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Control structures for optimization: examples from chemical industry

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Abstract: We analyze and exemplify how some classical control structures can be used for optimizing a chemical process directly. Some key structures in this context are split-range control and mid-ranging control. In applications, split-range control is primarily used to manage several manipulated variables (valves) affecting the same controlled variable, without explicit reference to a control objective, or optimization criterion. However, the same basic principle can be used for directly optimizing a process, or subprocess. In some cases that scheme provides a simpler and more clear cut solution than MPC. A similar observation applies to mid-ranging control (also known as input resetting control, or valve position control).

Keywords: process control, chemical industry, optimizing control, split-range control, mid-ranging control

1. INTRODUCTION

By “classical control structures” we mean such well known multivariable schemes as cascade control, feedforward control, ratio control, etc. Those are described in numerous textbooks, e.g. Marlin (2000) and Smith and Corripio (2006), and compared to Model Predictive Control in Forsman (2016). In this paper we show how some classical structures can be used for on-line optimization in ways that are not well known from literature. The most important structures in this context are split-range control (SRC) and mid-ranging control (sometimes called input resetting control or valve position control).

2. SPLIT RANGE CONTROL BASICS

“Split-range control” in its simplest form consists in connecting the output u of a controller to several manipulated variables (MVs), typically valves, through a look-up table. More generally, we will call any structure where several MVs are calculated algebraically from the same controller output split-range control. This means that introducing SRC reduces the number of degrees of freedom available for control of a process.

A classical application of SRC is in temperature control, when both heating and cooling may be needed, using different process equipment for cooling and heating.

A simple example of an SRC application motivated by economic optimization is showed in (Fig 1). The primary control specification is to control the level in the feed tank. This is done by a single level controller (LC) that manipulates two valves, v_1 and v_2. The liquid in the top stream, coming from the storage tank through v_1, is cool, and the liquid in the bottom stream is hot. The process has two degrees of freedom (DoF), since we have two MVs and just one controlled variable (CV), namely the level.

The extra DoF can be used for optimization: It is preferred to take the hot liquid coming directly from plant 1 before taking cold liquid from the storage tank, because the first step in plant 2 requires hot liquid. So by ensuring that the feed to plant 2 is as warm as possible, we minimize steam usage there.

This optimization problem is easily solved by an SRC. The block named “SR” in (Fig. 1) implements the two look-up tables illustrated in (Fig. 2). In words: “When the control signal u is between 0% and 50% valve v_1 is fully closed, and v_2 opens from 0% to 100%. If u increases further, from 50% to 100% v_2 is fully open, and v_1 opens from 0% to 100%.”

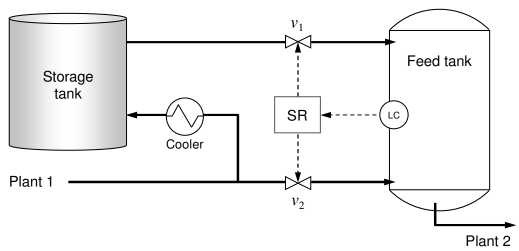

Fig. 1. Split-range control applied to level control example.

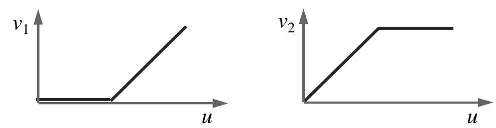

Fig. 2. SRC: Valve positions as functions of control output.

It is clear that this control scheme provides a solution to the energy optimization problem while ensuring that the level in the feed vessel is controlled. It is also worth noticing that it is difficult or maybe impossible to achieve the same control behavior using traditional MPC, considering v_1 and v_2 as independent MVs.

There are some additional practical considerations to be made when implementing an SRC scheme like the one above. For example, if the valve characteristics are considerably different for v_1 and v_2, it may be advantageous to modify the lookup table so that the process gain from u to CV is reasonably constant across the operating region. If not, tuning the level controller could be unnecessarily difficult.

3. SRC FOR THROUGHPUT MAXIMIZATION

Consider a simple process consisting only of a heat exchanger functioning as a cooler of a product stream, as in (Fig. 3). The product temperature is measured by a temperature transmitter TT. The cooling water flow through the exchanger can be manipulated by the valve v_2, and the flow of product by the valve v_1. So this process has two DoF.

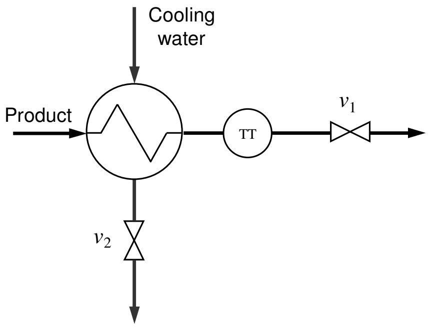

Fig. 3. Heat exchanger process.

This process step is in fact the bottle neck of the plant, so it is important to ensure that it is always running at maximum capacity. It is a strict requirement that the temperature should be controlled to its setpoint. In addition to this primary control specification we want the product flow to be maximized, so then we need to use both DoF.

The temperature is affected both by cooling water flow and product flow. Normally we would manipulate v_2 to control temperature and keep v_1 fully open in order to maximize production, as showed in (Fig. 4).

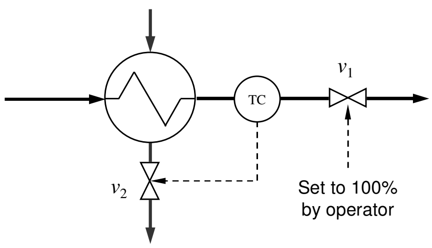

Fig. 4. Production maximization when cooling capacity is not limiting.

However, it could happen that cooling capacity is limiting production rate. In that scenario we may use v_1 for controlling temperature, thus connecting it to the TC, and keep v_2 fully open. So if we know beforehand what the limiting quantity ("active constraint") is, then we can make an MV-CV-pairing that ensures maximum throughput.

It is not uncommon that over time a constraint switches between being active and inactive. For example, during summer the temperature of the incoming cooling water may be so high that the cooling capacity is limiting, even though that is not the case during winter.

The SRC scheme described by (Fig. 5) and (Fig. 6) caters for active constraint switching. This structure can be seen as a kind of "dynamic variable pairing".

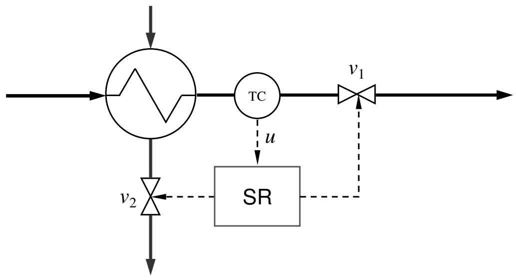

Fig. 5. SRC for production rate maximization in cooler.

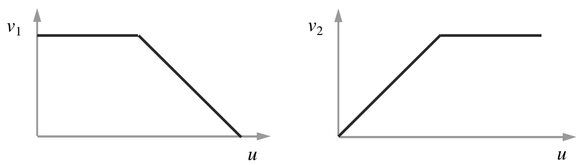

Fig. 6. SRC; valve positions as functions of u.

The above example is further elaborated and analyzed in Reyes-Lúa et al (2017).

Another example, of a different type, is given by (Fig. 7). Two processes P1 and P2 are separated by a buffer tank. The level of the tank is controlled by a P-controller LC. P1 is bottlenecking the entire plant, so it makes sense to manipulate the valve v_2 in order to control the buffer level, and to set v_1 = 100% so that production is maximized. In this case v_1 is the throughput manipulator (TPM) for the entire plant.

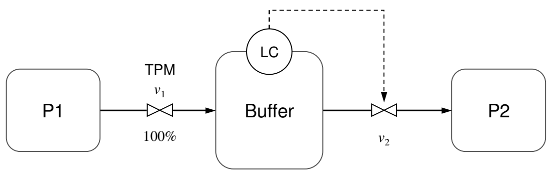

Fig. 7. Processes separated by buffer tank. P1 bottlenecking.

If instead P2 is the bottle neck, then the control structure in (Fig. 8) provides online optimization. Now v_2 is TPM.

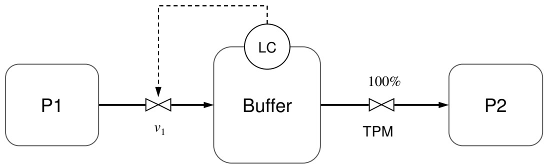

Fig. 8. Same plant as in Fig. 7, but P2 is bottlenecking.

If, again, we do not know beforehand if P1 or P2 is bottlenecking the plant, then the structure showed in (Fig. 9) provides on-line production rate maximization. In some sense there is no longer a TPM for the entire plant.

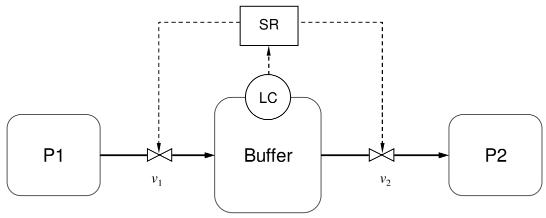

Fig. 9. SRC for maximizing throughput when bottleneck is moving.

4. MID-RANGING CONTROL

Mid-ranging control, or "input resetting", or "valve position control" is a classical technique for handling a process where two MVs influence the same CV, but with different gain and dynamics. The basic idea is to use two controllers: one that controls the CV by manipulating the fast and accurate MV, and one that slowly controls the operating point of the aforementioned by manipulating the slow and coarse MV. The latter is often called a valve position controller (VPC). Its CV is the MV of the first controller.

Fig. 10 shows a common way of implementing such a scheme. The most common reason for using VPC is to use the extra DoF to simultaneously address accuracy and rangeability, i.e. it is motivated by non-linearities (saturation and quantization). The setpoint for the VPC is often 50%, so that it aims at keeping the primary valve in the middle of its range, hence the name "mid-ranging".

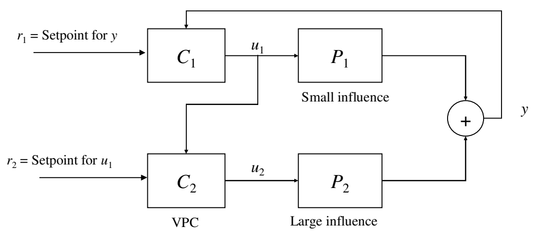

Fig. 10. Block diagram for a mid-ranging structure.

However, the same idea is also useful in optimizing control: the VPC could be used for ensuring that the back-off from an active constraint is at a prescribed level. This idea has been described by Shinskey (1998) and others.

Frequently the VPC scheme can be used for this purpose in the same cases as SRC but the resulting solution is only suboptimal, since it requires a certain back-off. In practice it may still be desirable, because it does not change the MV-CV-pairing. In the above example with heat exchanger throughput maximization, the control performance, e.g. temperature variability, may be significantly better using cooling water as MV than using product flow.

4. COOLING SYSTEM EXAMPLE

Consider a cooling system consisting of a refrigerating type of cooling machine, pressure equalization vessel, variable speed pump and two heat exchange units with control valves as shown in (Fig. 11) of Appendix A.

The system has four manipulated variables: input power to the cooling machine, pump speed and two valve positions for each of the heat exchangers.

The cooling machine outlet temperature, the pressure upstream of the heat exchangers and the temperatures of the two cooled streams from the heat exchangers are measured and can be controlled.

The transfer function matrix for this 4x4 system is highly interacting. To decrease the interaction between the subsystems, the pressure is controlled by manipulating the pump and the coolant temperature at the cooling machine outlet is controlled by manipulating the cooling machine input power. The most straightforward control structure for the temperatures of the cooled streams exiting the two heat exchangers is to simply control each temperature by manipulating the valve that affects the coolant throughput, as in (Fig 11).

Since the available cooling power in the cooling machine is limited, it could occur that the temperatures of one or both cooled streams from the heat exchangers cannot be kept at setpoint level due to too large cooling in the heat exchangers.

Assuming that there exists a known priority between controlled temperatures, a split-range implementation could ensure that this priority is met while utilizing the cooling machine maximally. In (Fig. 12), Appendix A, this split-range solution is illustrated. The high-priority temperature control, in this case TC1, primarily uses its own valve and secondarily limits the second temperature controller's output (valve) through a minimum selector.

The prioritizing split-range structure is extendable and could be used when more heat exchangers are added to the system. This solution handles the case when the high-priority temperature control is deviating from its setpoint due to too high coolant temperature, not the case where the valve saturates due to insufficient differential pressure.

The simple pressure control from (Fig. 11) and (Fig. 12) has a constant setpoint. Of course, a high pressure could be chosen as to keep the differential pressure from being limiting, however there is an energy optimization to consider. It is wasteful to have a high pressure and small valve openings at the heat exchangers.

A structure that optimizes the pump speed to save energy is a VPC acting on the maximum valve opening of the two (or more) heat exchanger valves, as shown in (Fig 13). The setpoint to the VPC should be close to 100% yet retain room for control.

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Appendix A. COOLING SYSTEM FIGURES

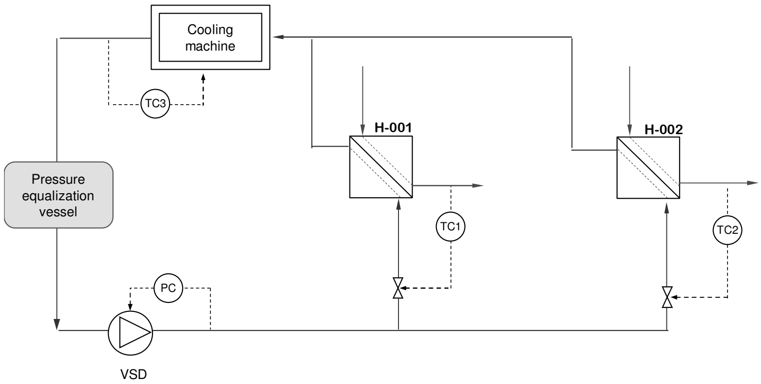

Fig. 11: Cooling system: completely decentralized control.

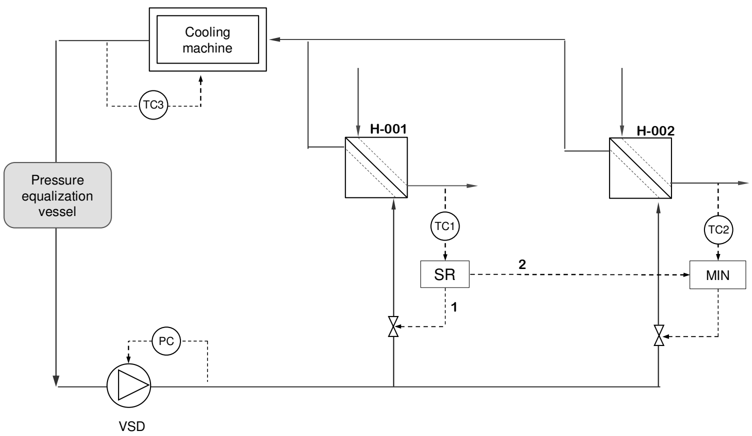

Fig. 12: Cooling system: SRC used for optimization.

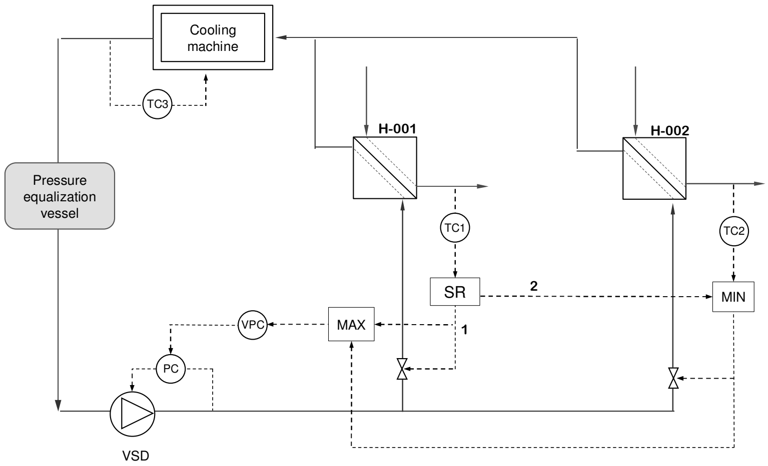

Fig. 13: Cooling system: SRC in combination with VPC and selectors, used for optimization.