

A PID de-tuned method for multivariable systems, applied for HVAC plant

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Abstract. A simple yet effective de-tuning of PID parameters for multivariable applications has been described. Although the method is felt to have wider application it is simulated in a 3-input/ 2-output building energy management system (BEMS) with known plant dynamics. The controller performances such as the sum output squared error and total energy consumption when the system is at steady state conditions are studied. This tuning methodology can also be extended to reduce the number of PID controllers as well as the control inputs for specified output references that are necessary for effective results, i.e. with good regulation performances being maintained.

1. Introduction

The three-term or PID (Proportional, Integral and Derivative) controller is still by far the most widely used industrial controller due to its simplicity and robustness. The controller has traditionally been developed for SISO applications and various tuning and setting up procedures (see for example in [1]) have been developed to assist the commissioning of PID loops. Advances in auto-tune the PID parameters in an adaptive manner have been developed and commercially used [2]; both analogue and digital versions exist that also include intelligent methods [3][4]. The PID controllers have also widely been used in multivariable applications where their commissioning is less well formalised. The normal approach is to use a robust and adhoc de-tuning philosophy to reduce the gains so that the multivariable application can operate [5][6] but no overall optimality is considered. It would be useful if a more generic methodology is available which allows PID controllers to be setup in such multivariable situations. In this way the classical merits of PID controllers can be extended to general multi loop implementations. A solution for addressing this difficulty is to apply state-space methods where the matrices of PID gains are obtained by observing the outputs of the system when step inputs are applied in turn [7]. In this manner the system inputs and outputs can be “connected” to give rise to the dominant “diagonal” systems as well as the most important cross coupling interactions. However establishing the most diagonal form is difficult and is based on trial and error approach. This methodology has been improved [8] so that the PID gains are obtained in a more unified manner but the trial and error foundations persist. A more recent method to auto-tune the multi-loop PID controllers is to combine sequential loop closing and relay tuning, which is proposed [9] but this method only applies to square systems, i.e. the number of inputs equals the number of outputs and hence it cannot be used for wider applications. There are many other methods and regimes to obtain the PID gains that based on generic and intelligent approaches, for example as discussed in [10].

In this paper, we propose a far simpler PID tuning methodology also based on open-loop step responses but focusing on the performance of individual PID controllers. The method is felt to be application independent but for convenience it is discussed here through its implementation to a

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building energy management system (BEMS) with three inputs and two outputs (non-squared system).

2. Multi PID-loop controller

In this multivariable system, we assume that the number of output and input are m and n respectively. The traditional method for designing the control system for this situation is to use m PID controllers for each input. Therefore, we require to utilise $m \times n$ or mn PID controllers for the overall system. The block diagram for this configuration is shown in figure 1 where PID#11, PID#12, ..., PID# mn are the PID controllers and M_{ij} , $i = 1, 2, \dots, m$ and $j = 1, 2, \dots, n$ are their respective outputs to drive the control inputs u_i . The PID output signals are given by:

$$\text{PID\#}ij: M_{ij} = K_{p_{ij}} e_j + K_{i_{ij}} I_j + K_{d_{ij}} \frac{de_j}{dt} \quad (1)$$

where output errors, e_j are given by $e_j = y_{Rj} - y_j$. Here, y_j and y_{Rj} are the actual and desired outputs respectively. $K_{p_{ij}}$, $K_{i_{ij}}$ and $K_{d_{ij}}$ are the proportional, integration and derivative gains for controllers PID#11, ..., PID# mn respectively. For a digital PID implementation, the integration term with respect to time t can be approximated by the Euler method, which employs

$$\int_0^t e_j(t) dt \equiv I_j(t) = I_j(t-T) + e_j(t) T \quad (2)$$

where T is the sampling period, and the derivative term is given by

$$\frac{de_j(t)}{dt} = \frac{e_j(t) - e_j(t-T)}{T} \quad (3)$$

Each control input u_i , to drive the plant is obtained by summation of the m PID outputs

$$u_i = M_{i1} + M_{i2} + \dots + M_{in}, \quad (4)$$

with constraints: $u_i(\min) \leq u_i \leq u_i(\max)$. The objective here is to tune the PID gains for optimum performance so that the outputs remain at required setpoints over the control period. The performance of the tuned controller will be judged by looking at the regulation errors as well as the number of inputs consumed. Clearly a good controller design should have small errors and consume less inputs as well as the number of controllers used.

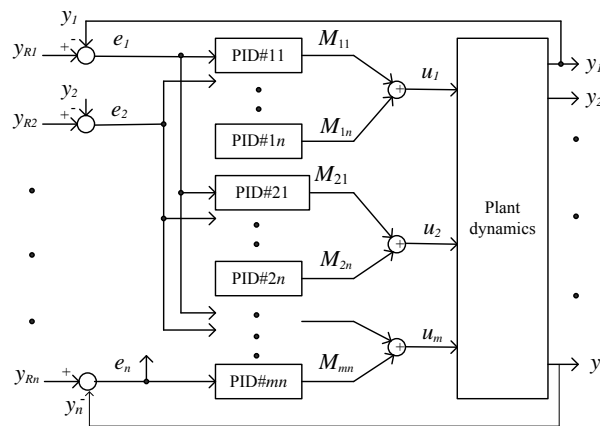


Figure 1. A PID controller structure for multivariable system

A. Ziegler and Nichols (Z-N) tuning rules

There are many methods of PID tuning and a well-known one is the classical Ziegler and Nichols tuning rules [11] from which were followed on the open loop step test and the PID gains are given by

$$K_{p_{ij}} = \frac{1.2}{K_{ij}} \frac{\tau}{\alpha}, \quad K_{i_{ij}} = \frac{K_{p_{ij}}}{2\alpha} \quad \text{and} \quad K_{d_{ij}} = K_{p_{ij}} \frac{\alpha}{2} \quad (5)$$

where $K_{ij} = \frac{\Delta y_{sj}}{\Delta u_{si}}$ is the slope of change in process value y_{sj} against the step change in manipulated value, u_{si} . α and τ the output delays as shown in figure 2. The integration term, I_j from equation (2) will make the output M_{ij} increasing or decreasing against time depending on either positive and negative error, e_j respectively, so the limits, $I_j(\min) \leq I_j \leq I_j(\max)$ shall be imposed in the setting up of the controller to avoid these winding up effects.

This PID controller is then tested on a 3 input/ 2 output model of building energy management system (BEMS), also known as HVAC plant at Loughborough University, UK with known plant dynamics as reported in [12]. The three inputs are the heater, cooler and humidifier with maximum power, $u_i(\max)$ of 5.0, 2.7 and 2.6 kW respectively. The outputs are the room temperature and its relative humidity. They have presented the plant dynamics in a linear difference equation with sampling period of 5 minutes. Other parameters such as the surrounding temperature and humidity inside and outside the room/ building, solar irradiation, occupancy and the door opens and closes are treated as the disturbances and noises respectively to this plant dynamics. The results at various output setpoints have shown that the control performances are poor with large output error and majority of the 6 PID act like an on/ off controller where the output fluctuations are large and majority of the control inputs swing between off and on (maximum) limits due to the above imposed constraints. In another word, the Ziegler-Nichols tuning rules are not suitable for multivariable system because a good controller shall vary only between the control inputs ranges in order to regulate the outputs with acceptable error. The Z-N method is only applicable if all the loops are independent of each other and this does not apply to this multivariable case. Example of the result is shown in figure 3 where the required room temperature (y_{R1}) and relative humidity (y_{R2}) were set at 25°C and 50%rh respectively and found that the temperature and humidity sum squared error for the last 100 samples were 68.5 °C² and 8181.0 %rh². In view of this performance it appears beneficial to investigate whether it was possible to develop a methodology so that the PID gains could be de-tuned in multivariable situations so that the resulting controllers yield better performances.

B. A PID de-tuning method

Based on these simulation studies, it is felt that the PID gains obtained by Z-N for each controller needs to be modified. We propose the procedure as follows: assume that the first set of PID controllers nos. 11, 12, ..., 1*m* is used in the first control loop (u_1), the set of second with PID nos. 21, 22, ..., 2*m* for u_2 , etc. The proposed de-tuning algorithm is as follows:

Step 0: Set m, n and obtain the Z-N gains Kp_{ij} , Ki_{ij} and Kd_{ij} for $i = 1, 2, \dots, m, j = 1, 2, \dots, n$ from the open loop step responses as given in equation (5). Set $-1 \leq I_j \leq 1$ for convenience.

Step 1: Simulate the results for a period where the responses have reached a steady state conditions (ssc) as shown in figure 3.

Step 2: Records M_{ij} maximum, $M_{ij}(\max)$ and minimum, $M_{ij}(\min)$ at ssc for all combination of i and j . Compute the maximum swing for each PID, $M_{ij}^s = \text{abs}[M_{ij}(\max) - M_{ij}(\min)]$

Step 3: Compute the de-tuning (reducing) factor, ε_{ij} for each PID; $\varepsilon_{ij} = \frac{u_i(\max) - u_i(\min)}{M_{ij}^s}$. Thus, the

PID output in equation (1) becomes: PID# ij :

$$M_{ij}^d = \varepsilon_{ij} [Kp_{ij} e_j + Ki_{ij} I_j + Kd_{ij} \frac{de_j}{dt}] \quad (6)$$

and the control input in equation (4) is replaced by:

$$u_i = M_{i1}^d + M_{i2}^d + \dots + M_{in}^d \text{ where } i = 1, 2, \dots, m \quad (7)$$

with similar input constraints.

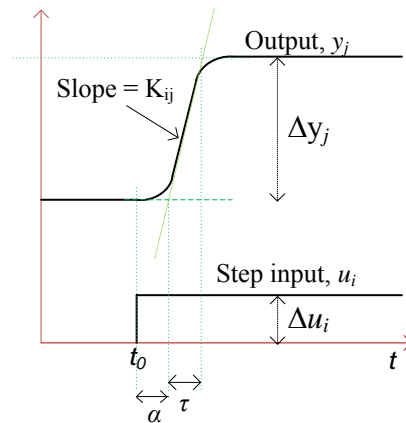


Figure 2. Open-loop system step response

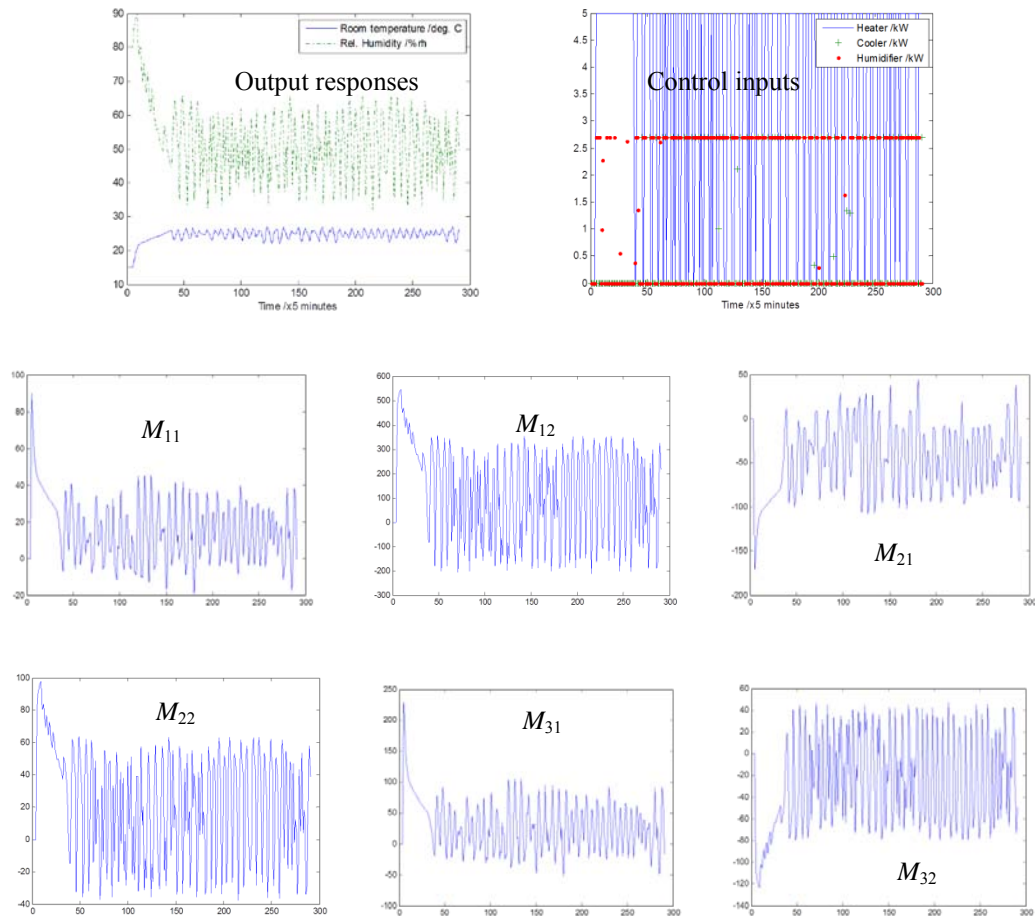


Figure 3. Control performance via Ziegler-Nicholls rules on 3 input/ 2 output BEMS for references $y_{R1} = 25^\circ\text{C}$ and $y_{R2} = 50\%\text{rh}$ and without noise

C. Simulation Results

For setting up the initial Z-N PID controller parameters, the open loop step responses were carried out on the model as described in Section 2 where the control inputs were step increased from 0% to 100% of their maximum powers and then calculate for $K_{p_{ij}}$, $K_{i_{ij}}$ and $K_{d_{ij}}$, $i = 1, 2$ and 3 and $j = 1, 2$; these parameters are given in table 1. The performance results for required setpoints ($y_{R1} = 25^\circ\text{C}$ and $y_{R2} = 50\%\text{rh}$) as shown in figure 3 were obtained. But, when the detuned PID gains were used, i.e. $K_{p_{ij}}$, $K_{i_{ij}}$ and $K_{d_{ij}}$ were reduced by ε_{ij} factor as indicated in equation (6), the performance results as shown in Figure 4 were improved significantly.

We can see that a good regulation has been achieved and the performance over the last 100 sampling intervals is as follows:

- output sum squared errors are $0.0003\text{ }^{\circ}\text{C}^2$ and 0.001 \%rh^2 for the temperature and the relative humidity respectively; and
- required control input energies are 29.5, 5.8 and 10.9 kWh for the heater, cooler and humidifier respectively.

To add a degree of realism into our simulation studies, we can insert some white noise processes V_1 and V_2 to the room temperature and relative humidity respectively. For convenience a pseudo random binary sequences (PRBS) generated using 6 shift registers [13] with magnitudes $V_1 = \pm 0.5^{\circ}\text{C}$ and $V_2 = \pm 0.5\text{ \%rh}$, were used as the noise processes. These represent large disturbances to the plant dynamics and consequently should effect the system quite significantly. These terms were then included into the system of identical settings as used in figure 4. The simulated result is shown in figure 5 where the control performances for the last 100 sampling intervals are as follows:

- output sum squared errors are $1.8\text{ }^{\circ}\text{C}^2$ and 96.2 \%rh^2 for the temperature and the relative humidity respectively; and
- required control input energies are 29.5, 5.8 and 10.9 kWh for the heater, cooler and humidifier respectively.

Moreover, the settling periods are 340 minutes and 135 minutes for the temperature and the relative humidity respectively.

We also found that the controller is capable to regulate the output for required setpoint of $y_{R1} = 20^{\circ}\text{C}$ and $y_{R2} = 40\text{ \%rh}$ and this is shown in figure 6

Table 1. PID gains and their reduction factors applied for The BEMS plant

Input	M_{ij} (kW)	Kp_{ij}	Ki_{ij}	Kd_{ij}	M_{ij}^S (kW)	$u_i(\text{max})$ - $u_i(\text{min})$ (kW)	ε_{ij}
Heater, u_1	M_{11}	6.41 (kW/ $^{\circ}\text{C}$)	84.34 (kW/ $^{\circ}\text{C}_\text{h}$)	0.12 (kW_h/ $^{\circ}\text{C}$)	64.9	5.0	0.0770
	M_{12}	-7.88 (kW/ \%rh)	-231.71 (kW/ \%rh_h)	-0.077 (kW_h/ \%rh)	566.6	5.0	0.0088
Cooler, u_2	M_{21}	-9.04 (kW/ $^{\circ}\text{C}$)	-265.92 (kW/ $^{\circ}\text{C}_\text{h}$)	-0.077 (kW_h/ $^{\circ}\text{C}$)	152.2	2.7	0.0177
	M_{22}	-1.41 (kW/ \%rh)	-41.34 (kW/ \%rh_h)	-0.0119 (kW_h/ \%rh)	101.2	2.7	0.0494
Humidi fier, u_3	M_{31}	18.31 (kW/ $^{\circ}\text{C}$)	152.58 (kW/ $^{\circ}\text{C}_\text{h}$)	0.55 (kW_h/ $^{\circ}\text{C}$)	158.0	2.6	0.0316
	M_{32}	1.78 (kW/ \%rh)	52.35 (kW/ \%rh_h)	0.015 (kW_h/ \%rh)	127.3	2.6	0.0392

This simulation result can also be used to analyse for possible components reduction in a control system so that the overall cost of installation is reduced. Moreover, this can also reduce the fighting among inputs for similar objective, i.e. to regulate the outputs but contribute to the waste of energy. As shown in figure 4, the cooler requirement for the prescribed setpoint is lowest at steady state conditions and it may not require to regulate the output. If so, the cooler as well as PID#21 and PID#22 controllers can be eliminated. A simulation was done for this case and the result is shown in figure 7 where it is found that the controller is still capable to regulate the output. Similarly, it is found that the humidifier is least required for other setpoints such as for $y_{R1} = 20^{\circ}\text{C}$ and $y_{R2} = 40\text{ \%rh}$ since the heater can also function as to reduce the relative humidity. So, when the humidifier as well as PID#31 and PID#32 are excluded from this controller, we found that the controller can well perform its function and this is shown in figure 8.

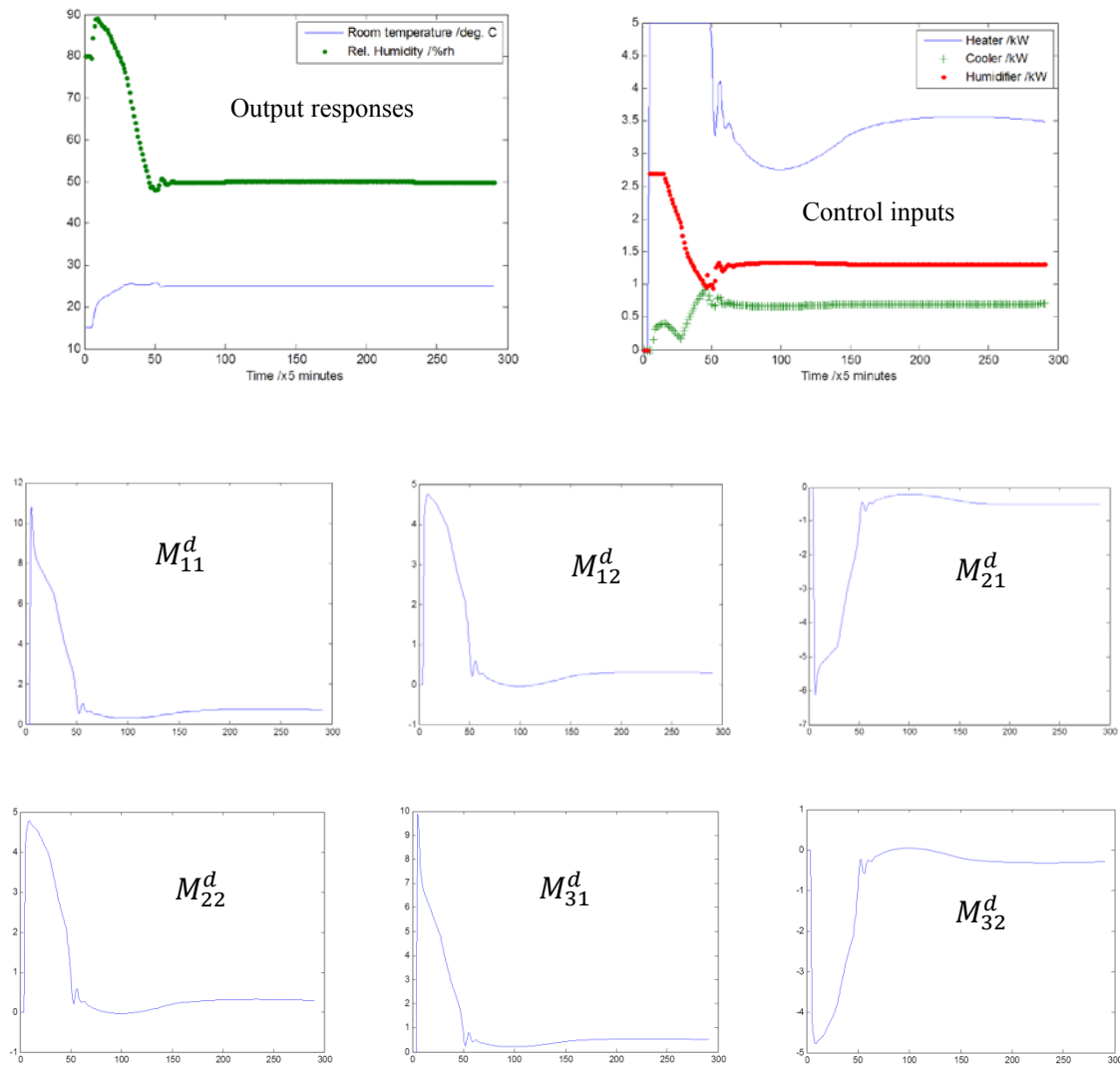


Figure 4. Control performance via modified gains on 3 input/ 2 output BEMS for $y_{R1} = 25^\circ\text{C}$ and $y_{R2} = 50\%\text{rh}$ (no noise)

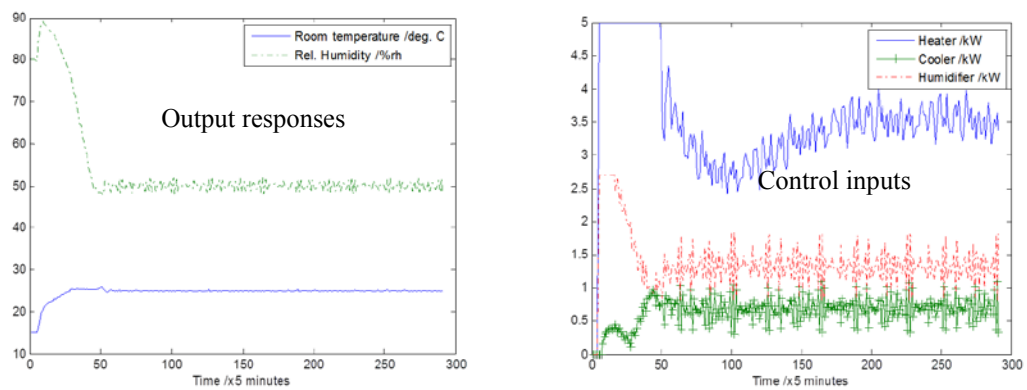


Figure 5. Control performance with PRBS stochastic noises of magnitude ± 0.5

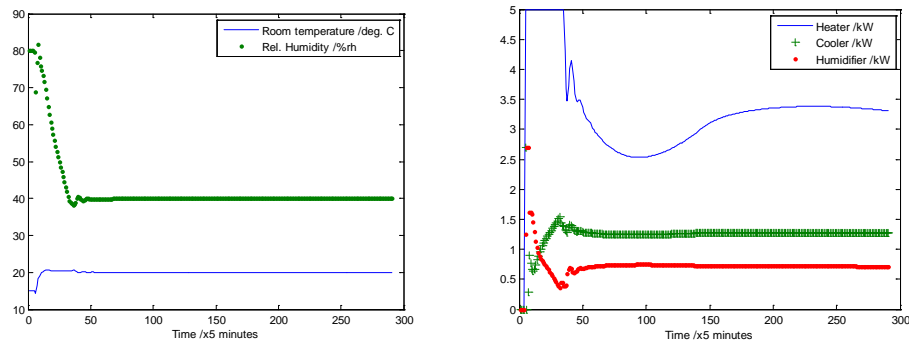


Figure 6. Control performance for $y_{R1} = 20^{\circ}\text{C}$ and $y_{R2} = 40\%\text{rh}$

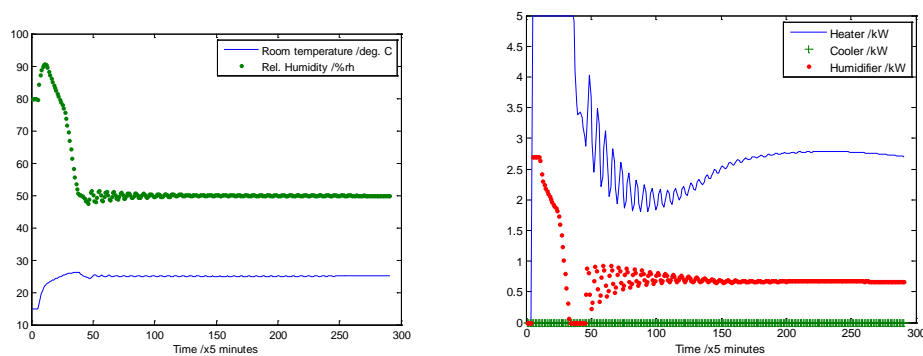


Figure 7. Control performance without cooler for $y_{R1} = 25^{\circ}\text{C}$ and $y_{R2} = 50\%\text{rh}$

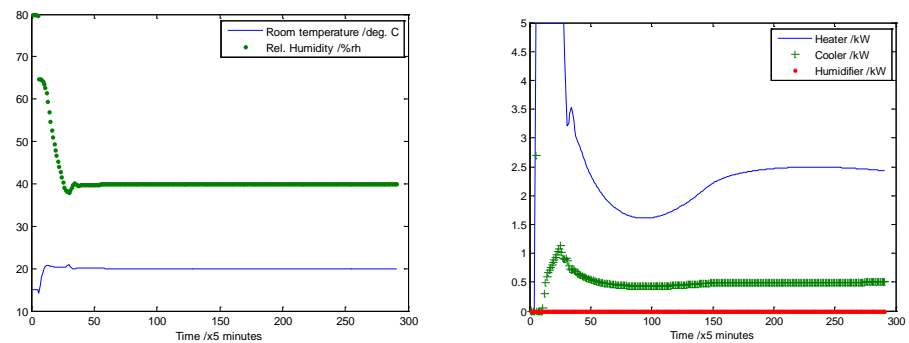


Figure 8. Control performance without humidifier for $y_{R1} = 20^{\circ}\text{C}$ and $y_{R2} = 40\%\text{rh}$

3. Conclusions

In this paper a simple yet effective de-tuning methodology for PID controllers in multivariable applications has been described. It has been shown that good control performances can be achieved by using the de-tuning factors to modify the Z-N proportional, integration and derivative gains. The methodology has also been useful for reducing the number of PID controllers as well the control inputs that are necessary for the selected setpoint in order to reduce the overall cost.

The result has also shown that this tuning methodology is suited to the control of HVAC systems and may be applicable to the effect PID based control of general multivariable systems.

4. References

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