

Model Predictive Anti-Surge Control of Centrifugal Compressors with Variable-Speed Drives

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Abstract: In this article torque assisted anti-surge control (TASC), a compressor anti-surge control system based on model predictive control (MPC) is presented. TASC is implemented on an embedded system for the control of compressor stations with electrical variable-speed drives (VSD) which are used in applications such as natural gas transportation via pipelines. The manipulated variables of the proposed advanced controller are the electric motor torque and the position of a recycle valve, whereas the measured quantities are the same as those of a typical compressor control application including the pressure ratio and the gas flow. The TASC scheme uses the linear approximation of a nonlinear dynamic model to predict the behavior of the compression system. The information contained in the compressor map is incorporated into the nonlinear model as a 3rd order polynomial approximation. The surge line is taken into account as a constraint in the MPC formulation. Control action is calculated by solving an optimization problem in real-time at the control unit level with cycle times as low as 20 ms. The potential benefits of the proposed control strategy are evaluated in a simulation scenario corresponding to a potential deep surge event typically used in anti-surge control validation exercises. The simulations are carried out in a hardware-in-the-loop setting. In the evaluation, the performance of TASC is compared to a conventional anti-surge control approach. Due to the predictive capability and the manipulation of the motor torque, TASC is observed to achieve a safer and more efficient operation of the compressor station.

Keywords: *Nonlinear mpc, compressor modeling, anti-surge control, variable speed drive*

1. INTRODUCTION

Centrifugal compressors constitute a vital part of the process machinery in the oil and gas industry. In many applications, compressors represent a significant portion of the overall plant capital cost, while being at the same time the major energy consumers in the process. In addition, centrifugal compressors are very sensitive to changes in operating conditions and have a limited operational range. If these limits are exceeded the compressor can be damaged beyond further use. One of these operational constraints is the requirement to avoid surge. The surge phenomenon is an unstable operation mode of a compression system that occurs when the developed compressor head drops below the network resistance. Surge corresponds to fluctuation of flow and pressure with possible adverse side-effects such as overheating or mechanical damage. Surge events may be violent enough to damage a compressor in a few cycles and as a consequence the avoidance of surge is a strict safety requirement for compressor protection systems.

The objective of anti-surge control is to keep the flow and the pressure under a curve known as the surge limit. This limit identifies the operation modes affected by surge. State-of-the-art anti-surge control schemes rely on logic operations using control lines to trigger the opening of valves in order to

recycle or blow off the compressed gas to the atmosphere. Recycling in this context means allowing the gas to recirculate via dedicated piping from the compressor outlet back to the inlet to ensure forward flow through the compressor. The major disadvantage of this approach is that the mechanical energy delivered to the recycled gas is partially wasted. Traditionally compressors in the oil and gas industry were driven by gas turbines, which are capable of changing the rotational speed, but only to a limited extent and at a relatively slow rate. Therefore, rotational speed and drive torque are generally not considered for anti-surge control applications even though it is known to be a possible method (Nisenfeld, 1982).

Variable-speed electrical drives (VSD) on the other hand are capable of changing the drive torque much faster and within a broad range of rotational speeds without having to incur a large efficiency penalty. This possibility to access the torque of the electrical drive as a high performance actuator for surge control led to a series of control systems research, e.g. by Gravidahl et al in 2002. This article presented a variant of the active surge control concept based on a control law for the compressor impeller speed, which could stabilize any operating point in the compressor map. Even though experiments on test rigs were able to demonstrate its feasibility, i.e. Bøhagen and Gravidahl (2008) or Boinov et al.

(2006), the drive torque based active surge control approach did not make a way into industrial applications.

In this article we propose a drive torque assisted anti-surge control scheme (TASC) where the traditional understanding and purpose of anti-surge control is maintained, but the drive torque is used together with the recycle valve or valves to prevent the occurrence of surge. Introduction of the drive torque as an input for anti-surge control leads to a multivariable control problem and the prevention of surge can be considered as an output constraint for control applications. Model predictive control (MPC) is a common choice in the industry to solve such multivariable and constrained control problems. The only obstacle for a traditional industrial MPC implementation for anti-surge control is the stringent real-time requirements of compressor anti-surge control, which can have execution cycle times down to 40 ms. In this regard recent years have seen both a significant increase in computational capabilities of control hardware and a significant amount of work dedicated to the implementation of MPC at faster rates using explicit solutions (for a survey paper see Alessio and Bemporad, 2009) and real-time solutions on embedded systems. Some related works can be found in Wills et al. (2005), Ferreau et al. (2007), Geyer et al. (2009) and Van den Broeck, et al. (2011). In the present work for the application of TASC the latter approach of online MPC implementation on a dedicated microcontroller is chosen. The results show that MPC based anti-surge control is feasible within the sampling rates required for this purpose. Moreover, it is shown in comparison with a conventional anti-surge control strategy that increasing the energy efficiency of the compression process is possible and that the electrical drive torque supports the recycle valve action ensuring a safer operation of the system.

2. MPC FOR COMPRESSOR ANTI-SURGE CONTROL

The use of MPC for compressor control has been suggested and studied by several articles in the literature. Smeulers et al. (1999) implemented a linear MPC on a system with two compressors where the anti-surge control was carried out by a faster low level controller. Johansen (2002, Molenaar (2007) and Grancharova et al. (2007) considered anti-surge control as a test example for explicit nonlinear MPC formulations. However in all of these studies, only the position of a close coupled valve was considered as a manipulated variable and rotational speed or the drive torque was not used as a degree of freedom for control. In addition, a comparison of these MPC based algorithms with conventional control systems for typical anti-surge control validation scenarios was not provided. In this section of the present article the considered model and an MPC formulation for TASC is presented.

2.1. Compressor Model

Greitzer et al. (1976) developed a dynamic compressor model capable of representing the characteristics of surge for both axial and centrifugal compressors. This model maps out not only the compressor but also the whole compressor system and it can be used to predict if surge will occur. The

compressor model used for MPC design in this study is mainly based on the work of Gravdahl and Egeland (1999). They developed the dynamic compressor models further and included in their model a speed dependent compressor characteristic. The model can be summarized with the following equations:

$$\frac{d\omega}{dt} = \frac{1}{J} (\tau_{drive} - \tau_{comp}) \quad (1)$$

$$\frac{d\psi_c}{dt} = \frac{1}{t_\psi} (\psi_{c,ss}(\dot{m}_1, \omega) - \psi_c) \quad (2)$$

$$\frac{d\dot{m}_c}{dt} = \frac{A_c}{L_c} (p_1 \cdot \psi_c - p_2) \quad (3)$$

$$\psi_{c,ss} = c_0(\omega) + c_1(\omega) \cdot \dot{m}_1 + c_2(\omega) \cdot \dot{m}_1^2 + c_3(\omega) \cdot \dot{m}_1^3 \quad (4)$$

$$\tau_{comp} = \sigma \cdot r^2 \cdot |\dot{m}_1| \cdot \omega \quad (5)$$

Eq. (1) represents the inertial dynamics of the compressor shaft in the direction of its rotation, where ω is the rotational speed of the shaft and τ the torque. In (2), the dynamical compressor pressure rise characteristic is captured, where ψ is the pressure ratio, \dot{m}_1 the inlet flow and t_ψ the time constant. (3) represents the dynamics of the compressor mass flow, where p_1 is the inlet pressure, p_2 the outlet pressure, A_c the outlet duct cross section and L_c the duct length. (4) defines a cubic interpolating polynomial approximation identified from compressor maps as a function of the compressor speed ω and of the inlet flow \dot{m}_1 . (5) defines the compressor torque τ_{comp} as a function of inflow and compressor speed (Bøhagen and Gravdahl, 2008), where σ is the slip factor and r the radius of the shaft.

2.2. Plant Model

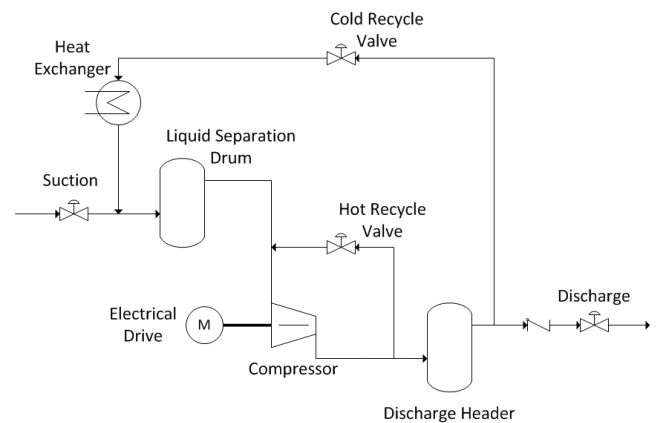


Fig. 1. Generic Compression Plant Schematic.

The plant model has been developed by considering a typical layout of a natural gas compression station as it can be seen in Fig. 1. The main elements of the plant are a centrifugal compressor driven by a VSD (modelled as described in the previous subsection), a heat exchanger that cools down the compressed gas, two tanks able to separate the gas from condensed liquids and two recycle valves, one recycling cooled gas and one recycling hot gas even though only the

cold recycle is considered for control for the purpose of this study. The overall model of compressor and separator tanks resulted in six differential equations. Another state was added to the system to represent specifically the dynamics of the recycle valve.

2.3. Anti-Surge Control via MPC

A VSD provides the most efficient process control possibility for compressor operation. However it has to be noted that only the pressure rise or the throughput can be independently controlled by the VSD. In the context of the present article it will be assumed that the suction and discharge valves are not available as manipulated variables for the MPC and that the only additional control objective other than TASC is to maintain either the pressure or the throughput at a desired operating point as specified by an external set point signal. It should however be pointed out that there is a priority separation with the TASC and other process control related objectives such that in case of a disturbance that can lead to surge the TASC objectives will dominate and during this transient period the process control tasks will have secondary priority. The steady state solution will be dependent on the weights chosen for the different objectives and since the process control and anti-surge control tasks are carried out within the same MPC controller the interaction between these two tasks will be handled simultaneously.

For TASC the same measurements are used as in a conventional approach namely (i) the inlet pressure, (ii) the outlet pressure, and (iii) compressor flow, but unlike the conventional surge control two manipulated variables are used which are (a) the cold recycle valve and (b) the torque of the VSD. As described in section 2.2 the complete model corresponding to the flow sheet in Fig. 1 is used in the MPC design to predict and optimize the behaviour of the compression system. The nonlinearities of the employed model are mainly resulting from the compressor characteristic and the flow through the valves.

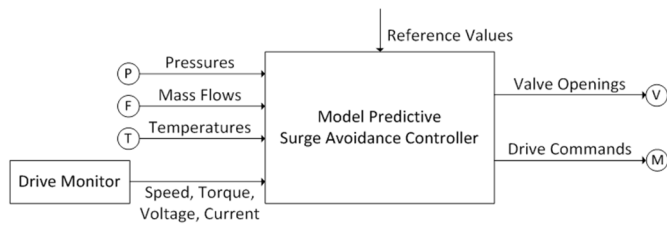


Fig. 2. Inputs and outputs of an MPC based anti-surge control system.

In the implementation of the TASC, first the state estimates of the compressor model are necessary to formulate the optimization problem at the actual state. For this purpose an Extended Kalman Filter (EKF) is used. Based on pre-filtered measurements, mainly flows and pressures, and using the nonlinear plant model the EKF estimates the six states of the compressor model. Before solving the minimization problem, a linearization step is introduced, in order to have a linear model structure for the optimization part. Note that the

linearization is evaluated every time step at the estimated states.

Finally, the MPC algorithm solves the optimization problem corresponding to the objectives of throughput control and maintaining the operation within the constraints, which are partly incorporated also into the objective function as costs. The constraints include the surge limit, maximum drive torque, speed, and acceleration-deceleration limits, as well as valve constraints i.e. limits and rates on opening and closing. The mathematical formulation is a typical quadratic program, where the linear model is formulated as:

$$\xi(k+1) = A_k \xi(k) + B_k u(k) + f_k \quad (6)$$

$$\eta(k+1) = C_k \xi(k) + D_k u(k) + g_k \quad (7)$$

with the condensed input and state vector is defined to be

$$z = [u(k), u(k+1), \dots, u(k+p), \xi(k), \xi(k+1), \dots, \xi(k+p)].$$

The reference values for the future states and inputs are

$$r = [u_r(k), u_r(k+1), \dots, u_r(k+p), \xi_r(k), \xi_r(k+1), \dots, \xi_r(k+p)].$$

By using those definitions, the optimization problem to be solved can be stated as

$$\begin{aligned} \min_z \quad & (z - r)^T \cdot Q \cdot (z - r) \\ \text{s. t.} \quad & H_{in} \cdot z \leq k_{in} \\ & H_{eq} \cdot z = k_{eq} \end{aligned} \quad (8)$$

It is also possible to include the optimization of the compressor efficiency based on the compressor map and by minimizing the flow through the recycle valves, although this was not implemented in the present work. Temperature effects are also possible to integrate into the model as additional states and for consideration in the compressor efficiency calculations. For the current study, an assumption of a perfect recycle cooling is made and temperature effects are not considered. The inputs and outputs for a more general MPC based anti-surge control system are shown in Fig. 2.

3. HARDWARE SETUP

In this section the embedded control system for the deployment of model predictive TASC is described. In order to facilitate the computationally demanding execution of model predictive control on an embedded system, the embedded system should possess sufficient computational resources. The chosen embedded system is ABB's high performance control unit AC 800PEC depicted in Fig. 3. The reasons for selecting the AC 800PEC were that it provides fast sampling rates up to cycle times of 100 μ s and sufficient computational power for demanding applications. It is based on a 32bit Power PC processor with up to 600MHz speed, including an FPGA and a 64bit IEEE Floating Point Unit.

The AC 800PEC is specially designed for handling very demanding power electronic control tasks, but it is also well integrated into ABB's extended automation system 800xA and supports a number of different I/O modules and communication interfaces. Furthermore, the AC 800PEC supports all five IEC61131-3 programming languages using ABB's Control Builder as well as automatic generation of C and C++ code via Real-Time Workshop from Mathworks.



Fig. 3. ABB high performance controller AC 800PEC.

The results shown in the following section correspond to simulations carried out on the AC 800PEC under real-time conditions. It was possible to solve the MPC problem on the hardware within the required sampling time range of the system. This step involved customization of certain computational aspects including the solution of the optimization problem. It has to be also noted here that there is a trade-off between the cycle time and the horizon used for the MPC. Shorter cycle times limit the length of the horizon, which can reduce the control performance. Longer horizons are possible with longer cycle times which can however reduce the responsiveness of the solution.

Therefore, an optimal solution needs to be designed taking into account also the limitations of the hardware. For the current application the cycle time was varied from 20 ms to 150 ms and the longest possible horizon achievable for these cycle times were determined. In all instances satisfactory control performance was reached but in the next section results with 100 ms sampling are presented, which were relatively better.

4. SIMULATION RESULTS

Several scenarios are proposed in the literature for the validation of anti-surge control schemes, e.g. Dukle and Narayanan (2003), Wu et al. (2007) and Patel et al. (2007). The specific scenario considered in this article in order to demonstrate the potential control performance of TASC to drive the system into surge is the sudden step-like closure of a process valve on the compressor discharge side with the compressor operating at rated condition in steady-state was chosen to drive the system towards surge. For this purpose, as a disturbance the discharge valve in consideration is closed from an 80% open state to 30% at 800 ms. Without intervention of an anti-surge control system, the compressor would run into deep surge within 300 ms. In the following

the conventional anti-surge control using a cold recycle valve is compared to the TASC strategy introduced before.

In Fig. 4, the evolution of the pressure ratio and compressor flow operation is shown in the compressor map for the discharge valve closure. As long as there is no disturbance, the system is in steady state and remains at the starting point in the map until the disturbance occurs.

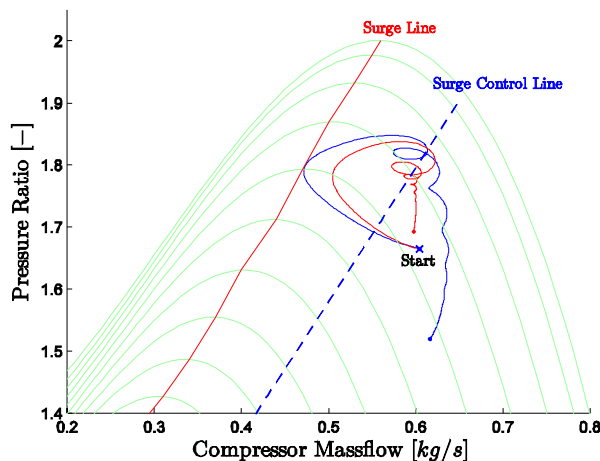


Fig. 4. Evolution of operating points in the compressor map for conventional control (blue) and TASC (red).

The green lines show constant speed curves, while the red line represents the surge line limit. The dashed blue line shows the activation line for the conventional PI-based anti-surge control with only the recycle valve. As it can be seen in the figure, the conventional approach can prevent the system from surge. Nevertheless the margin to the surge line is very small. The TASC approach in comparison manages to keep a significantly larger distance from the surge line than the conventional approach.

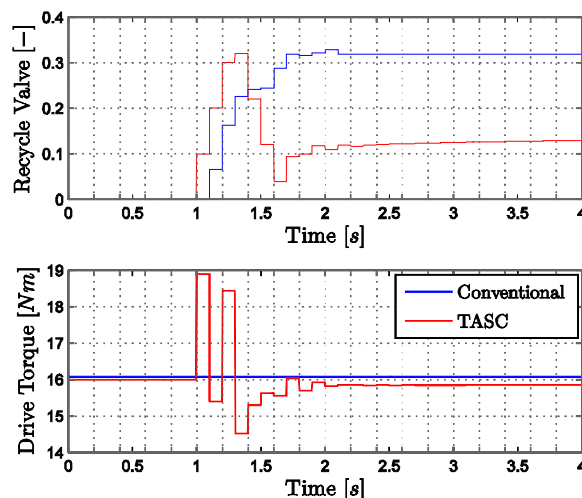


Fig. 5. Control signals for conventional control and TASC.

The reason for the improved response can be explained with the help of Fig. 5, where the control input signals are shown. The conventional control uses only the recycle valve, based on the distance to surge control line. The signal shows a fast

valve opening command in the beginning and an almost constant action in the later part of this disturbance scenario. This results in an inefficient use of the recycle flow. In contrast, the MPC based control signal initially shows a larger recycle valve signal with relatively larger steps pushing the rate of change limits of the recycle valve response.

Two other noticeable differences in the response of the different control approaches are that (i) the MPC starts to take action against the approaching surge almost immediately compared to the conventional approach, which needs to wait for the control line to be crossed delaying its response by about 100 ms and that (ii) MPC uses - at least during transients - less recycle opening than the conventional control resulting in reduced specific energy consumption for compression. This can be a relevant concern and therefore a potential improvement for plants that are operating within the surge limits for the total flow with a certain amount of recycle flow, where due to disturbances the operation always has a transient character. Please also note that Fig. 5 does not represent the actual recycle flow but only the signal to the recycle valve. The actual valve position and the recycle flow follows with a slight delay according to the dynamics specified in the model. Another point to note is that for the conventional approach the control signal to the recycle valve is kept constant after crossing back to the right of the surge control line instead of enforcing the control line as a set point. The reason is that typical anti-surge control systems move the control line further right after such a disturbance based on empirical relations and the results shown in this article will be a fair comparison at least for the initial transient responses.

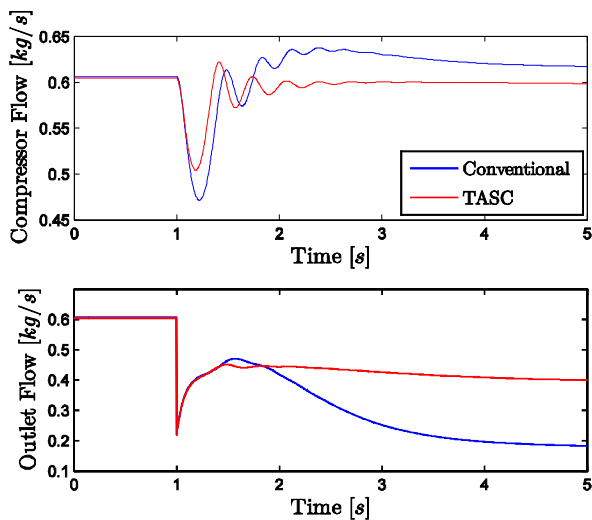


Fig. 6. Compressor flow for conventional control and TASC.

The MPC response is also supported by the torque action shown in the lower part of Fig. 5. Opening the valve to a larger amount and using torque pulses in the beginning of the disturbance, the MPC approach improves the performance of the anti-surge control. The explanation for this result is that the temporary influence of torque on the system maintains a higher flow while also increasing the pressure ratio, which is

later compensated and reduced by the recycle flow. Even though the throughput or discharge pressure control in the system is not the topic of the present article. Fig. 6 and Fig. 7 depict the influence of the disturbance on the flows and pressures in the system and it is possible to argue that the average deviation of the process conditions from the starting point is smaller for the MPC controlled system compared to the conventional approach.

Typically the opening of the recycle valve leads to pressure flow oscillations in compression systems due to the excitation of resonant frequencies of the flow network. As it is illustrated in Fig. 6, the mass flow through the compressor oscillates for both cases even though it was expected for TASC to reduce these oscillations. This can be pointed out as a shortcoming of MPC for handling frequency domain objectives. Nevertheless the more aggressive use of both the recycle valve and the electrical drive torque with the MPC algorithm does not necessarily lead to larger pressure and flow oscillations compared to traditional anti surge control. It is also worthwhile to point out that the MPC application always resulted in stable operation during the simulation studies with various starting conditions and disturbance scenarios. However robustness with respect to plant-model mismatch is not studied in this article. This is an important point and it will be one of the topics for further work in this area.

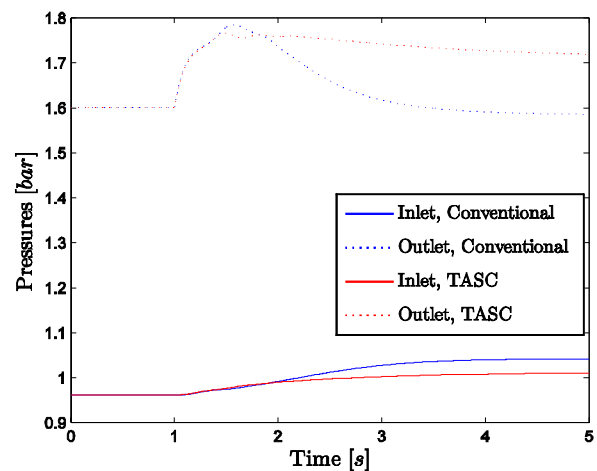


Fig. 7. Compressor flow for conventional control and MPC.

5. CONCLUSIONS

A compressor station driven by a VSD has been modeled and analyzed to investigate anti-surge control strategies. After the introduction to conventional anti-surge control strategies, a new approach based on MPC has been developed that also utilizes the VSD torque as an additional degree of freedom for anti-surge control referred to as TASC. Using the compressor station model, the MPC problem could be formulated accounting for load variations, disturbance rejection goals, constraints on inputs and limits on surge distances. The proposed algorithm consists of an EKF, a linearization step and the solution of the MPC optimization problem. To investigate if this arrangement can be used in a

real-time environment, the proposed control strategy was implemented on an embedded device. For this purpose, the ABB control system AC 800PEC was chosen and used to implement the strategies. All simulations were conducted in real-time on the embedded control system. The results can be summarized as follows:

- It is possible to run the TASC algorithm in real-time and to compute the optimal solution within the limit of one sampling time satisfactory for anti-surge control applications
- The performance of the new TASC approach improves considerably the system response by providing a larger margin to the surge limit and reduced recycle flow during transient conditions
- Torque integration into the anti-surge control supports the recycle valve action and ensures a safer operation of the compressor operation. Moreover, no over-speed risk is observed by the active torque control approach

Further work will focus on improving the MPC algorithm by considering frequency response characteristics of the pressure flow network. Additional investigations are necessary to confirm the improvement in anti-surge control performance via the TASC approach for different case studies and different control performance validation scenarios. The influence of the shape of the compressor map on the torque response and the possibility to use this information as an indicator for control improvement via the TASC method is going to be investigated. Robustness of the TASC to plant-model mismatch is also a further point of research. Another possible research direction is to consider achieving active surge control via the MPC method in case when it is not possible to avoid going into surge due to a large disturbance and an investigation to see if after active stabilization the compressor could be moved back to the stable region.

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