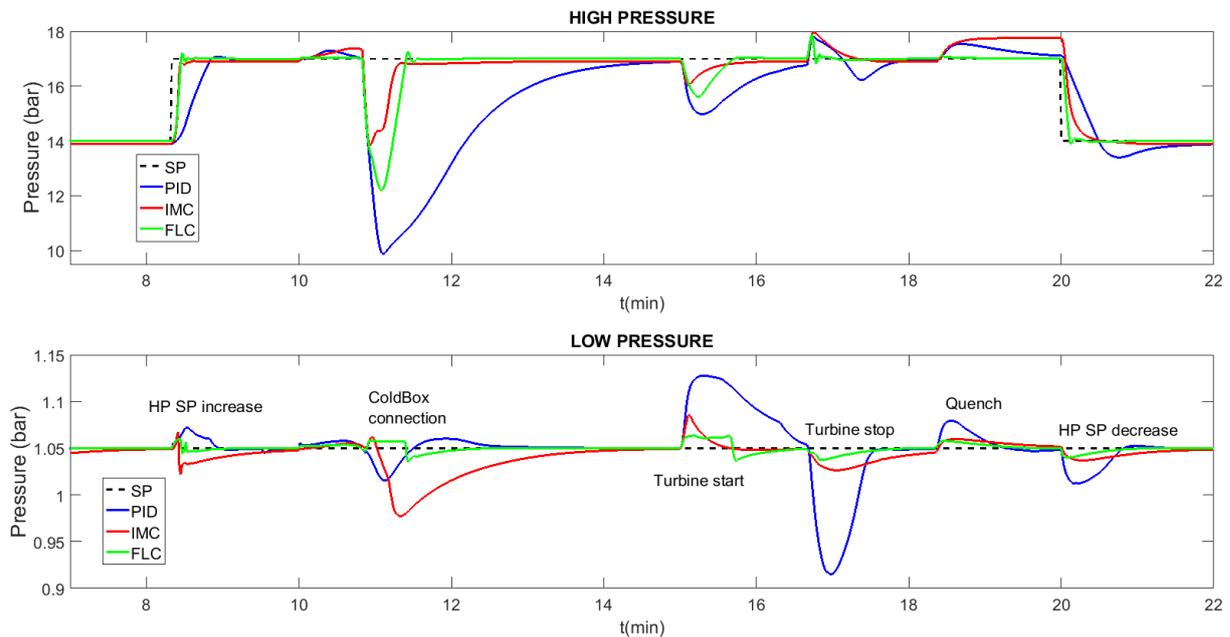
Figure 5. Pressure control comparisons between PID, FLC and IMC

As previously stated, the focus of the analysis is to compare the IMC with the FLC, using the PI control as a reference. In the Step in HP_SP, is possible to see an overshoot on the HP control with the FLC, while the IMC responds just as fast, but without an overshoot. On the other hand, the regulation of the LP is faster in the FLC case. Over the next two disturbances, the FLC performs a faster and more effective control action in the LP than the IMC. However, the HP tracks back to the SP faster under the IMC control method. Lastly it is possible to notice a small steady-error in the HP of the IMC, not present in the FLC.

In the second and final section of the simulation representing four disturbances, the FLC presents a faster response than the IMC in the HP. It is important to highlight the good performance of the fuzzy regulation over the quench disturbances. These situations are unpredictable and capable of causing enormous problems in real application when not well treated [14]. As is possible to see, the two solutions respond differently to this kind of disturbance. This fact can be explained by the principle on which the control methods are based. The IMC has its foundations on the knowledge of the systems dynamics, which changes drastically under this circumstance. On the other hand, the FLC is more concerned about the desired behavior than the normal dynamics, which improves its response facing this kind of problems. This is the same reason why the IMC reacts better than the FLC to other kind of disturbances, such as the steps on the HP set-point, where the system dynamic do not change.

Other simulations were also performed under the same test protocol but adding a delay of 0.1 s on measurements to evaluate the robustness of control methods regarding this variant. In this case, the FLC performs more unpredictably, indicating a poor robustness to a delayed system. The IMC controller shows a really good capability of dealing with this change, though.

8. Conclusion and Future Development
Both the Internal Model Control and the Fuzzy Logic Control take time to be created at first, given that they need different mind sets than the classical PI approach. For the IMC, a deeper knowledge of the process dynamics is the key for a good controller. However the FLC focuses on

the desired behavior, rather than the system's natural behavior. Implementing those methods should get easier and more effective once the unorthodox way of thinking is understood.

This study led us to a better understanding of these solutions, which might be useful not only for the application on compression stations, but also for more complex systems. It is important to remember that the importance of these methods is to solve problems over the capacity of the classical PI control. The knowledge acquired with this study is being applied to the case described by [16], and it is believed to help solving the hard effects of the quench disturbances that the PI controllers are currently having difficulties to struggle with.

Moreover, the research for better methods is a continuous work at CERN, hence future developments are already planned.

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