Control of Warm Compression Stations Using Model Predictive Control: Simulation and Experimental Results

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Abstract. This paper deals with multivariable constrained model predictive control for Warm Compression Stations (WCS). WCSs are subject to numerous constraints (limits on pressures, actuators) that need to be satisfied using appropriate algorithms. The strategy is to replace all the PID loops controlling the WCS with an optimally designed model-based multivariable loop. This new strategy leads to high stability and fast disturbance rejection such as those induced by a turbine or a compressor stop, a key-aspect in the case of large scale cryogenic refrigeration. The proposed control scheme can be used to achieve precise control of pressures in normal operation or to avoid reaching stopping criteria (such as excessive pressures) under high disturbances (such as a pulsed heat load expected to take place in future fusion reactors, expected in the cryogenic cooling systems of the International Thermonuclear Experimental Reactor ITER or the Japan Torus-60 Super Advanced fusion experiment JT-60SA). The paper details the simulator used to validate this new control scheme and the associated simulation results on the SBTs WCS.

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1. Introduction

Large superconducting tokamak devices produce significant pulsed heat loads on magnets, due to huge eddy currents encountered in the magnetic system, to AC losses and to neutron flux radiations coming from the plasma. Such high pulsed loads disturb the cryogenic plant that is cooling the magnets, and make it necessary to use appropriate control strategies. The aim is to maintain the stability of the overall process subject to the variable thermal load and to satisfy operational and safety constraints (turbine operational temperature range, maximum capacity of the helium tank, compressor suction and discharge pressures, etc.).

Currently, technological solutions (such as thermal buffers, as described in [11], by-pass valves, etc.) are studied to smooth the effect of the thermal disturbance on the cryoplat and to avoid the over-dimensioning of the process. These solutions have to be combined with specific control algorithms, resulting in optimally designed closed-loop systems that can operate near their maximum capacity without the need for too conservative security margins.
The recent interest in advanced control methodologies has motivated many studies on modelling and control of cryogenic plants. In particular, several dynamic simulators have been proposed by [5, 13, 4, 8, 15] for operator training, dimensioning and/or control design. Based on a better dynamic modelling of the underlying process, advanced control schemes have been proposed which were often dedicated to a particular key variable. For instance, scalar model predictive control (MPC) of the helium bath temperature at 1.8 K using a Joule-Thomson expansion valve has been proposed in [16]. In [14], the problem of the bath pressure control is addressed, while in [6, 9], the high pressure level is monitored in order to control the bath level. In [7], the optimal multivariable control of a refrigerator is proposed, considering pulsed heat loads.

In this paper, we propose to achieve the control of warm compression stations (WCS) by model predictive control (MPC), a kind of model-based synthesized controller that handles both constraints and optimality by formulation [10]. This paper is organized as follows: section 2 is recalling the previous experimental results obtained with a CERN warm compression station for LHC with model-based multivariable controller, while section 3 presents the warm compression station for which the new MPC controller has been designed. Section 4 is focused on deriving the MPC control scheme while section 5 presents simulation results. Section 6 concludes the paper and gives ideas for future work.

2. Previous Results
In this section, the previous results obtained at CERN on the 4.5MW compression station will be very briefly recalled. The details about model set-up, advanced LQ control design and the experiment can be found in [2].

![Figure 1](image)

Figure 1. General trends of the test. The left part of the graph represents trends of the LP, MP and the HP under the LQ control scheme while the right part of the graph represents the same quantities, under a PID control scheme

One can see on Figure 1 that the result obtained on pressure stability is encouraging. But the main drawback of this method is that there is no possibility of switching actuators to manual mode, since every actuator is controlled by the multivariable scheme. This is why this paper proposes a new method called MPC (LQ with constraints) to control warm compression stations.
3. The SBT\(^1\) Warm compression station

In this section, the SBT’s warm compression station will be introduced and modelled. The first subsection presents the objectives and key figures of the SBT’s warm compression station while section two presents how to set-up the simplified model used to generate the MPC controller.

3.1. SBT’s WCS presentation and modelling

Figure 2 presents a synoptic view of the SBT’s warm compression station. Variables to be regulated are the low pressure \(P^C\) and the high pressure \(P^H\). Disturbances are coming from the cold box (not represented), namely the high pressure flowrate \(M^H\) and the low pressure flowrate \(M^C\). Five actuators are used to achieve the control objective: two compressors (\(C1\) is driven by variable frequency, \(C2\) is directly driven by the network), and three control valves. \(V1\) is the bypass valve, used in the case where the cold box isn’t connected (to bypass the flow generated by the compressors) or if the flowrates \(M^H\) and \(M^C\) are lower than the minimum fluid flow handleable by the compressors. The SBT compression station is capable to handle a 72 g/s flowrate. It consumes an electrical power of 330 kW. The \(V2\) and \(V3\) valves are the so-called charge and discharge valve. They are designed to add or to withdraw gas from the process, and they are shown in Figure 3 as an illustration.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{synoptic.png}
\caption{Synoptic view of the SBT’s compression station. Arrows represent the flow direction. The block between the \(V2\) and \(V3\) valves represents the capacity buffer of 10 m\(^3\)}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{charge_discharge.png}
\caption{Charge and discharge valves, namely \(V2\) and \(V3\) in Figure 2}
\end{figure}

To model the compression station in order to validate the controller design in section 4, we used the Simcryogenics library for Matlab/Simulink/Simscape [3]. The dynamical and algebraic equations that are implemented in the library can be found in [2]. Figure ? shows the Simulink validation model that has been assembled.

3.2. SBT’s WCS modelling for control

The previous section described the simulation model built for the warm compression station, while this section is about the linearized model used to design the controller. According to [2], the differential equation that governs pressures evolution w.r.t. time is given by (1), in which

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Figure 4. SBT’s warm compression station simulation model using the Simcryogenics library for Matlab/Simulink/Simscape. Inputs 1 to 5 (in red in the coloured version) represent controllable inputs, while 6 and 7 (in magenta) are flow disturbances. Input 8 represents the low pressure fluid temperature considered to be 300 K. Outputs 1 and 2 (in light blue) represent controlled outputs while outputs 3 to 5 (in green) are non-controlled.

$M^H$ and $M^C$ respectively denote the flowrates going to and from the coldbox. These two flows are considered to be the source of process disturbances. $M_{C1}$ and $M_{C2}$ respectively denote the flowrates handled by the first and second compressor, while $M_{V1}$ represents the flowrate passing through the bypass valve $V1$. $M_{V2}$ and $M_{V3}$ depict the flows generated by the charge valve ($V2$) and discharge valve ($V3$). These five variables are the control (manipulated) variables of the process. $K^H$ and $K^C$ are inertia terms linked to the pipes volumes.

$$
\begin{bmatrix}
K^H & 0 \\
0 & K^C
\end{bmatrix}
\begin{bmatrix}
\dot{p}^H \\
\dot{p}^C
\end{bmatrix}
= \begin{bmatrix}
1 & 1 & -1 & 0 & -1 \\
-1 & -1 & 1 & +1 & 0
\end{bmatrix}
\begin{bmatrix}
M_{C1} \\
M_{C2} \\
M_{V1} \\
M_{V2} \\
M_{V3}
\end{bmatrix}
+ \begin{bmatrix}
-1 & 0 & +1
\end{bmatrix}
\begin{bmatrix}
M^H \\
M^C
\end{bmatrix}
$$

(1)

The state space model described by (1) is non-linear because flows $M_{V1}$, $M_{V2}$, $M_{V3}$ are non-linear in pressure $P^H$ and $P^C$. To synthesize a linear MPC controller, a discrete-time linear time invariant model of the following form is to be used:

$$
z^+ = Gz + Hw$$

(2)

To get such a model, (1) will be linearized and discretized in time around an operating point of interest, namely: $u = u_0$, $w = w_0$, $x = x_0$, $\rightarrow \dot{x} = 0$ leading to the following expression:

$$
E \cdot \dot{x} = A\dot{x} + Bu + Fw
$$

(3)
where $\tilde{x}$, $\tilde{u}$ and $\tilde{w}$ depict the deviations from the linearization point of the variables $x$, $u$ and $w$ while $A$ represents the Jacobian of the system, precisely:

$$A = \left. \frac{\partial \dot{x}}{\partial x} \right|_{x_0,u_0,w_0}$$  \hfill (4)

The $B$ matrix is not full rank: one can notice that the two first columns are equal and that the third column is the opposite of the first two. To ensure genericness of the controller design, a new vector $u_2$ will be defined, associated with its $B_2$ matrix:

$$u_2 = \begin{pmatrix} M_{\text{prod}} \\ M_{\text{ch}} \\ M_{\text{dis}} \end{pmatrix}, \quad B_2 = \begin{bmatrix} +1 & 0 & -1 \\ -1 & +1 & 0 \end{bmatrix}$$  \hfill (5)

with $M_{C2} + M_{C1} + M_{V1} = M_{\text{prod}}$, $M_{\text{ch}} = M_{V2}$ and $M_{\text{dis}} = M_{V3}$. This leads to the final continuous linear model of our WCS:

$$E \cdot \dot{x} = A \tilde{x} + B_2 \tilde{u}_2 + F \tilde{w}$$  \hfill (6)

leading to the discrete-time model that will be used in the next section to generate the MPC controller:

$$x^+ = A^d \tilde{x} + B^d_2 \tilde{u}_2 + F^d \tilde{p}$$  \hfill (7)

where the superscript $+$ is used to define the value of the original variable at the next sampling period and the superscript $d$ is used to define the discrete-time version of the original matrices, that can be obtained by using the $c2d(.)$ MATLAB command.

4. MPC derivation for WCS

This section describes how to set up the linear Model Predictive Control (MPC) to control the WCS.

4.1. Conversion function

One can see that in the previous section, the discrete-time linear model presents the concept of virtual actuators. The virtual actuators value (in kg/s) will have to be converted into actual control action for the system actuators (in Hz or %). This is the purpose of the conversion described in [2].

4.2. MPC formulation

The MPC is both concerned with constraints and optimality. The next sections will describe constraints that hold on the process as well as the cost function to be minimized to control the plant.

4.2.1. Constraints

Like on every system that exists, actuators actions are bounded, and it is sometimes preferable to limit the excursion of the controlled/measured outputs. The MPC controller can handle constraints like:

$$\underline{y} \leq y_{k+i} \leq \bar{y}, \quad \underline{u} \leq u_{k+i} \leq \bar{u}, \quad \delta u \leq \delta u_{k+i} \leq \bar{\delta u}$$  \hfill (8)

where $y$ represents the measured output of the system and $\delta u$ the variation speed of actuators. Variables with upper bar and under bar respectively represent the maximum and minimum allowed values for the original variable. Valves opening is obviously to be into the $0$ – $100\%$ range while compressor $C1$ is limited to a speed of $53Hz$. In this paper, it has been chosen to limit the low pressure excursion. The limit is indicated on the simulation Figures.
4.2.2. Optimality

This section explains the formulation of the cost function for the model predictive controller. Despite the fact that disturbances are neither measured nor predictable, the pressures have to reach their set point under any circumstances. That is why an integral extended state approach has been chosen in [2]. This strategy is not applicable in our case since we sometimes want to block the actuators (and consequently the set points will not be reached) and thus integrals of the errors will diverge and make the system unstable. Instead of using integral action, an estimation of the disturbances will be made and used as a set point for \( u_{k+i-1} \), leading to the following cost function to be minimized:

\[
J(u_{k+i}, x_k) = \sum_{i=0}^{N_p-1} \left( x_{k+i+1} - x_{sp_{k+i+1}} \right)^2 + \left( u_{k+i-1} - u_{sp_{k+i-1}} \right)^2 \tag{9}
\]

this way, the \( u_{sp} \) is supposed to be the appropriate value to follow for the \( u \) control variable in order to stabilize the plant. It is obtained using a Kalman filter state observer [12] that is not detailed here. The weight matrices \( Q \) and \( R \) are then chosen to ensure that the state is converging to the reference state.

4.2.3. Final problem

After a few math, (9) and (8) can be put into the following form:

\[
\mathcal{P}(p, x_k) = \min_p J(p, x_k) = \frac{1}{2} p^T H p + p^T h(x_k)
\text{s.t.} \begin{cases} 
\Omega p - \omega(x_k) \leq 0 \\
p \leq p \leq \overline{p}
\end{cases} \tag{10}
\]

in which \( \mathcal{P}(p, x_k) \) represents a quadratic programming problem (QP) to be solved using an appropriate solver. In the (10), \( p \) is the optimisation variable while matrices and vectors \( H, h, \Omega, \omega, p, \overline{p} \) define the problem.

Figure 5. Starting the warm compression station from 1 bar on both pressures. The starting procedure is done as fast as possible by opening the \( V2 \) valve at 100%, and the bypass valve \( V1 \) accordingly.

Figure 6. Normal situation with a flow disturbance (due to turbine start/stop or pulsed heat loads). Pressure are returning to their set point with no oscillations.
5. Simulation results
This section presents the simulation results obtained by solving the problem (10) at each sampling period. The problem has been solved with the algorithm presented in [1] that has been proved to be PLC-compatible. Figure 5 shows how the system reacts when the simulation is initialized at atmospheric pressure. Figure 6 presents the simulation of the system subjected to disturbances during normal operation. Figure 7 shows how the system reacts when disturbed by some non manageable difference between the inflow and the outflow. Finally, Figures 8 and 9 present the behaviour of the process when the discharge valve or the charge valve opening is blocked to zero for some reason.

Figure 7. Critical situation: the in and out flows difference is such that the charge or discharge valve cannot handle it. Charge and discharge valve are opened at 100% and the high pressure is then going up or down since the low pressure is not allowed to get out of the dashed bars

Figure 8. The discharge valve is blocked until time is equal to 150 s. The discharge valve can be blocked for example when WCS is polluted and the gas in the buffer is pure

Figure 9. The charge valve is blocked until time is equal to 150 s. The charge valve can be blocked for example when there is not enough helium available for all the experiments
6. Conclusion
This paper is proposing a new approach to control warm compression stations. This control formulation ensures that setpoints are reached and makes the process constraints (minimum low pressure, maximum high pressure, etc...) to be respected if possible, leading to a possible increase in process availability if subjected to large disturbances. This new algorithm is now ready to be be tested on the SBT’s warm compression station in a near future. In the framework of the French National Research Agency (ANR), task agreement ANR-13-SEED-0005, this kind of algorithm will also be tested on a CERN 4.5MW warm compression station.

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