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Systematic Design of Split Range Controllers ⋆

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Abstract: Split range control is a common advanced control structure in the process industry. It is primarily used to extend the steady-state operating range by using more than one manipulated variable (MV). More generally, it is used to switch to another MV when the original MV saturates. We propose a systematic procedure to design a split range controller considering the (different) dynamic effects of each MV on the output, as well as (steady-state) economics. We illustrate this procedure with a practical example.

Keywords: process control, constraints, split range control, optimal control, control specifications, control system design, control structures, PID control.

1. INTRODUCTION

Classical advanced control uses several standard functions (blocks) to cover cases not handled by the simple single-input single-output feedback controllers. Some examples are: cascade control, feedforward control, decoupling, selectors, split range control and valve positioning control.

Multivariable controllers such as Model Predictive Control (MPC) represent an alternative for some of these applications. However, MPC requires an explicit dynamic model. Furthermore, standard MPC does not allow to give-up completely controlling a variable and there is no systematic tuning procedure for MPC (Forbes et al., 2015).

This paper focuses on split range control (SRC), which is used when there are two or more manipulated variables (MVs) associated with one controlled variable (CV). The most common use of split range control is to extend the steady-state range by switching to another MV when the primary MV saturates; for example, to switch to electric heating when the hot water saturates. Some other names that have been used for split range control are *dual control agent* (Eckman, 1945) and *valve sequencing* (Lipták, 1985). Although split range control has been used for more than 75 years (Eckman, 1945; Fink, 1945), there is no systematic procedure for the design of split range controllers, to the best of the authors' knowledge.

This paper is organized as follows: in Section 2 we describe the split range control structure, while in Section 3, we describe how to get the desired controller gain for each MV by adjusting the slopes in the split range block. Section 4 proposes a systematic procedure for the design of split range control. We then implement this procedure in a case study in Section 5. In Section 6 we discuss about alternative control structures for split range control, and we make our final remarks in Section 7.

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2. CLASSICAL SPLIT RANGE CONTROL

Let the manipulated variables (MV_i) be denoted by u_i and the controlled variable (CV) be denoted by y. As shown in the block diagram in Fig. 1, most applications have two MVs (u_1 and u_2) and one CV (y). There is one single-input single-output controller (C) that calculates the internal signal (v) to the split range block (SR). C is commonly a PI controller. The split range block splits v into the two MVs (u_1 and u_2).

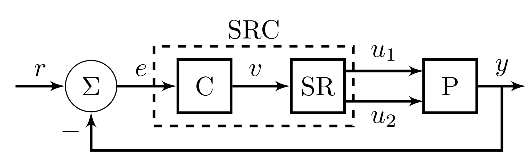

Fig. 1. Block diagram for split range control (SRC) with two MVs and one CV. SR is the split range block.

Fig. 2 depicts a typical split range block. When v is below the split value (v^*), u_1 is used to control the CV (y), while u_2 is saturated. At the split value, u_1 becomes saturated, and the controller starts using u_2 to control y.

The split value is located at the mid-point ($v^* = 50\%$) in Fig. 2, but there is no reason to use this particular value. Instead, v^* should be used as a design parameter for the split range block to adjust the dynamic response (Lipták, 1985; Glemmestad, 1997; Hägglund, 1997). Fixing v^* at a given value (e.g. 50%) is related to a common misconception, also found in most textbooks (e.g. Stephanopoulos (1984); Marlin (2000); Bequette (2002); Seborg et al.

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(2003)). The misconception is that v is the "controller output", and thereby the signal sent to the valves. However, the actual controller output are the signals u_i coming out of the split range block, whereas v is an internal signal in the controller with limited physical significance.

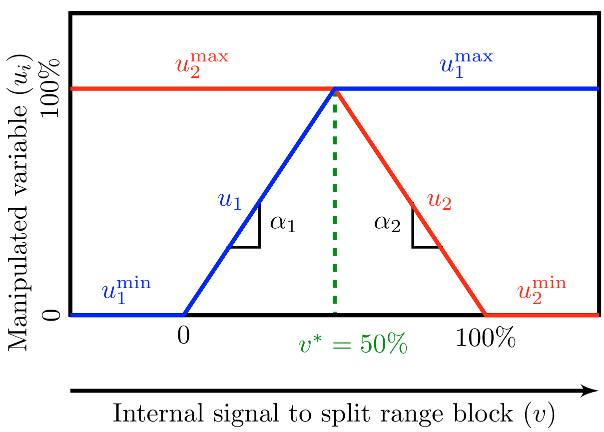

Fig. 2. Typical split range block giving the relationship between v and two MVs (u_1 and u_2). In general, the split value (v^*) should not be fixed at 50%.

In Fig. 2, the MV signals (u_i) (on the y-axis) are physically limited to be within the given range from 0% (e.g., fully closed valve) to 100% (e.g., fully open valve). The internal signal (v) (on the x-axis) is also shown to be scaled in the range 0% to 100%, but here there are no physical limits and v can be outside the range 0% to 100%.

This follows from the fact that the internal signal (v) is in deviation variables, whereas the outputs from the split range block (u_i) are physical variables. For example, when we are operating on the right side of Fig. 2, we have:

$$u_2 = u_2^{\max} + \alpha_2(v - v^*) \tag{1}$$

Let us try to explain why v^* is actually a design parameter. At a given operating point, the integral action in the controller will drive the physical MV_2 (u_2) to a given steady-state value. From Eq. (1), this means that the difference $v - v^*$ will have a given value. However, if we let v^* have another value, then u_2 and $(v - v^*)$ will remain the same, but the internal signal (v) will change.

The slopes in the split range block (α_i) have physical significance as controller gain contributions for each MV_i (u_i). Considering the signs of the slopes, we can distinguish two main cases. The first case is when the MVs have opposite effects (gains) on the CV. One of the earliest descriptions of this case is the use of split range control to maintain constant temperature by using steam when the surrounding temperature is low and cold water when it is high (Eckman, 1945; Fink, 1945).

The second case is when the MVs have the same effects, but one MV is preferred for economic reasons. For example, Fink (1945) considers the case with three MVs for temperature control of a reactor with an exothermic reaction: two for cooling and one for heating. In this example, one should first use cold water for cooling, and when the cold water valve cannot handle the heat load, one should also use the more expensive refrigerated water to maintain the reactor at the desired temperature.

3. SELECTION OF SLOPES

In split range control, several MVs (u_i) are calculated from the same internal signal (v). At a particular time, only one u_i is being used to control the CV (y). However, each of the MVs (u_i) has a different dynamic and static effect on the CV (y), and this should be considered when designing the split range controller.

From Eq. (1) and Fig. 2 it is evident that the slopes in the split range block (α_i) correspond to the gains from the internal signal (v) to the value of each MV_i (u_i). As a generalization of Eq. (1), the split range block can be represented as the linear function

$$u_i = u_{i,0} + \alpha_i \ v \quad \forall i \in \{1, \dots, N\} \tag{2}$$

where u_i is the value of each MV_i, v is the internal signal to the split range block, α_i is the gain from v to u_i (the slopes in Fig. 2, $\Delta u_i / \Delta v$), N is the number of MVs, and $u_{i,0}$ is a constant bias. Note that Eq. (1) and (2) are identical, with $u_{2,0} = u_2^{\max} - \alpha_2 v^*$.

What value should be select for the slopes (α_i)? As a starting point, it seems reasonable to select them to counteract the differences in the static loop gain ($K_{p,i}$) for each MV_i and to select $|\alpha_i|$ proportional to $1/|K_{p,i}|$. However, this is too simplified, as one should also consider the dynamic response for each MV_i.

Let the desired controller for MV_i be denoted $C_i(s)$. For example, it could be a PI controller with gain $K_{C,i}$ and integral time $\tau_{I,i}$. This is the controller we would like to have if we were free to choose any controller. $C_i(s)$ should be compared with the common controller $C(s)$, see Fig. 1, which could be a PI controller with gain K_C and integral time τ_I.

Including the split range block (where we have the slopes α_i), we see that the actual controller in Fig. 1 for MV_i is $\alpha_i C(s)$. However, since we only have one free parameter, α_i, it is not possible in general to make $\alpha_i C(s)$ equal to the desired $C_i(s)$. The best we can do is to use α_i to match the desired controller at the desired crossover (or bandwidth) frequency, which will be at frequency $\omega_{c,i} = 1/\tau_{c,i}$, where $\tau_{c,i}$ is the desired closed-loop time constant for MV_i.

Consider a PI controller $C(s) = K_C(1 + \frac{1}{\tau_I s})$. At frequency $\omega_c = 1/\tau_c$, we then find that the frequency response is given by $C(j\omega_c) = K_C(1 - j\frac{\tau_c}{\tau_I})$. From this, we find that $C(j\omega_c) \approx K_C$ for $\tau_c \ll \tau_I$, and $C(j\omega_c) \approx -j\frac{K_C}{\tau_I}\tau_c$ for $\tau_c \gg \tau_I$. We then have two main cases:

(1) *"Slow" (integrating or close-to integrating) process*, where $\tau_c \ll \tau_I$. The proportional gain ($K_{C,i}$) is the most important controller parameter because $C_i(j\omega_{c,i}) \approx K_{C,i}$. We select the slopes ($\alpha_i$), or equivalently the break points, to achieve:

$$K_{C,i} = \alpha_i K_C \quad \forall i \in \{1, \dots, N\} \tag{3}$$

Here $K_{C,i}$ is the desired controller gain for each MV_i and K_C is the proportional gain in the common PI controller in Fig. 1.

(2) *"Fast" process*, where $\tau_c \gg \tau_I$. Here, the most important controller parameter is the integral gain ($K_{I,i} = K_{C,i}/\tau_{I,i}$) because $C_i(j\omega_{c,i}) \approx -j\frac{K_{C,i}}{\tau_{I,i}}\tau_{c,i}$. Thus, for such processes instead of computing the

slope (α_i) according to Eq. (3), we should compute it according to $K_{I,i} = \alpha_i K_I$, or equivalently:

$$\frac{K_{C,i}}{\tau_{I,i}} = \frac{\alpha_i K_C}{\tau_I} \quad \forall i \in \{1, \ldots, N\} \tag{4}$$

Here $K_{C,i}$ and $\tau_{I,i}$ are the desired PI settings for the controller $C_i(s)$ for MV_i, whereas K_C and τ_I are the settings used in the common PI controller.

3.1 Controller tunings

In Eq. (3) and (4), $K_{C,i}$ and $\tau_{I,i}$ are the desired PI settings for each MV_i. One way to find good PI settings is to use the SIMC rules (Skogestad, 2003), in which we first identify a first-order plus time delay model

$$G_i(s) = \frac{K_{p,i}}{\tau_i s + 1} e^{-\theta s} \tag{5}$$

for each MV_i and then select the desired closed loop time constant ($\tau_{c,i}$) to calculate $K_{C,i}$ and $\tau_{I,i}$:

$$K_{C,i} = \frac{\tau_i}{K_{p,i}(\tau_{c,i} + \theta_i)} \tag{6a}$$

$$\tau_{I,i} = \min\{\tau_i, 4(\tau_{c,i} + \theta_i)\} \tag{6b}$$

Note that, from Eq. (3) and(4), if K_C is positive, then α_i has the same sign as $K_{C,i}$, which from Eq. (6a) has the same sign as the process gain $K_{p,i}$. We also note that selecting $\tau_{I,i} = 4(\tau_{c,i} + \theta_i)$ in Eq. (6b) corresponds to a "slow" process (case 1) and selecting $\tau_{I,i} = \tau_i$ corresponds to a "fast" process (case 2).

What value should we select for the integral time (τ_I) in the common controller? There is no simple answer to this. If one particular MV, let us say u_k, is used most of the time, then it is reasonable to select $\tau_I = \tau_{I,k}$. In other cases, one may select τ_I as some average of the desired $\tau_{I,i}$'s for the individual loops. What value should one choose to be on the "safe" side with respect to stability? It depends on whether we are matching K_C or K_I. If we have a "slow" process and are matching K_C according to Eq. (3), then selecting a large value for τ_I is safer. On the other hand, if we have a "fast" process and are matching K_I according to Eq. (4), then selecting a small value for τ_I is safer.

4. A NEW PROCEDURE FOR DESIGNING THE SPLIT RANGE BLOCK

Here, we propose a systematic procedure to design the split range block considering the different dynamics of each MV_i, as discussed in Section 3.

For the first steps, we need to make some decisions:

- S1 Define the range for the internal signal from the controller to the split range block ($v^{\min}, v^{\max}$) [1].
- S2 Find the minimum and maximum values for every MV ($u_i^{\min}$, $u_i^{\max}$). Here, we typically normalize the MVs, such that $u_i^{\min}$ and $u_i^{\max}$ is the same for every MV (e.g. $0\% - 100\%$).
- S3 Decide on the desired controller tunings for each individual MV_i. For example, one may use the SIMC rules (Eq. (6)) to find the desired PI controller proportional gain ($K_{C,i}$) and desired integral time ($\tau_{I,i}$).
- S4 For PI control, choose the integral time (τ_I) for the common controller, as discussed in Section 3.1.
- S5 Choose the order for the MVs based on physical and economic arguments. In this step, it is useful to make a graphical representation of the split range block (as in Fig. 2). This is further explained in Section 4.1.

The remaining steps are purely algebraic:

- S6 From Fig. 2, we note that we must have:

$$v^{\max} - v^{\min} = \sum_{i=1}^{N} \frac{u_i^{\max} - u_i^{\min}}{|\alpha_i|} \tag{7}$$

  Use Eq. (7) together with Eq. (3) for a "slow" process or Eq.(4) for "fast" process to find the slopes (α_i) for each MV_i and the common controller gain K_C.
- S7 Find the range of the internal signal covered by each MV_i (Δv_i), and thereby the split values (v_i^*), using Eq. (8):

$$\Delta v_i = v_i^* - v_{i-1}^* = \frac{u_i^{\max} - u_i^{\min}}{|\alpha_i|} \;\forall\, i \in \{1, \ldots, N\} \tag{8}$$

We should note that, as we have a common controller $C(s)$, anti-windup should only be activated when all the MVs are saturated. In Fig. 2, this would be at $v < 0\%$ or $v > 100\%$.

4.1 Ordering the use of MVs (Step S5)

The order of use of the MVs should be defined considering the effect on the process as well as economic aspects.

We suggest to order the MVs in the split range block according to the following procedure:

- S5.1 Define the desired or most economical operating point for every MV_i (e.g. fully closed or fully open valve).
- S5.2 Consider the effect of the main disturbance (or change in operating conditions) in both directions (when we move away from the most economical operating point). Then, group the available MVs into:
  - (a) MVs for which the value of the CV *increases* when we move away from the desired operating condition.
  - (b) MVs for which the value of the CV *decreases* when we move away from the desired operating condition.
- S5.3 Within each group, (a) and (b), order the MVs according to which one should be used first (less expensive) to which should be used last (more expensive). The MVs that should be used first will be located closest to the point defined in S5.1.

Example: Consider temperature control for a room. The CV is the room temperature ($y = T$) and the main disturbance is the ambient (outdoor) temperature ($d = T^{amb}$). The available MVs that affect room temperature ($y = T$) are: heating (u_3), cooling (u_2) and ventilation (u_1 in summer and u_4 in winter). To order the MVs we note that the desired operating point is to use no heating or cooling (to save money) and to have maximum ventilation (to have the best air quality).

[1] v is an internal signal, not the actual controller output, and it can be re-scaled freely. For example, the range can be -1 to 1 or 0% to 100%.

We now follow the procedure to order the use of the MVs:

S5.1 The desired operating point is when the ambient temperature ($d = T^{amb}$) is equal to the desired room temperature ($T^{ref} = T^{amb}$). At this point, heating and cooling are off, and the ventilation flow is at its maximum, to maintain the best air quality. For example, with a set point $T^{ref} = 22\,°C$ for the indoor temperature, the desired operating point is when the outdoor temperature happens to be $T^{amb} = 22\,°C$.

S5.2 If T^{amb} increases, we need to cool the room to maintain the desired room temperature. On the other side, if T^{amb} decreases, we need to heat the room. Then, we can group the MVs:
  (a) MVs that *increase* the room temperature (y) as the disturbance moves us away from the desired value, when $T^{amb} < T^{ref}$)
  - Heating (u_3)
  - Ventilation (u_4). Note that in the winter, reducing the ventilation will *increase* the room temperature (y)

  (b) MVs that *decrease* the room temperature (y) as the disturbance moves us away from the desired value, when $T^{amb} > T^{ref}$)
  - Cooling (u_2)
  - Ventilation (u_1). Note that in the summer, reducing the ventilation will *decrease* the room temperature (y)

S5.3 (a) In the summer, we first use cooling (u_2) and only when it reaches its maximum we start reducing the ventilation (u_1).
  (b) In the winter, we first use heating (u_3) and only when it reaches its maximum we start reducing the ventilation (u_4).

Fig. 3 shows the resulting split range block.

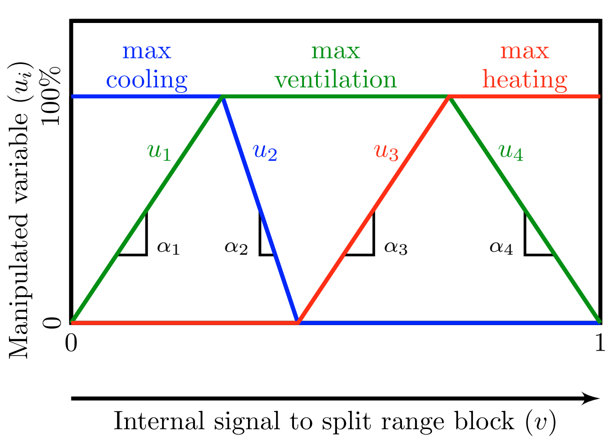

Fig. 3. Split range block for room temperature control with heating (u_4), cooling (u_2) and ventilation flow (u_1, u_4) as MVs.

5. CASE STUDY

In this section we show a simulation example of a similar room heating process, but in this case ventilation is not available as an MV.

5.1 Description of the system

We consider a room with two sources of cooling and two sources of heating:

- AC: air conditioning
- CW: cooling water
- HW: hot water (district heating)
- EH: electric heating.

The main disturbance is ambient temperature (T^{amb}) and the nominal ambient temperature is $T_0^{amb} = 18\,°C$. This will be chosen as the nominal room temperature $T = 18\,°C$.

The control objective is to keep the room temperature at $T = T^{ref}$. Fig. 4 shows the block diagram for this process, using one PI controller and a split range block.

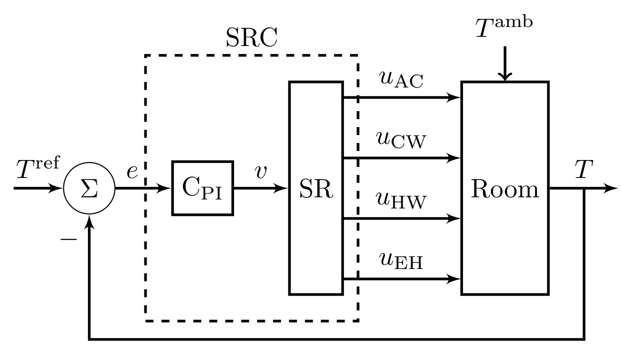

Fig. 4. Block diagram of split range control for controlling room temperature.

We model the room as a linear system:

$$T(s) = G_p(s)\; u(s) + G_d(s)\; d(s) \tag{9}$$

where:

$$u = [u_{AC} \;\; u_{CW} \;\; u_{HW} \;\; u_{EH}]^{\mathsf{T}}$$
$$G_p(s) = [G_{AC}(s)\; G_{CW}(s)\; G_{HW}(s)\; G_{EH}(s)]$$

Table 1 shows the gains ($K_{p,i}$), time constants (τ_i), and time delays (θ_i) for $G_p(s)$.

Table 1. Parameters for $G_{p,i}(s)$ from u_i to T.

$G_{p,i}$	$K_{p,i}$	τ_i [min]	θ_i [min]
G_{AC}	-5	8	2
G_{CW}	-10	15	3
G_{HW}	12	10	3
G_{EH}	8	5	1

The disturbance transfer function from T^{amb} to the room temperature (T) is:

$$G_d(s) = \frac{1}{15s+1} e^{-6s} \tag{11}$$

5.2 Design of the split range controller

We now follow the procedure in Section 4 and design the split range controller.

Step S1 The range of the internal signal to the split range block is defined as $v^{\min} = 0$, $v^{\max} = 1$, $v^{\text{tot}} = 1$.

Step S2 The MVs are scaled such that for every MV$_i$: $u_i^{\max} = 1$ and $u_i^{\min} = 0$.

Step S3 We have the required information to use the SIMC rules, and the PI controller tunings for each MV$_i$ are shown in Table 2. The SIMC procedure allows to select a different closed loop time constant ($\tau_{c,i}$) for each MV$_i$, considering its individual dynamics.

Table 2. Tuning parameters for each MV.

u_i	$\tau_{c,i} [min]$	$K_{C,i}$	$\tau_{I,i} [min]$
u_{AC}	2	-0.4000	8
u_{CW}	4	-0.2143	15
u_{HW}	3	0.1389	10
u_{EH}	3	0.1563	5

Step S4 We choose τ_I for the common PI controller. This is a "slow" process. To be "safe", we might want to use the largest value for $\tau_{I,i}$ ($15\,min$), but we will use $9.5\,min$, which is a compromise among all $\tau_{I,i}$ values.

Step S5 The next step is to order the use of the MVs.

S5.1 The most economical operating point is when $T^{amb} = T^{ref}$, and we can have all MVs fully closed.

S5.2 To maintain $T = T^{ref}$, we need to cool the room if T^{amb} increases, and to heat the room if T^{amb} decreases. With this in mind, we can group the MVs according to their effect on the room temperature. If $T^{amb} > T^{ref}$, we can use either CW or AC. Likewise, if $T^{amb} < T^{ref}$, we can use either HW or EH.

S5.3 Finally, we order the use of the MVs. As CW is less expensive than AC, we prioritize the use of CW over AC for decreasing room temperature. This locates CW closest the point where all the MVs are fully closed, and AC further away from this point. Likewise, we prioritize the use of HW over EH. Therefore, as shown in Fig. 5, the MV sequence in the resulting split range block is: u_1 = AC, u_2 = CW, u_3 = HW and u_4 = EH.

Step S6 We can now proceed to the algebraic steps of the procedure and calculate K_C and α_i by solving Eq. (3) together with Eq. (7). We find $K_C = 0.0482$ and the values for α_i reported in Table 3. In this case K_C is positive. We can observe that both for AC (u_1) and CW (u_2), $\alpha_i < 0$ (both decrease room temperature), while for HW (u_3) and EH (u_4), $\alpha_i > 0$ (both increase room temperature). This corresponds to the expected physical behavior of these MVs.

Step S7 Using the calculated values for α_i, we can find Δv_i from Eq. (8). Then, the bias in Eq. (2), is:

$$\begin{aligned} u_{\text{AC},0} &= u_{\text{AC}}^{\max} \\ u_{\text{CW},0} &= u_{\text{CW}}^{\max} - (\alpha_{\text{CW}})\,(\Delta v_{\text{AC}}) \\ u_{\text{HW},0} &= u_{\text{HW}}^{\min} - (\alpha_{\text{HW}})\,(\Delta v_{\text{AC}} + \Delta v_{\text{CW}}) \\ u_{\text{EH},0} &= u_{\text{EH}}^{\max} - (\alpha_{\text{EH}})\,(v^{\text{tot}}) \end{aligned}$$

Table 3 summarizes the information that describes the split range block for this system, and the final split range block is shown in Fig. 5.

Table 3. Values for α_i, Δv_i and $u_{i,0}$.

	AC	CW	HW	EH
α_i	-8.3067	-4.4500	2.8843	3.2448
Δv_i	0.1204	0.2247	0.3467	0.3082
$u_{i,0}$	1.000	1.5357	-0.9954	-2.2448

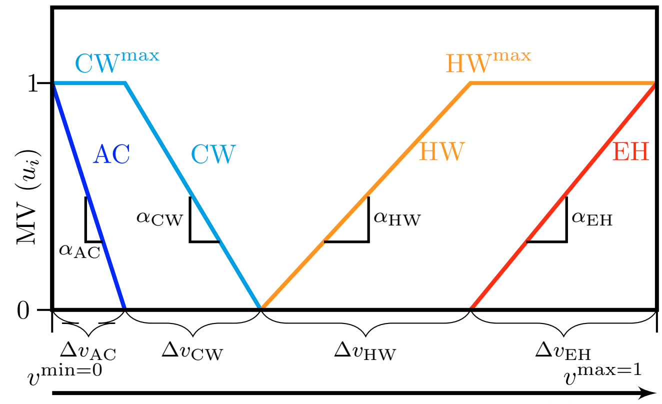

Fig. 5. Split range control diagram for room temperature control with air conditioning (AC), cooling water (CW), hot water (HW), and electric heating (EH).

5.3 Simulations

Changes in T^{ref}. The performance of this split range control design and tuning is tested for changes in temperature set-point T^{ref} of $+5\,°C$ at $t = 10\,min$, $+8\,°C$ at $t = 60\,min$, $-15\,°C$ at $t = 110\,min$, and an additional $-9\,°C$ at $t = 160\,min$.

Fig. 6 shows the closed-loop response for changes in temperature set-point. In the beginning, $T = T^{ref} = 18\,°C$. At $t = 10\,min$, we increase T^{ref} from $18\,°C$ to $23\,°C$. This is easily achieved using hot water (HW). At $t = 60\,min$, we further increase T^{ref} to $31\,°C$, and when HW becomes saturated at its maximum value, electric heating (EH) takes over to bring T to its desired set point.

When T^{ref} is decreased to $16\,°C$ at $t = 110\,min$, both cooling options (CW and AC) saturate initially and anti-windup is used for a short period. We should note that $\Delta T^{ref} = -15\,°C$, which is large. The AC is used only for a short time because at steady state it is sufficient to use cooling water (CW). Finally, when T^{ref} is decreased to $7\,°C$, CW saturates at its maximum value and we need to use the AC.

Disturbances in T^{amb}. The performance of this implementation is also tested for rejection of disturbances in T^{amb} of $+2\,°C$ at $t = 10\,min$, $+10\,°C$ at $t = 60\,min$, $-13\,°C$ at $t = 110\,min$, and an additional $-15\,°C$ at $t = 160\,min$. Fig. 7 shows the closed-loop response. The behavior is similar to the one observed for changes in set-point. At first, CW suffices to maintain $T = T^{ref}$, but when $T^{amb} = 30\,°C$, CW reaches its maximum value and it is necessary to use the AC. Similarly, when $T^{amb} < T_0^{amb}$, it is initially enough to use HW, but when T^{amb} decreases considerably, HW saturates at its maximum value and EH becomes the MV in use.

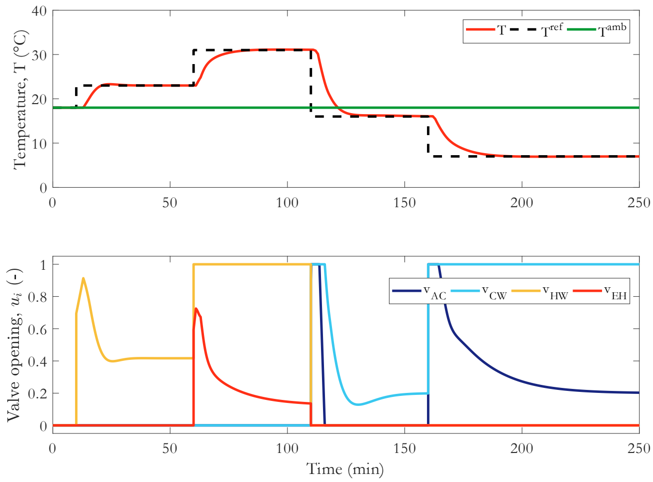

Fig. 6. Closed-loop response for changes in temperature set-point (T^{ref}).

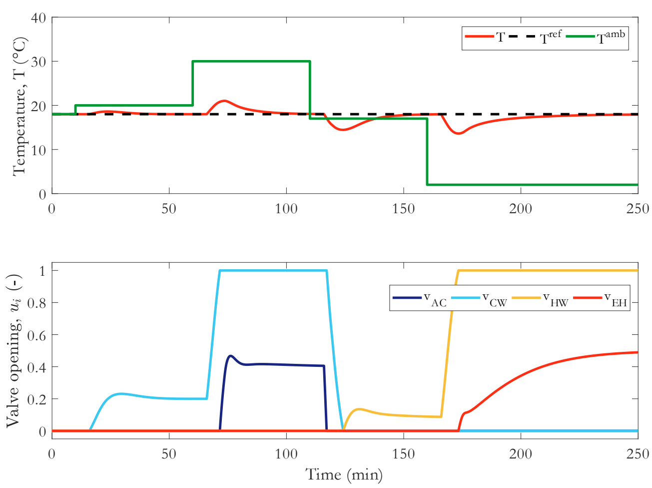

Fig. 7. Closed-loop response for changes in ambient temperature (T^{amb}).

6. DISCUSSION

It should be noted that every time that split range control is used, there are two other alternative control structures that should be considered. One is to use separate controllers for each MV, but with different CV set-points. The ordering of the MV use is then determined by the set-point values. This structure can be economically optimal in certain cases. The second alternative is to use valve position control on the primary MV. This alternative gives a loss (back-off) because one can never reach the constraint for the primary MV, but the advantage is that the same MV is always controlling the CV. The three alternative structures were compared on a simple case study in Reyes-Lúa et al. (2018) and a more detailed analysis is forthcoming.

7. CONCLUSIONS

Split range control is used when we want to switch manipulated variables (MVs). We have shown how to use the slopes (α_i) in the split range block, or equivalently the split values (v^*), as parameters to get the desired controller for each MV$_i$, using Eq. (3) and Eq.(4).

Based on this, we propose a systematic procedure to design split range control structure. An important step of this procedure is the ordering of MVs in step S5. This procedure can be applied to any number of MVs that are used to control one controlled variable (CV).

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