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Optimal Operation with Changing Active Constraint Regions using Classical Advanced Control ⋆

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Abstract: With "classical advanced control" we mean the control structures that are commonly used in industry for multivariable control. These have been in use for at least 50 years, but surprisingly there is little literature published on how to design such structures in a systematic manner. We present a design procedure to assure optimal operation when active constraint changes occur. In this paper, we focus on input saturation. We suggest to use a priority list of constraints as an important first step of the presented design procedure. We also discuss how to handle input saturation using split range control, valve position control (input resetting), and selectors. As a case study, we consider optimal operation and a priority list of constraints for a cooler with temperature and flow control, and evaluate alternative classical advanced control implementations that maintain optimality.

Keywords: process control, supervisory control, constraints, optimal control, control specifications, control system design, control structures, PID control

1. INTRODUCTION

The typical control hierarchy in a process plant decomposes the overall control problem on a time scale basis, as shown in Fig. 1. The upper layers are explicitly related to long-term scale economic optimization, and the lower layers correspond to the control system. The latter should follow the set points defined by the economic optimization layers and stabilize the plant. It is sub-divided in a supervisory control layer and a regulatory or stabilizing PID control layer.

The supervisory control layer is responsible for achieving feasible and optimal operation by calculating the set points for the regulatory layer. The manipulated variables (MVs) are the dynamic, physical, degrees of freedom used by the control system, while the controlled variables (CVs) are the system outputs. *Active constraints* are variables that should optimally be kept at their limiting value, e.g., maximum cooling for a compressor (active MV constraint) or maximum pressure in a reactor (active CV constraint).

If no disturbances were affecting the plant, optimal operation would always be achieved using the same control structure and set points in the regulatory control layer. However, a real plant is always subject to disturbances, and the optimal operation point changes accordingly. Common important disturbances are: changes in feedrate, composition and product specification, price variations, and drift in process parameters such as efficiencies.

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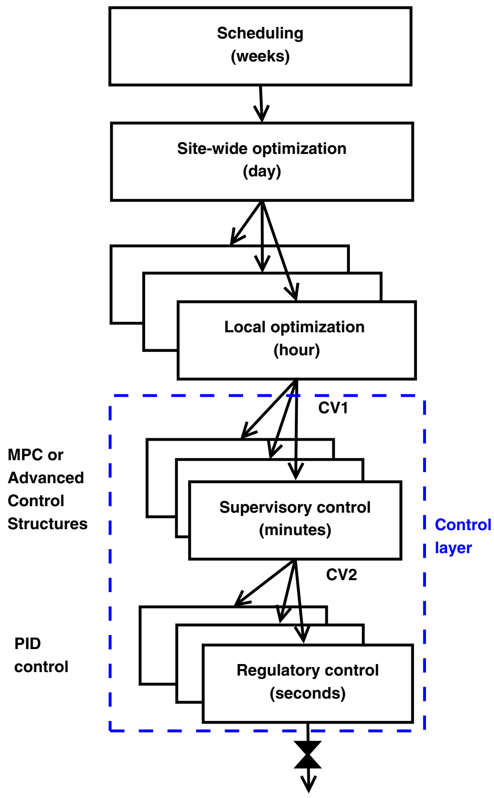


Fig. 1. Typical control hierarchy in a process plant (Skogestad, 2004)

There are a few general guidelines to design the control layer considering economic optimization (Price et al., 1994; Aske and Skogestad, 2009; Skogestad, 2004):

(1) *Active constraints* should be controlled.
(2) Sensitive and "drifting" variables should be controlled by the regulatory control layer.
(3) Inventory control loops should be designed *around* the throughput manipulator (TPM) according to the radiation rule, and never *across* the TPM.
(4) To avoid a long loop and the resulting back-off, the TPM should be located close to the bottleneck.

The supervisory control layer is commonly designed using classical advanced control structures with PID-controllers and simple blocks. Alternatively it can be designed with Model Predictive Control (MPC). The main advantage of MPC in terms of economics is that it inherently handles constraints and represents a unified systematic procedure to control multivariable processes (Mayne, 2014). However, standard MPC may not handle changes in active constraints effectively, except by the indirect use of weights in the objective function, which are selected by trial and error. This scheme may not allow one to give up completely controlling a variable. Furthermore, it is not always easy to find tuning parameters that achieve the desired performance, as explained in Forbes et al. (2015).

To handle such cases, one must either introduce logic, slack variables with penalty functions or implement a two-stage MPC. In the latter approach, we first generate a *priority list* by ranking the constraints. In the first stage, we solve a sequence of local steady-state optimization problems, each time adding a new constraint, following the *priority list*. This stage provides information regarding feasibility of the control objectives. In the second stage, we use the gathered information to formulate the dynamic optimization problem for the MPC. This way, we assure satisfying high priority constraints over lower priority constraints (Qin and Badgwell, 2003; Strand and Sagli, 2004; Aske et al., 2005).

In many cases, optimal or *near*-optimal operation can be achieved using classical advanced control structures, such as the ones described in Section 2, in the supervisory layer. However, its design using classical control structures often lacks a systematic and holistic procedure (Forsman, 2016). In Section 3, we suggest using a *priority list* of constraints as the basis for designing the supervisory control layer with classical control structures. This way, we address optimization objectives and changes in active constraints, along with the regulatory objective. In Section 4, we apply our proposed procedure and implement advanced control structures in a cooler with temperature and flow control in which cooling may saturate under certain conditions.

2. CLASSICAL ADVANCED CONTROL STRUCTURES

Classical advanced control uses different control structures to define the set points for the regulatory layer when a single loop PID-controller is not sufficient. Typical examples of advanced control structures routinely used to improve process performance are: cascade control, feedforward control, and decoupling (Seborg et al., 2003). In this paper, we focus on structures that can be used to handle constraint changes due to input saturation: split range control (SRC), input resetting or valve position control (VPC), as well as selectors.

2.1 Split Range Control (SRC)

SRC can is used when there is more than one candidate MV to control one CV. The typical application is when more than one MV is required to cover the whole steady-state range of the controlled variable, mainly because the primary MV may saturate. Above the split value the controller manipulates MV1; below this value, it manipulates MV2, as depicted in Fig. 2.

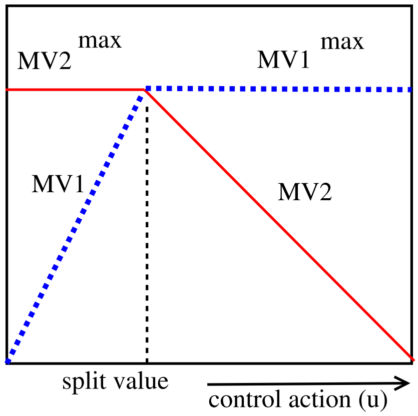


Fig. 2. Simple representation of split range control (SRC).

The split value can be used as a tuning parameter to get different controller gains for each controller. An alternative is to use a multiplication factor for each input. However, the integral term is the same for both MVs. This avoids the need to initialize the integral term when switching from MV1 to MV2. A disadvantage is that the dynamics from each MV to the CV may not be the same.

2.2 Two different controllers

SRC is commonly presented as an alternative to using different controllers for each MV. When two controllers are used, each one has an independent tuning. Set points should be separated sufficiently, so that only one controller is active at a given time, while the other has driven its valve to a limit (Smith, 2010). With this configuration, the CV may easily oscillate, making it difficult to reach the optimal value.

2.3 Input Resetting or Valve Position Control (VPC)

VPC can also be used when we have two MVs and one CV. In this case, MV1 always controls the CV, whereas MV2 takes MV1 to the desired position.

A common application of VPC is to use the two MVs to improve the dynamic response. MV2 is the main input, but used alone it does not give acceptable control, usually because it is too slow. We therefore use MV1, a faster input, to improve the response. We cannot use only MV1, either because its range is small or because it is expensive to use. A typical example is to arrange two valves in parallel, where MV1 is a small and fast valve, whereas MV2 is a large and slower-acting valve. MV1 is then used to control the CV, and MV2 is used to *reset* MV1 to a desired steady-state value (Shinskey, 1988).

A less common scheme, which is the one that we consider in this paper, is to use two MVs to extend the steady-state range to control an important CV (CV1). MV1 is the main manipulated variable, which controls CV1. MV2 normally controls CV2. However, for certain disturbances MV1 could saturate. We then use MV2 to prevent MV1 from saturating and maintain control of CV1. Since MV2 normally controls CV2, a selector has to be used. As we always use MV1 to control CV1, we avoid the change of dynamics we have in SRC. Shinskey (1988) describes this solution for temperature control in a reactor, where the feed rate is reduced if the cooling saturates.

It should be noted that when optimal operation is near the constraint for MV1 (fully open or fully closed valve), VPC achieves only *near-optimal* operation because some *back-off* is used to maintain the valve within the controllable range, so that it can reject process disturbances. Therefore, the valve stays at the *near-end* of its range.

A third case of VPC, which may be viewed as a sub-category of the first case, is when the main control objective is stabilization and we only have one physical MV. In this case, MV2 is the CV set point, which may be adjusted to avoid saturation of MV1.

2.4 Use of Selectors

Selectors can be used when one MV is used to control several CVs. In this case, there is a controller for each CV and the MV value is selected among the controller outputs, usually with a *max/min* function. This alternative is sometimes called *override control* (Seborg et al., 2003).

Selectors are also used when implementing SRC, VPC, and two different controllers (see Section 4.3). In terms of optimal operation, this allows to always drive the system towards the active constraints.

3. OPTIMAL OPERATION USING CLASSICAL ADVANCED STRUCTURES

The design of advanced control structures requires a thorough analysis of the process that yields valuable information about how process variables interact, which is also required to find the optimal operation point.

In terms of economics, the most important role of the supervisory control layer is to keep the operation in the right *active constraint region*, which is a region in the disturbance space defined by which constraints are active within it (Jacobsen and Skogestad, 2011). Ideally, one should obtain all the active constraint regions, but this is very time consuming and not realistic, even for quite simple processes. Also, even if one had this information, it would be difficult to use it online, at least for complicated cases. In practice, a simpler approach is to obtain a *priority list* of controlled variables and constraints.

3.1 List of Priorities

To specify operation, we should specify the same number of CVs as the number of MVs we have. MVs are always the same, but the CVs will depend on the operating point, and there will generally be more potential CVs than MVs. As a starting point to define which CVs we should control, we recommend to list and prioritize all the constraints that can become active. By placing the most important constraints at the top, the *priority list* typically has the following categories and structure:

- (P1) *MV inequality constraints:* physical constraints, which cannot be given up because it is simply not feasible.
- (P2) *CV inequality constraints:* these constraints may possibly be given up.
- (P3) *MV or CV equality constraints:* optimal operation is reached by meeting these constraints, but they may possibly be given up.
- (P4) *Desired throughput:* this can be given up, which is when we reach a bottleneck.
- (P5) *Self-optimizing variables:* can be given up.

It is important to remark that the ordering of items P2, P3 and P4 may vary, and the actual priority list may be longer or shorter than this typical list. It should also be noted that constraints in P3 may include the same variables that are already used in P1 and P2.

Physical MV constraints, which cannot be given up, should be placed at the highest priority (P1), and as long as the problem is well-defined it is always possible to find a feasible solution. Economic objectives such as desired throughput, which can be given up but assure optimal operation, would have a lower priority.

Usually, the nominal case is characterized by fewer active constraints, and the nominal operation point is often unconstrained. Thus, the order of how controlled variables should be given up as new constraints become active when we move away from nominal operation typically follows the reverse of the priority list.

3.2 Procedure

We propose the following procedure to design the supervisory layer using advanced control structures to handle the case of changing active constraints:

1. Write the *priority list* for the constraints and specific control objectives.
2. Start designing the control system for a situation with few active constraints, with most priorities satisfied. This is often around the nominal operating point.
3. Pair MVs with CVs according to the following *input saturation pairing rule: an important CV (which cannot be given up) should be paired with a MV that is not likely to saturate* (Minasidis et al., 2015).
4. Analyze how disturbances may cause new constraints to become active. Here, it may be instructive to identify the *active constraint regions* (optimal operation) as a function of important disturbances.
5. If we reach a new MV constraint, we must give up controlling a CV.
    - If the *input saturation pairing rule* was followed, no special action is needed, as we can give up controlling the low priority CV with which the saturated MV is already paired.
    - If it was not possible to follow the *input saturation pairing rule*, then the important (high priority) CV must be reassigned to a MV which is controlling a CV that can be given up. This can

be achieved using SRC, VPC, or two controllers with different set points, all combined with a *min/max* selector block.

(6) If we reach a new CV constraint, then a less important CV must be given up, using a *min/max* selector.

4. OPTIMAL CONTROL OF A COOLER

We analyze a cooler. The main control objective of this case study is to keep the outlet temperature in the hot stream at its set point ($T_H = T_H^{sp}$) by using cooling water (F_C). Additionally, we would like to set the throughput of the hot stream ($F_H = F_H^{sp}$), ideally at $F_H^{sp} = F_H^{max}$. The main disturbance is the cooling water temperature (T_C^{in}).

The process has two MVs, one corresponding to F_C and another to F_H. The obvious control strategy is to use F_C to control T_H, and use a flow controller for F_H, as shown in Fig. 3. We note that the flow loop follows the above mentioned *input saturation pairing rule*. Thus, no logic is needed when this loop saturates, except that the controller requires anti-windup. However, as it is required that T_H is always controlled and F_C may saturate for a high throughput (F_H), the temperature loop does not follow the pairing rule and reconfiguration may be needed.

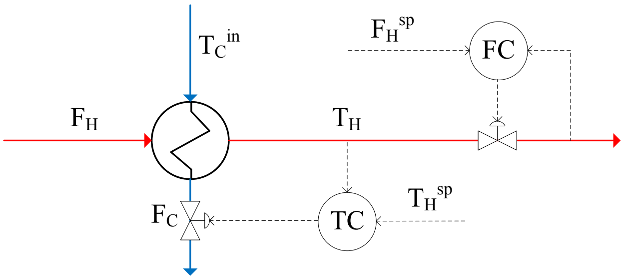


Fig. 3. Cooler with temperature and flow control [1] .

4.1 List of Priorities

Table 1 shows the constraints for the studied system.

Table 1. Constraints for the cooler system.

MV constraints	CV constraints
$F_C \le F_C^{max}$	$T_H = T_H^{sp}$
$F_H \le F_H^{max}$	$F_H = F_H^{sp}$

The physical MV constraints define the feasibility region. As they must always be met, these should be placed at the highest priority. $T_H = T_H^{sp}$, which is the control objective, is in priority level 2. Finally, we have the desired throughput at the lowest priority. In this case, there are no CV inequality constraints or self optimizing variables.

(P1) MV inequality constraints:
- $F_H \le F_H^{max}$
- $F_C \le F_C^{max}$

(P2) MV or CV equality constraints:
- $T_H = T_H^{sp}$

(P3) Desired throughput:
- $F_H = F_H^{sp}$

Having $F_H = F_H^{sp}$ at the lowest priority means that we can accept $F_H \neq F_H^{sp}$ in order to achieve $T_H = T_H^{sp}$.

[1] Note that the flow controller is not shown in the following figures.

4.2 Active Constraint Regions

There are two MVs, two MV inequality constraints, and two CV equality constraints. As $T_H = T_H^{sp}$ must be controlled always, we have one remaining degree of freedom and three potential constraints. This results in three possible active constraint regions, which are shown as a function of F_H and T_C^{in} (disturbance) in Fig. 4:

- Region 1: $F_H = F_H^{sp} < F_H^{max}$
- Region 2: $F_H = F_H^{max}$
- Region 3: $F_C = F_C^{max}$

In all regions $T_H = T_H^{sp}$. Note that in region 1, none of the two inequality constraints are reached, and it is possible to keep $T_H = T_H^{sp}$ and $F_H = F_H^{sp}$ using both available MVs. In regions 2 and 3, $F_H = F_H^{sp}$ must be given up. In region 2, F_C must be manipulated in order to keep $T_H = T_H^{sp}$, while in region 3, $F_C = F_C^{max}$ and F_H needs to be reduced below its maximum in order to keep $T_H = T_H^{sp}$.

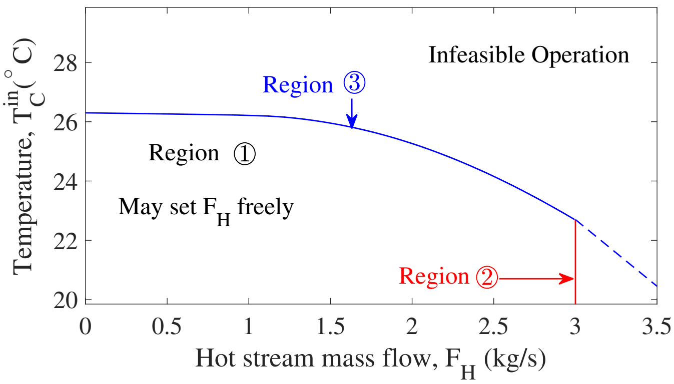


Fig. 4. Active constraint regions for the cooler.

4.3 Evaluation of Classical Advanced Control Structures

We now evaluate three control structures in a simulation using a dynamic countercurrent heat exchanger model with 10 cells: (a) SRC, (b) VPC, and (c) two controllers (*TC* and *TC2*) with different set points. The performance of each option is tested for rejection of disturbances in T_C^{in} of $+2\,°C$ at $t = 200\,s$, and an additional $+4\,°C$ at $t = 2000\,s$. It should be noted that the three evaluated structures include a *min* selector for CV selection; that is, giving up controlling $F_H = F_H^{sp}$.

Controller tuning The tuning parameters K_c and τ_I for the PI-controllers in table 2 were determined by fitting a FOTD model (K, τ, θ) obtained from open-loop step responses of the process, and applying the SIMC tuning rules (Skogestad, 2003). The open-loop responses in T_H for a step in the MVs (F_C and F_H) are depicted in Fig. 5. The tuning for temperature controller *TC*, which manipulates F_C, is the same for the three evaluated structures. The closed-loop time constant is $\tau_c = 2\,\theta = 88\,s$. For *TC2*, which manipulates F_H, $\tau_c = 10\,\theta = 70\,s$.

Fig. 6 shows the response of F_C to a step in F_H, keeping $T_H = T_H^{sp}$. This closed-loop response is required for tuning the VPC, which was tuned for tight control, i.e. $\tau_c = \theta = 12\,s$.

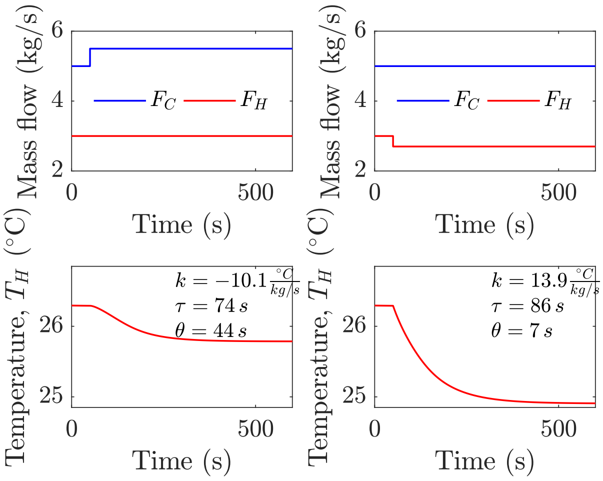


Fig. 5. Open-loop response in T_H for a step in F_C and F_H.

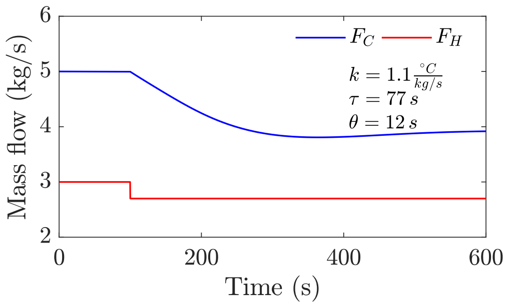


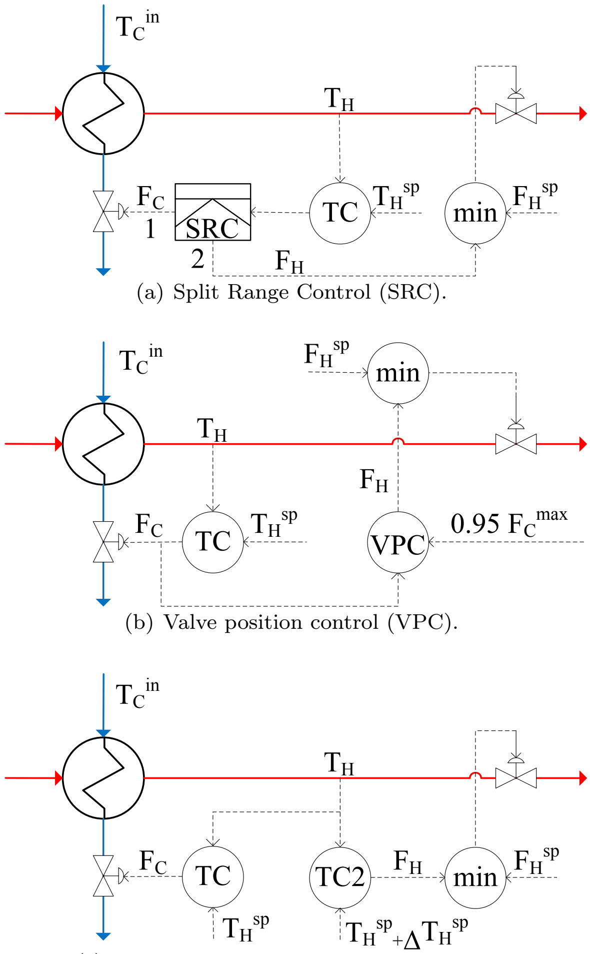
Fig. 6. Response in F_C for a step in F_H; used to tune the valve position controller (VPC).

Table 2. Tuning parameters.

Parameter	TC	VPC	TC2
K_C	-0.055	3	0.080
$\tau_I\ (s)$	74	77	86
$\tau_c\ (s)$	88	12	70

a) Split Range Control (SRC) The advantage of this structure is that there is only one temperature controller. By implementing SRC with a *min* selector block, as in Fig. 7(a), the controller can be designed to always operate at the optimum. Once $F_C = F_C^{max}$, F_H is used as MV to control T_H, as illustrated by the dynamic simulation in Fig. 8(a). As we are using deviation variables, the split range block is designed such that the split value is at $u = 0$, for simple implementation. To account for the different gains that F_C (negative gain) and F_H (positive gain) have on T_H, the output of the controller is respectively multiplied by 1 and -2. The integral term is the same for both MVs.

b) Valve Position Control (VPC) With this alternative, T_H is always controlled using F_C, while the VPC block takes the cooling water valve to 95 % opening by regulating F_H, as shown in Fig. 7(b). However, because of the *min* selector, the VPC block only becomes active when F_C exceeds 95 % of its maximum value. The advantage of this structure is that it always uses the same controller for T_H (TC), avoiding any change of dynamics.

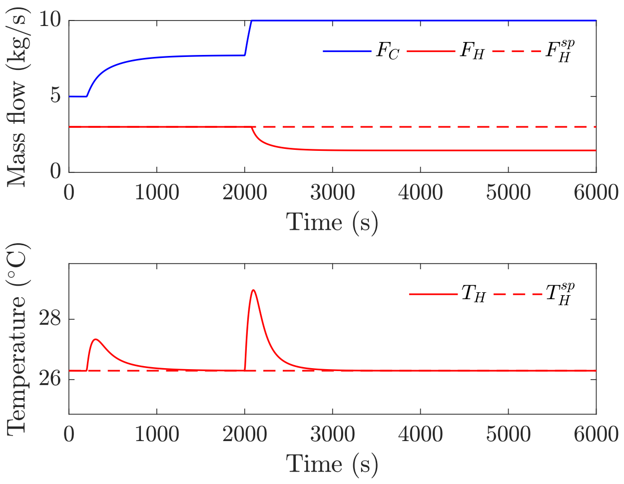


(a) Split Range Control (SRC).
(b) Valve position control (VPC).
(c) Two controllers with different setpoints.

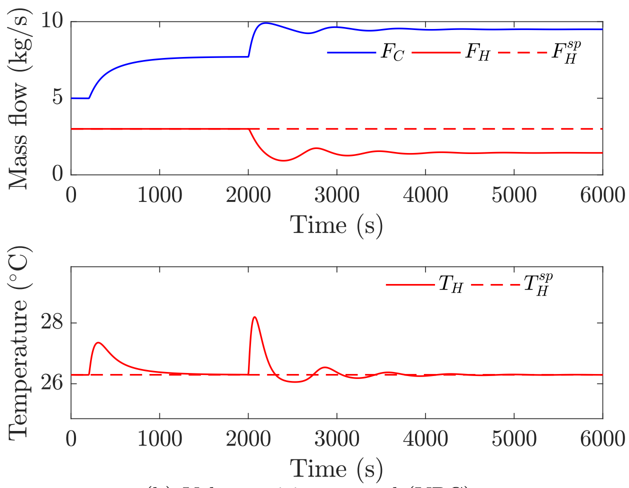
Fig. 7. Analyzed control structures for cooler.

The performance of this case is tested for the same disturbances in T_C^{in} as in the SRC case. Fig. 8 shows a more oscillating response of VPC compared to SRC. VPC is tightly tuned ($\tau_c = \theta$) which results in an aggressive behavior and oscillations. To remove the oscillations for this example, τ_c for VPC should be increased to at least $30\,\theta$, which in turn would result in an extremely slow response, with much poorer performance. Anti-windup is required on the VPC block because a *min* selector is implemented. Strictly, F_H should be manipulated by the VPC block once F_C reaches $0.95\,F_C^{max}$. However, when anti-windup with back-calculation is implemented, it starts acting before the set point for F_C is reached. This explains why the temperature overshoot for VPC (Fig. 8(b)) is slightly smaller than for SRC (Fig. 8(a)).

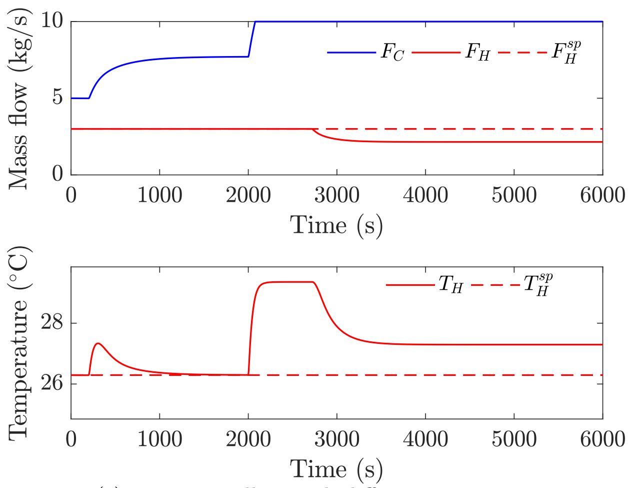
c) Two Temperature Controllers A third possible control structure is to implement two temperature controllers with different set points, as shown in Fig. 7(c). Different set points are needed to avoid interactions between the two controllers. TC uses F_C as MV, and has a set point $T_H^{sp} = 26.3\,°C$. On the other hand, $TC2$, with set point $T_H^{sp} + \Delta T_H^{sp} = 27.3\,°C$, uses F_H as MV. This solution is not optimal because we use two different set points for T_H. Unlike SRC and VPC, when F_C is saturated, $T_H \neq T_H^{sp}$ at steady state, as observed in Fig. 8(c).



(a) Split Range Control (SRC).



(b) Valve position control (VPC).



(c) Two controllers with different setpoints.

Fig. 8. Disturbance rejection with analyzed structures.

5. CONCLUSION

Formulating a priority list of constraints provides a systematic approach for designing classical advanced control structures. For cases with input saturation, split range control (SRC) is the only strategy that always allows optimal economic operation under changes in the active constraints, because it keeps the MV at the constraint. Using either valve position control (VPC) or two controllers requires a back-off from optimality. In the presented example, SRC also shows the best dynamic performance.

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