B.T.S FEE [D. Bord lycée St Michel – 54] *sem 14*

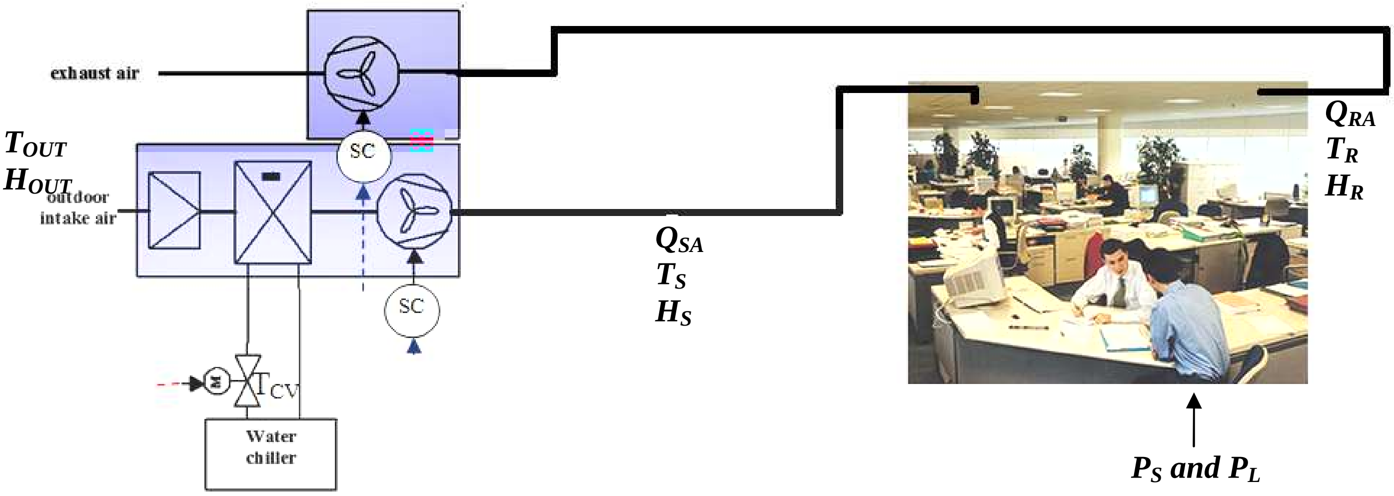
# Process Control & Instrumentation part IV
# Control loops

This chapter aims to bring basic knowledge of control strategies in HVAC systems through a real case study: ***Temperature control of an open office***.

**Objectives:** At the end of this course, you should be able to:

- Define process control principles and terminology
- Define basic components of control system
- Describe the effects of ON/OFF control
- Describe the effect of proportional control, PI control and PID control.
- Tune PI controller and understand the need to tune PID controller properly
- Distinguish the difference between open loop and closed-loop control system
- Define advantages of cascade control strategy.

**Hypothesis:** Let's consider the open office shown as below. We only consider summer season. This open office is characterized by its sensible loads $P_S$, latent loads $P_L$, air volume flow rate $Q_{SA}$, indoor temperature $T_R$ and Humidity $H_R$. The current system provides a constant volume flow ($Q_{SA}$). Humidity is not controlled but constant indoor temperature is required for comfort of occupants whatever loads variations. We also consider well balance ductworks that imply $Q_{SA}$= $Q_{RA}$



## I. How to maintain constant indoor temperature manually: Practical approach

- *Considering hypothesis, can you list the different origins of thermal loads variations:*
  - Internal loads:
    human bodies release heat and water
    computers and lighting release heat
  - external loads:
    external climate variations
    position of the sun throughout the day
    building insulation

*Open simulation folder “**office sans regul**” and run executable file. Verify and change, if necessary, the initial conditions:*

*number of occupants: 0*
*outdoor temperature : 32°C*
*outdoor relative humidity: 40%*
*valve opening: 0%*

- *What are indoor temperature and moisture value?*
  - The same as outdoor

- *What happens when number of occupants increases up to 30?*
  - Indoor temperature and moisture rise

- *What should you do to bring indoor temperature down to 24°C?*

Students propose and try different solutions. The objective is to let them highlighting that:

They need to observe the temperature
They need to open manually the water chiller valve, progressively otherwise temperature drops too quickly.

- *Now it’s getting late, let’s call it a day! everybody pack up and go back home, but you need to maintain 24°C during the night, and outdoor temperature drop to 26°C.*

Students realize it is a struggle to adjust temperature.

- *Finally, what are you doing exactly when you’re adjusting the temperature?*

1. You need crucial information: what is the value of indoor temperature required? 24°C.
2. Simultaneously, you observe the temperature by the means of a thermometer.
3. You compare what you want with what you’ve got
4. You think about action to lead in order to open or close the valve
5. Your brain sends a signal to your hand to turn on and off the valve
6. You repeat the sequence 1-2-3-4-5 until what you observe is equal to what you want

This is the fundamental principle of control. To control a physical quantity X, you need to:

- **Measure** the value by the means of a sensor
- **Compare** the measured signal variable **PV** and the Set Point **SP**
- **Think about** how to act properly to reduce or eliminate the error $\varepsilon = SP - PV$
- **Generate** a control signal $Y_R$ as a function of $\varepsilon$
- **Vary** the **control variable** by modulating valve opening

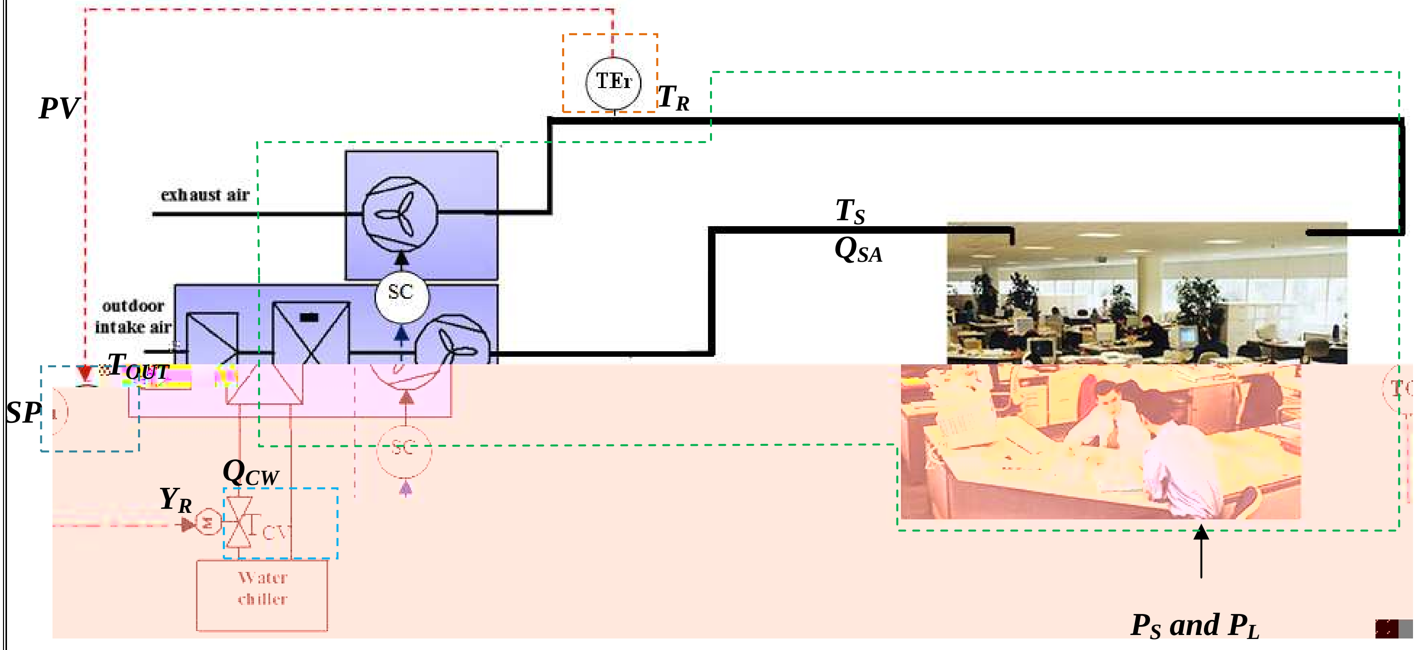
- *What type of devices would you need to install in order to replace Human being?*
  - A sensor or temperature transmitter
  - A controller
  - A actuator for command valve opening, such as: solenoid, motor, pneumatic transducer

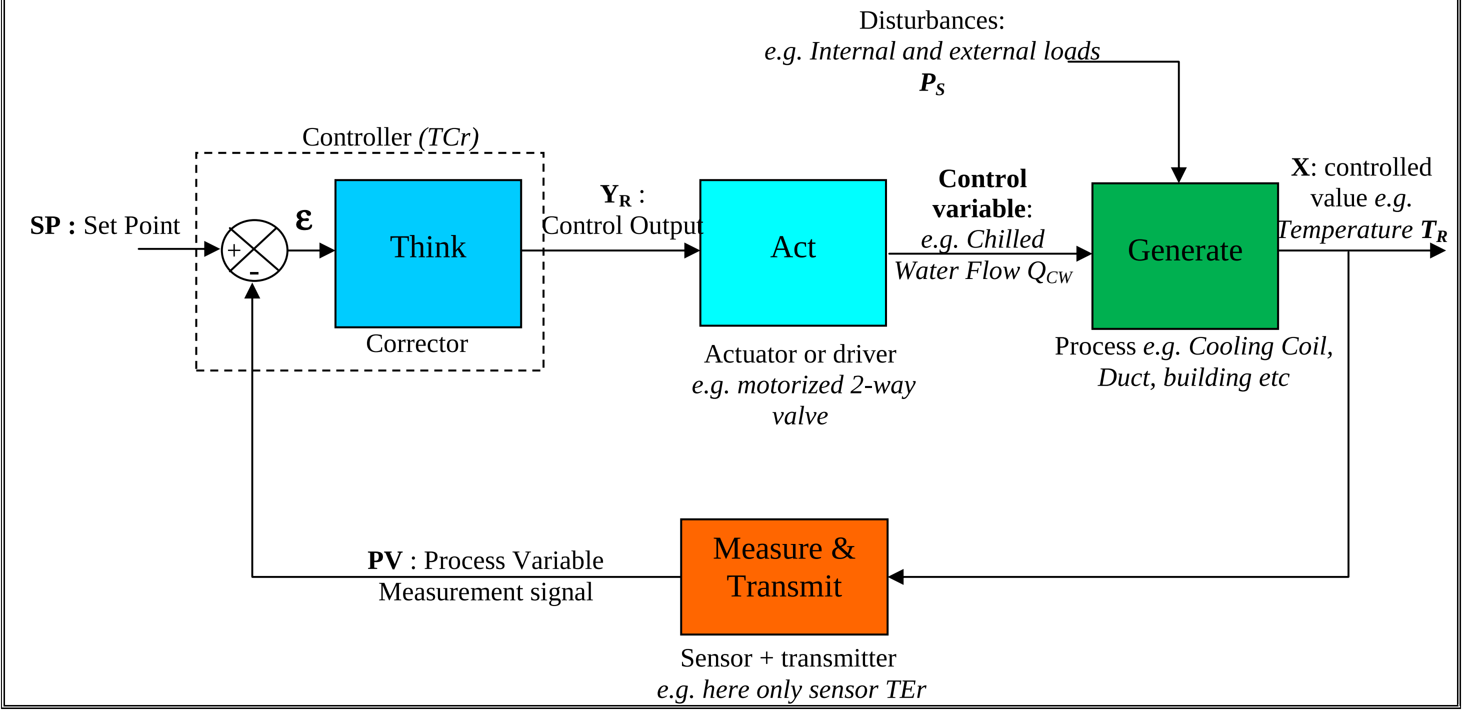
## II. How to maintain constant indoor temperature automatically: The closed-loop

### 1. Terminology and definitions

- **X** is the controlled value
- **PV** is the process variable or measurement signal
- **SP** is the Set Point
- **ε** is the error, **ε=SP-PV**
- **Corrector** is the algorithm that generate **$Y_R$ :** Either **PID algorithm** or **ON/OFF**
- **$Y_R$** is the control signal, also called **CO** as **Control Output:** Either progressive or ON/OFF signal.
- **TCV** is the Temperature Control Valve that modulates the **Control Variable (**which is a physical quantity)
- **Disturbances** are all external or internal factors that disturb controlled value **X**

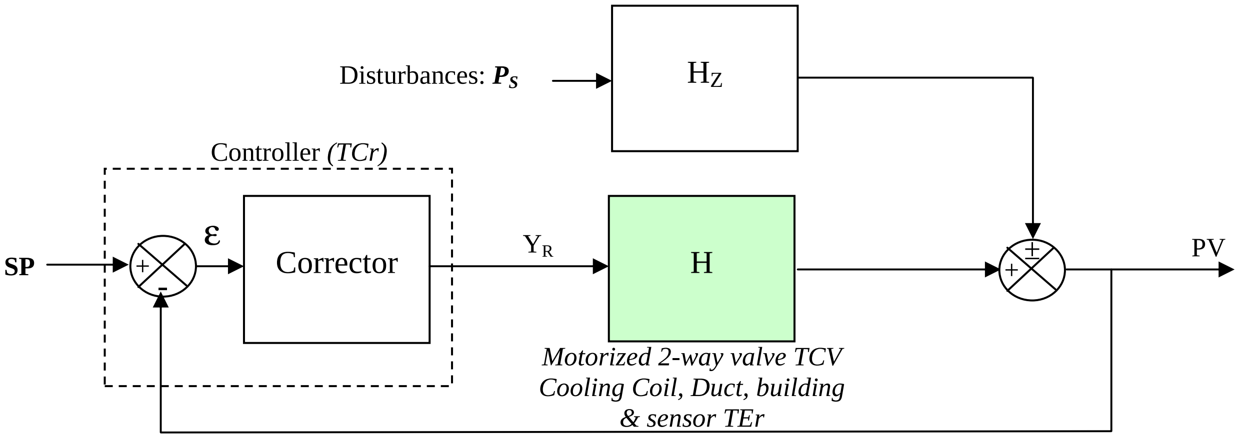
### 2. Closed-loop blocks diagram



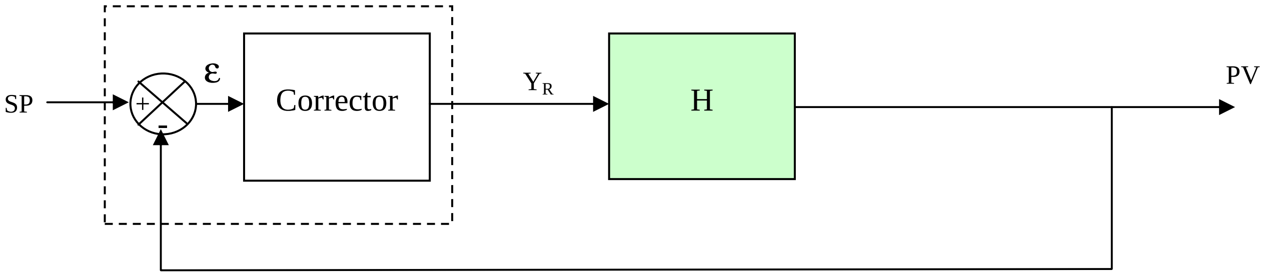


In order to simplify blocks diagram, one considers that **“Act”**, **“Generate”** & **“Measure”** functions can merge together to create a single function **H.** The reduced blocks diagram becomes,

**At part load conditions:** SP remains constant but Disturbances may vary



**At Set Point change:** Disturbances remain constant but SP may vary

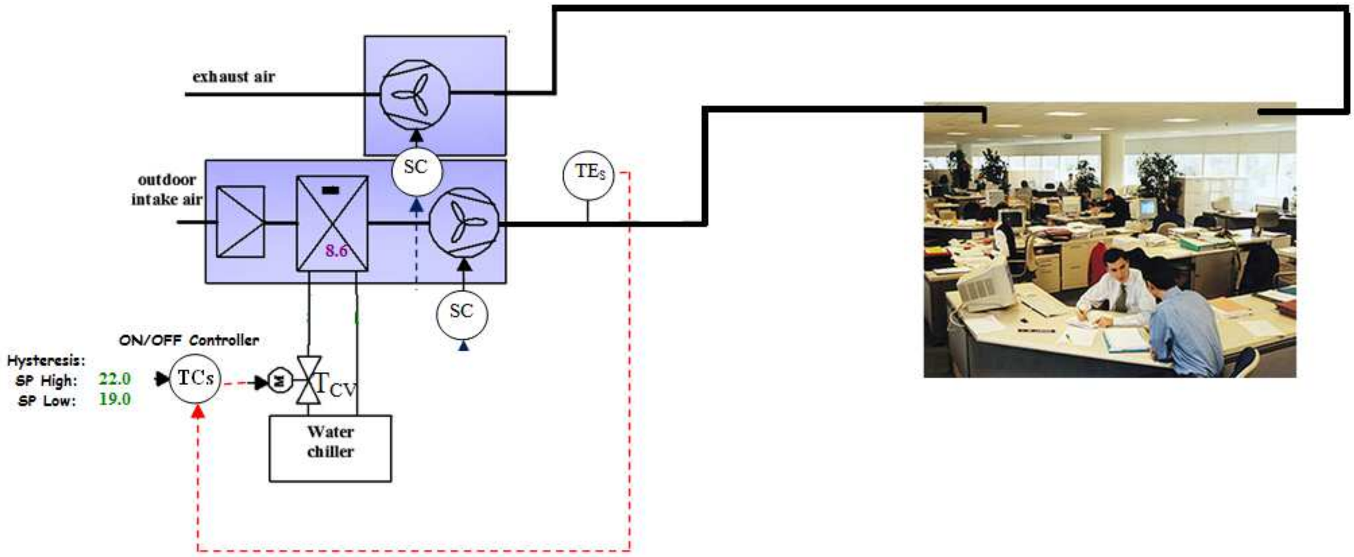


- **H** is the process transfer function
- **$H_Z$** is the disturbance transfer function

## III. ON/OFF control

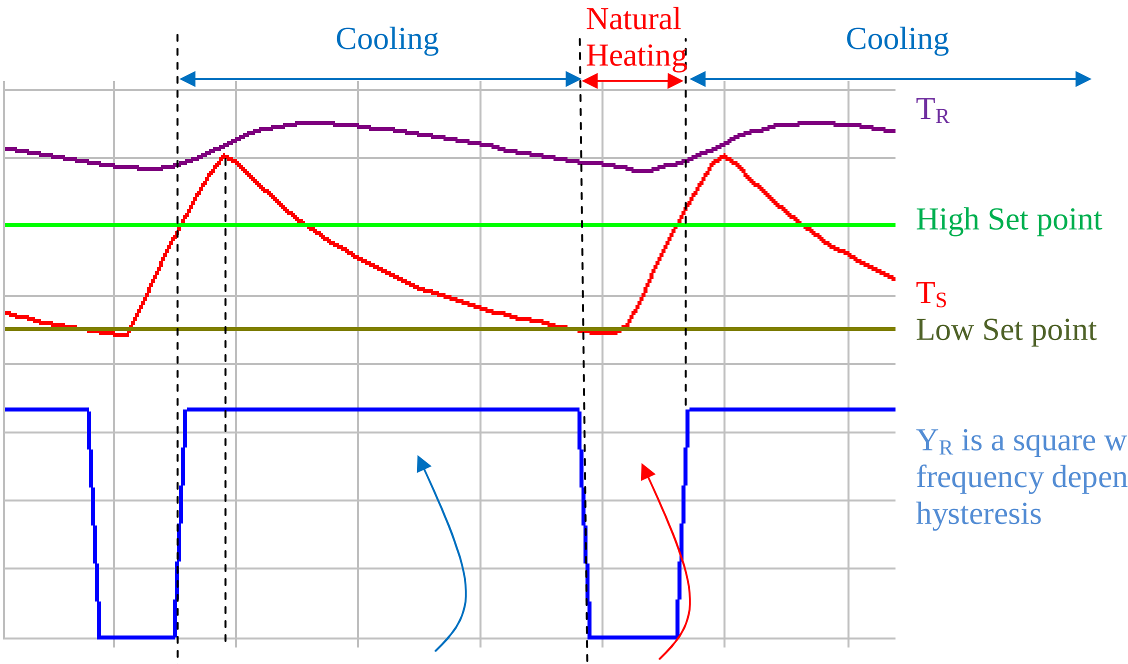
In order to study the performance of ON/OFF control, we consider the following context: Control of supply air temperature **$T_S$.** The required supply air temperature is roughly around 20°C.

- *Label the schematic diagram with:* ***$T_S$ , PV ,SP, $Y_R$***
- *Encircle the following functions: "Think", "Act", "Generate", "Measure" and "H"*



- *Open simulation folder "**office regul ON/OFF**" and run executable file. Verify and change, if necessary, the initial conditions:*
  - *number of occupants: 0*
  - *outdoor temperature : 32°C*
  - *outdoor relative humidity: 40%*
  - *$TC_S$ Hysteresis:*
    - *Set point High: 22°C*
    - *Set point Low: 19°C*
- *Observe the evolution of trends. Change Hysteresis parameters. What do you observe and what conclusions can you draw about ON/OFF control?*
  - The ON/OFF controller switch the output $Y_R$
  - $Y_R$ is a square wave whose frequency depends on hysteresis
  - The control valve is either totally opened or totally closed
  - $T_S$ and $T_R$ are periodic signals
  - $T_S$ and $T_R$ amplitude and frequency depend on hysteresis
  - The smaller the hysteresis is, the higher the risk of damaging control valve is

## How does ON/OFF control work?



$Y_R$ is a square wave whose frequency depends on hysteresis

$T_S$ go above High Set point, as a result:

- $Y_R$ is switched ON
- Valve opens, cooling capacity increases
- But $T_S$ continue to rise for a short spell, due to process inertia and then decrease.

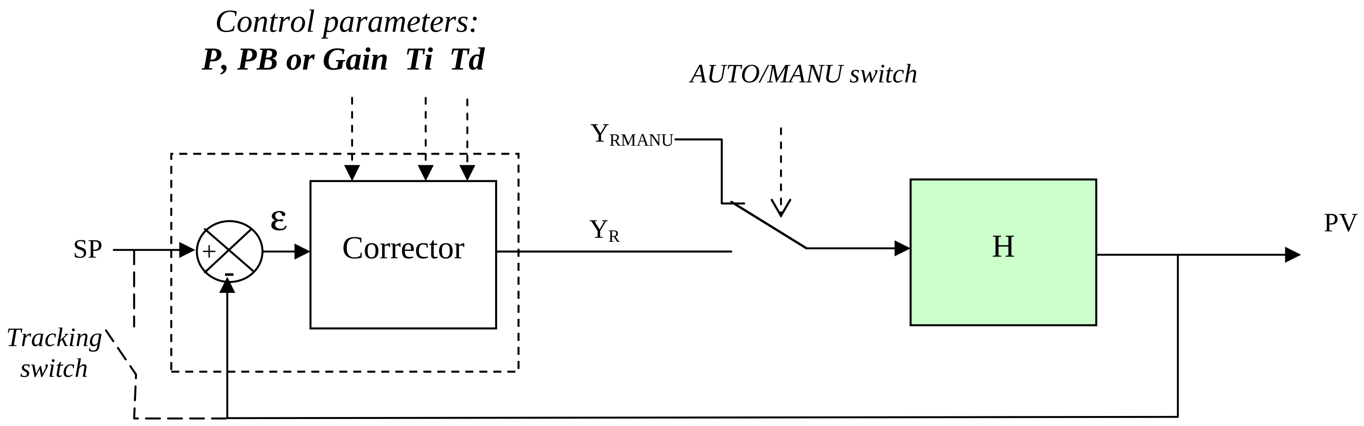
$T_S$ go bellow Low Set point as a result:

- $Y_R$ is switched OFF
- Valve closes, cooling capacity drops quickly
- $T_S$ rise quickly, due to high air flow rate bringing in a large amount of warm air

Even if this control strategy requires cheap devices such as **Thermostat** and **electrical on/off valve**, **ON/OFF control** does not provide good performance in that case

## IV. Industrial PID controllers features

- **Blocks diagram**



- **PB:** Proportional Band = 100/Gain [%]
- **Gain or P :** Proportional Gain
- **$T_i$ :** Integral value is a time constant set in **second, minutes** or **repeat/mn**
- **$T_d$ :** Derivative value is a time constant set in **second or minutes**
- **AUTO/MANU control:**
  - **Automatic** mode: Process is controlled automatically by the controller
  - **Manual** mode: you control the process by yourself.

- **Set Point tracking control:** only available in Manual mode, the tracking mode makes Set Point tracking Process Variable in order to eliminate error **ε** just before moving to Automatic mode.
- **Direct/Reverse acting control**: This mode defines which way $Y_R$ varies.
  - If PV increase when $Y_R$ increase, you choose the **Reverse acting** mode
  - If PV decrease when $Y_R$ increase, you choose the **Direct acting** mode

- *In the case study, what acting control mode should you choose? Justify your answer.*
  - **If $Y_R$** ↑ then valve opening ↑ and $Q_{CW}$ ↑ thus cooling capacity↑, as a result Indoor temperature & **PV** ↓. You choose **Direct acting** mode.

## V. Effects of P.I.D actions

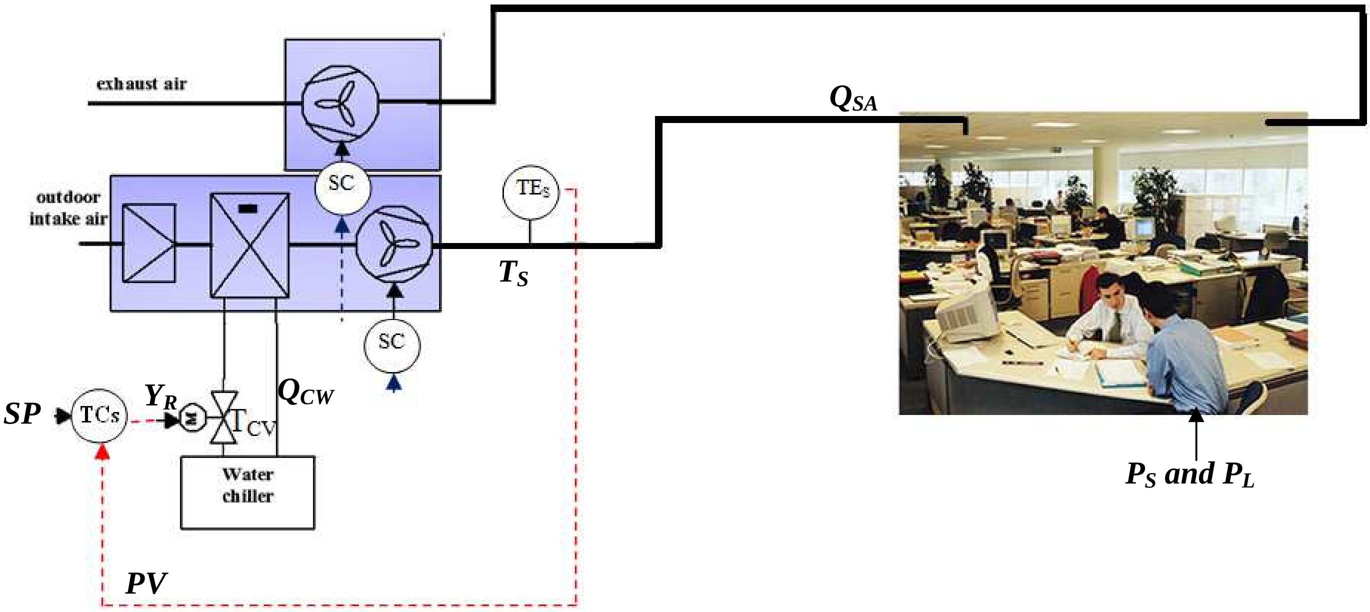
### 1. Caution

**Never, never, never** start any Controller in Automatic mode without ensuring Controller is properly tuned.

In order to highlight dangers of such action, teacher leads experiment using a system of water flow controlled by a controller with bad PI parameters

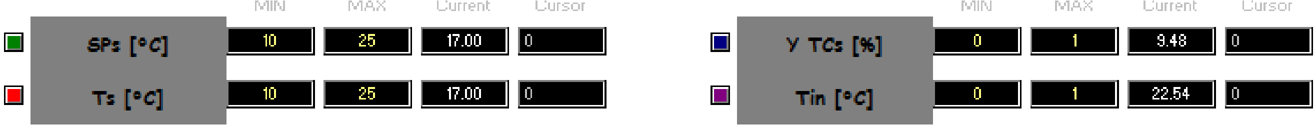
### 2. Context for this study

In order to study the effects of PID actions, we still consider the control of supply air temperature **T**$_S$
The required supply air temperature can vary from 17°C to 21°C. This is the **controlled range**.



- *Open simulation folder "**office regul soufflage**" and run executable file. Verify and change, if necessary, the initial conditions:*
  - *number of occupants: 0*
  - *outdoor temperature : 32°C*
  - *outdoor relative humidity: 40%*
  - *TC$_S$:*
    - *Manual*
    - *Internal Set Point*
    - *tracking control*
    - *Y$_R$ =0%*
    - *PB=100%*
    - *I=0 r/mn*
    - *D=0mn*

- *Configure the recorder as shown below*

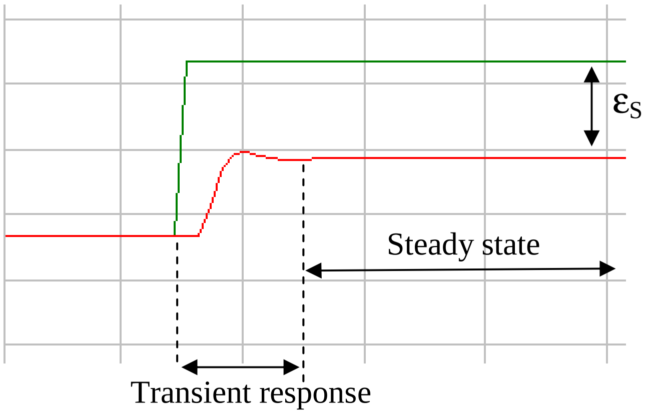


| | | MIN | MAX | Current | Cursor |
|---|---|---|---|---|---|
| 🟩 | SPs [°C] | 10 | 25 | 17.00 | 0 |
| 🟥 | Ts [°C] | 10 | 25 | 17.00 | 0 |

| | | MIN | MAX | Current | Cursor |
|---|---|---|---|---|---|
| 🟦 | Y TCs [%] | 0 | 1 | 9.48 | 0 |
| 🟪 | Tin [°C] | 0 | 1 | 22.54 | 0 |

## 3. Proportional control

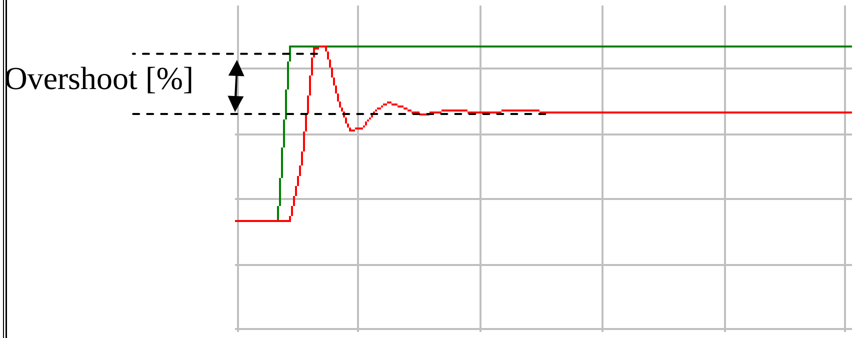
- *Adjust manually $T_S$ at 17°C, ensure Set Point = 17°C*
- *Move on to automatic mode, and make a* ***Set point step change*** *from 17 to 21°C.*
- *What do you observe?*



- Error remains after transient response: that is **steady state error** or **static error**

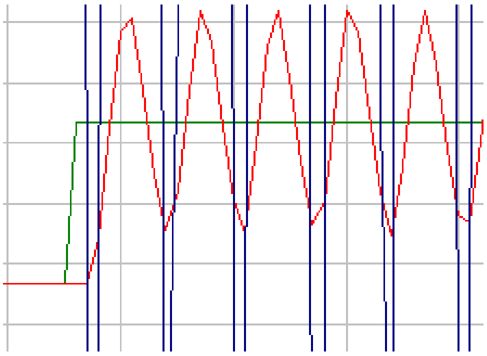
- *Do it again twice: PB=50% then PB=20%*
- *What do you observe and what conclusions can you draw about P control?*

**PB=50%, Gain=2**



- Static error is reduced but overshoot has increased

**PB=20%, Gain=5**



- The system is unstable
- Valve open and close periodically.
- Temperature oscillates like a sine wave

**Proportional control:**

Doesn't provide accurate control
Gain reduces static error but influences stability

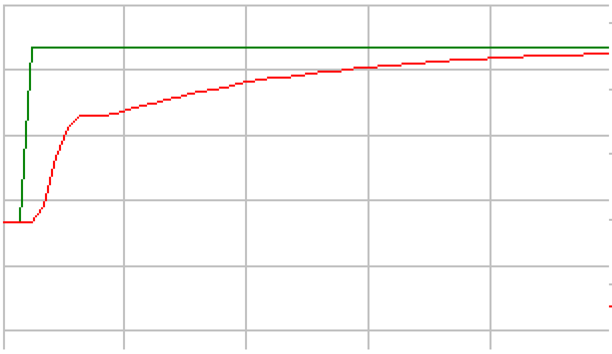
## 4. Proportional & Integral control

- *Move on to automatic mode and for these 4 sets of Proportional & Integral parameters:*
    - *PB=100%, I=30s and D=0mn*
    - *PB=100%, I=3s and D=0mn*
    - *PB=100%, I=7,5s and D=0mn*
    - *PB=50%, I=7,5s and D=0mn*

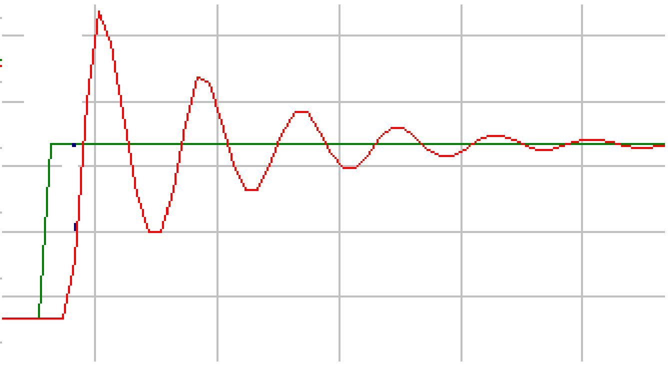
  *make a Set point step change from 17°C to 21°C.*

- *What do you observe and what conclusions can you draw about PI control?*

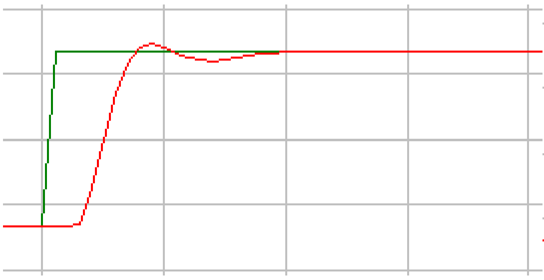
Case N°1



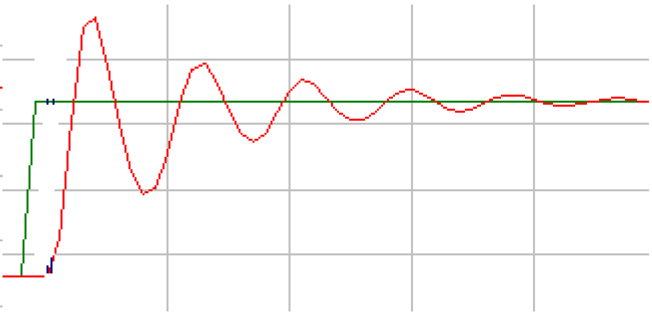
Case N°2



Case N°3



Case N°4



- Integral action provides accuracy

**Proportional & Integral control:**

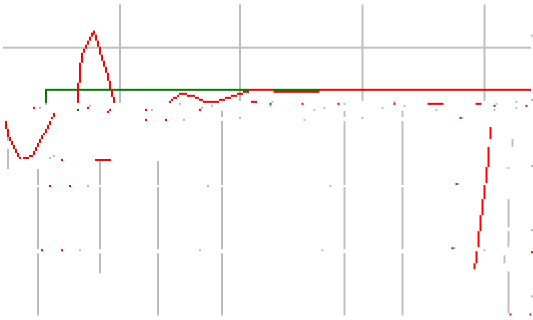
Provides accurate control in any cases but a proper combination of PI value is required to avoid instability

## 5. Proportional, Integral & Derivative control

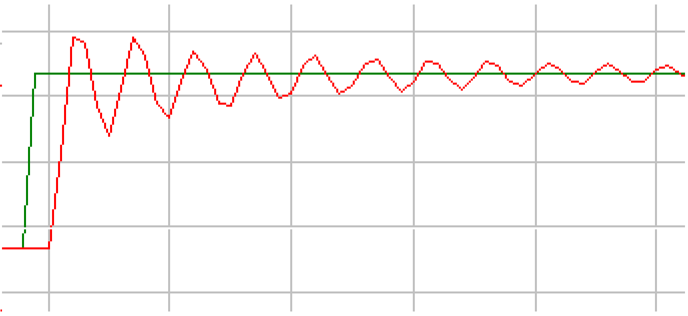
- *Move on to automatic mode and for these 2 sets of parameters:*
    - *PB=50%, I=7,5s and D=0,02mn*
    - *PB=50%, I=7,5s and D=0,05mn*

  *make a Set Point step change from 17°C to 21°C.*

Case N°1



Case N°2



- *Compare these results to the previous one (Part N°4. Case N°4). What do you observe and what conclusions can you draw about PID control?*
    - Derivative action improves stability but overshoot remains high.

**Proportional, Integral & Derivative control:**

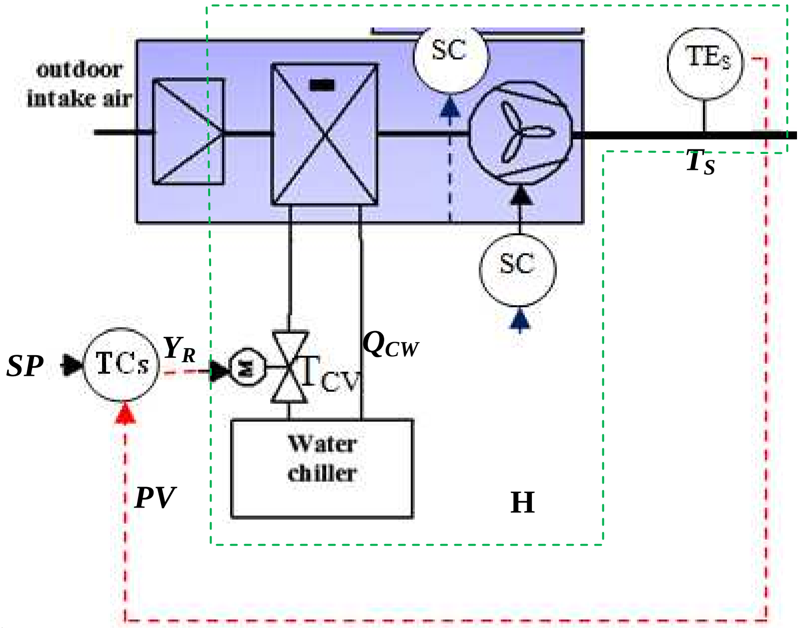
Derivative control brings stability but a proper combination of PI & D value is required to avoid instability.

## VI. How to tune a Controller

Tuning a controller consists of adjusting PID parameters in order to achieve the required performances:

- Accuracy : Measure=Set point at steady state
- Quick response
- Good stability

There are several methods to tune a PID controller. In this chapter, we focus on a model-based method that implies you have the transfer function model of the process.



**H** parameters are:

- Its static gain **K**= $\Delta PV/\Delta Y_R$
- Its time constant **τ** [s]
- Its time delay **T** [s]

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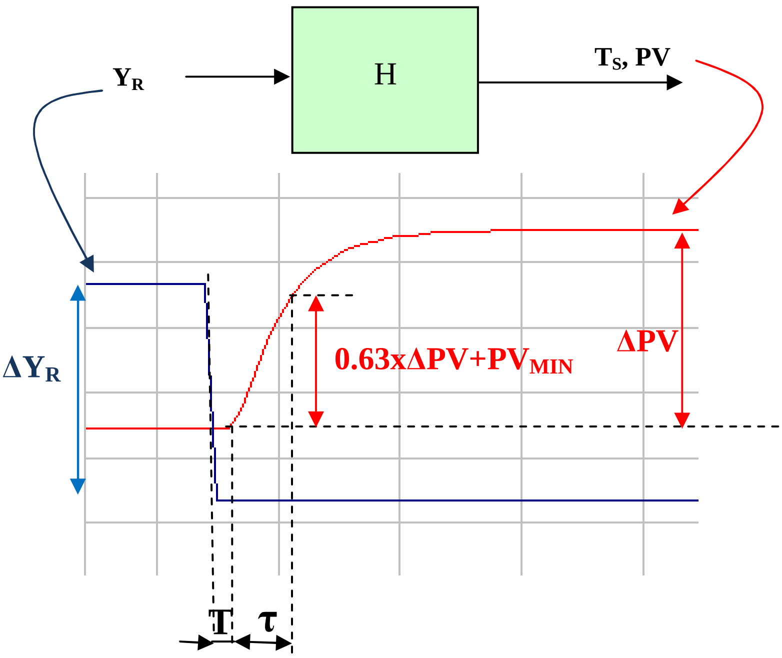
### 1. Graphical method for process modeling



**Method procedure:**

- *Ensure controller is in manual mode*
- *Start on the recorder.*
- *Adjust $Y_R$ in order to lead PV to low limit of the control range, e.g. around 17°C*
- *Wait for steady state*
- *Make a $Y_R$ step change in order to lead PV to high limit of the control range, e.g. around 21°C*
- *Wait for steady state then stop recording.*
- *Deduce H parameters*

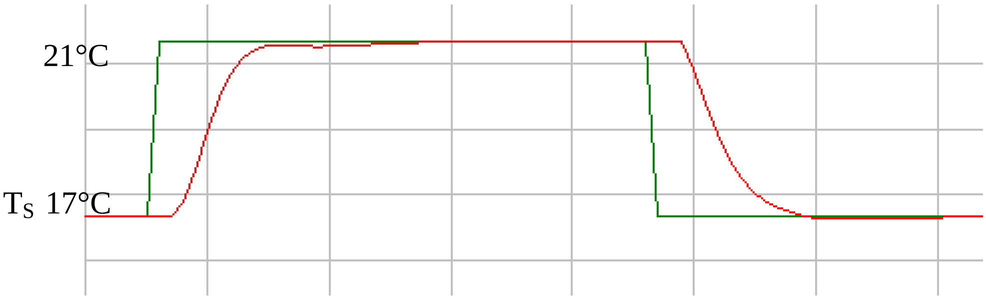
## 2. Calculation of P & I parameters

A PI controller is good enough for such process control. Use these formulas:

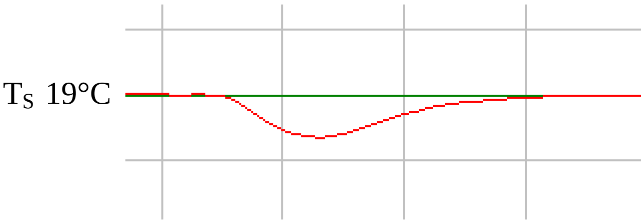
- **Ti = τ**
- **Gain = τπα/(2KT)** α depends on the type of response you want: 0,5 > α > 0,2. The smaller the coefficient α is, the faster the response is but the higher overshoot is.

- *Calculate the PI parameters and test the closed-loop performance:*
  - *Make set point step change from 17 to 21°C and vice versa*
  - *Then enter a 19°C set point, wait for steady state and bring outdoor temperature down from 32 to 26°C*
    *What do you observe?*

Set point step responses



Disturbance response

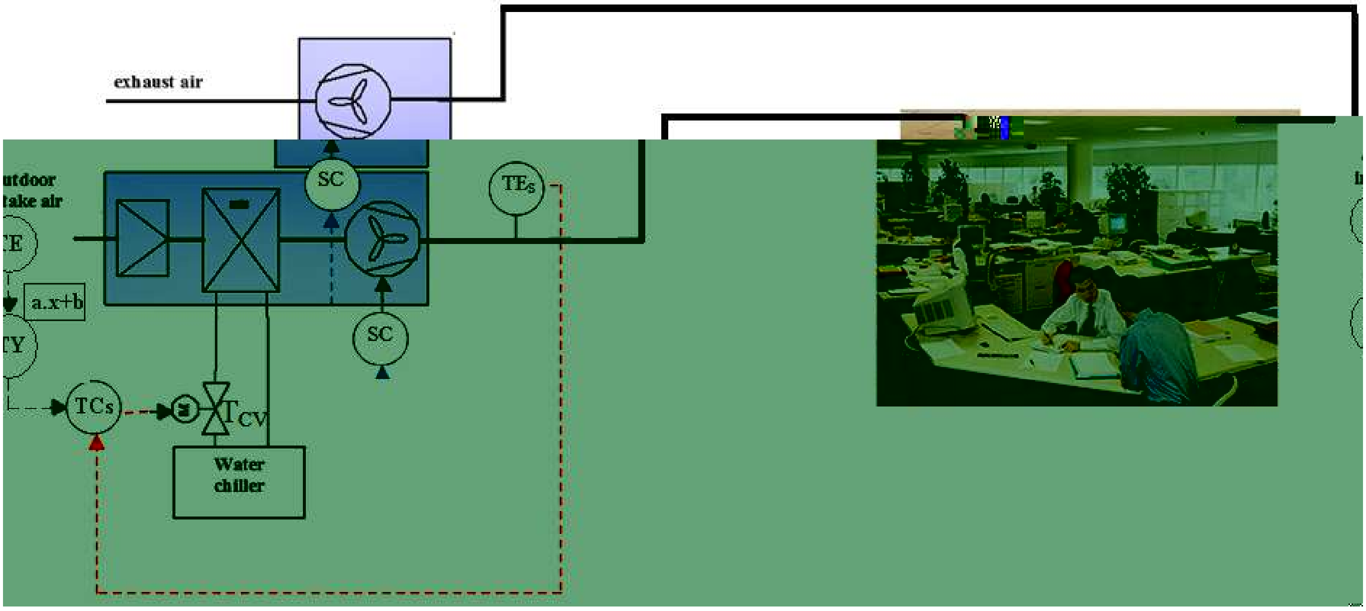


We can conclude that **when a Controller is properly tuned** then:

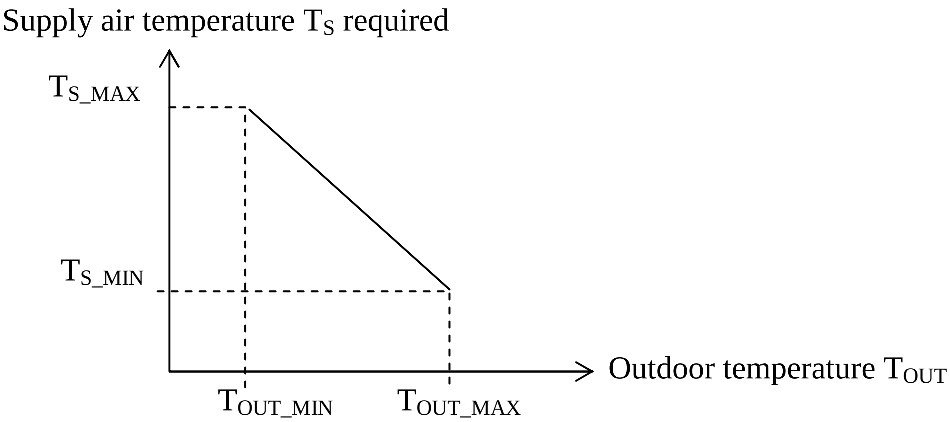
- **If Set point step response is good then disturbance response may be good too**

## VII. Controlling indoor temperature using Open loop control

In this context, open loop control means we don't control directly indoor temperature but rather supply air temperature, taking in account outdoor temperature variations.



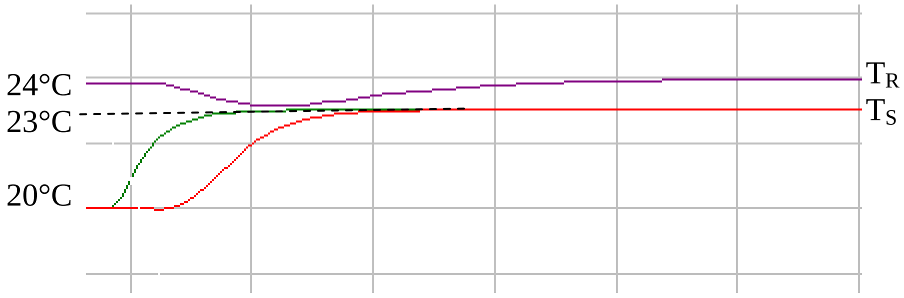
TY is a linear function that converts outdoor temperature into a Set Point sent to $TC_S$ :



- *Open simulation folder "**office regul open loop**" and run executable file. Verify and change, if necessary, the initial conditions:*
  *number of occupants: 0*
  *outdoor temperature : 32°C*
  *outdoor relative humidity: 40%.*

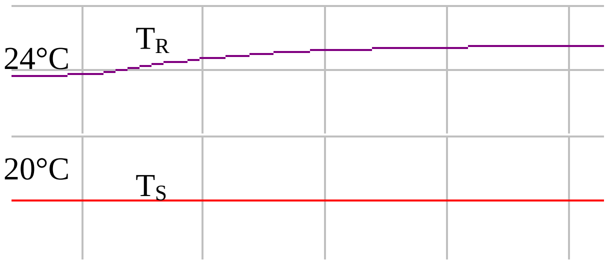
- *Without any calculations, how can you get the values: $T_{S\_MAX}$, $T_{S\_MIN}$, $T_{OUT\_MIN}$ and $T_{OUT\_MAX}$ ?*
  - When outdoor temperature $T_{OUT} \leq 24°C$, you don't need to cool the air thus $T_{S\_MAX}=24°C$
  - When outdoor temperature is 32°C, you're supposed to know $T_S$ value that gives $T_R=24°C$, Indeed $T_S$ is one of the considerations required for sizing air handling unit.

- *Ensure $TC_S$ is properly tuned then set TY parameters. Test this open loop strategy changing outdoor temperature from 32 to 26°C. What do you observe?*



  - As it’s getting cooler outside, supply air temperature $T_S$ varies automatically by the means of $TC_S$, as a result indoor temperature $T_R$ remains roughly constant.
  - This strategy seems to be efficient as regard of outdoor temperature variations.

- *What’s happening when number of occupants vary from 0 to 30?*

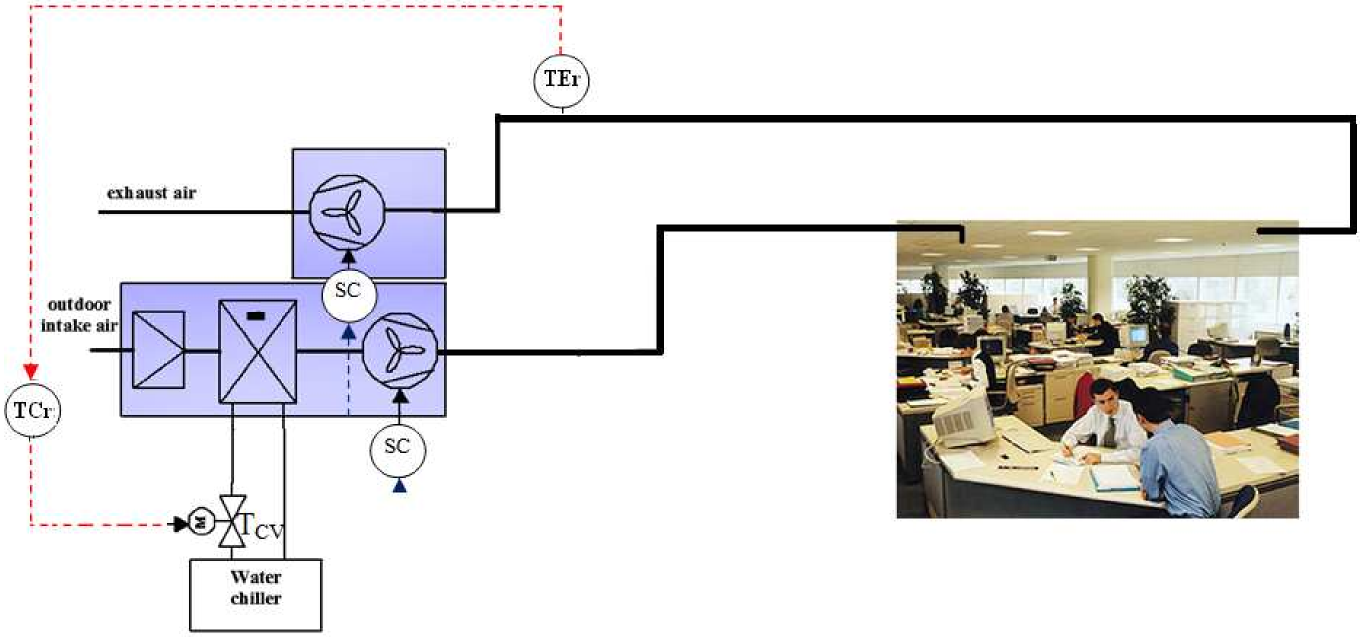


  - Indoor temperature $T_R$ rises and deviates from its required value when the number of occupants increases, even if $T_S$ remains constant.

- *What conclusions can you draw about open loop control?*

  - This strategy reduces influence of external loads variations is not suitable for internal loads variations.

## VIII. Controlling indoor temperature using closed-loop control

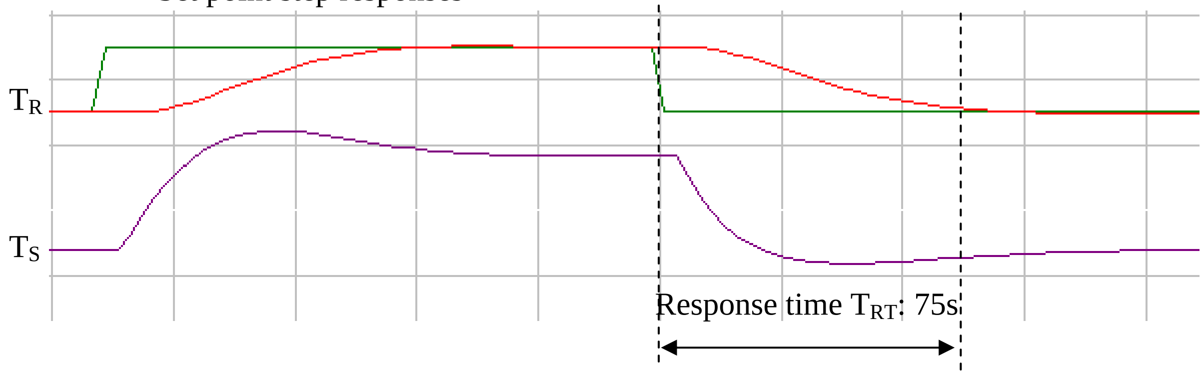


- *Open simulation folder “**office regul reprise**” and run executable file. Verify and change, if necessary, the initial conditions:*

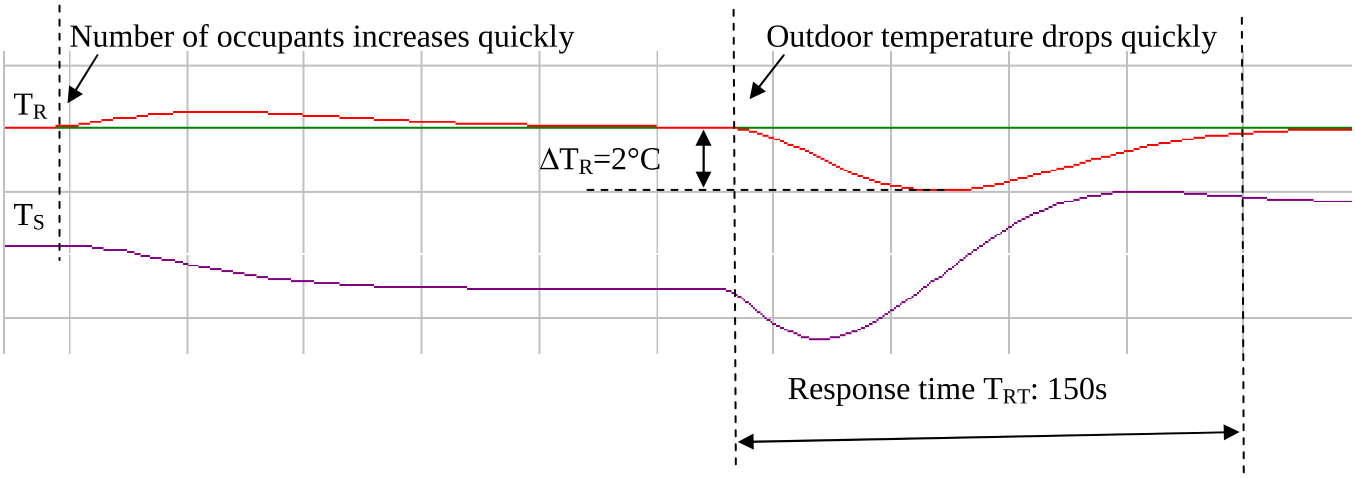
  *Number of occupants: 0*
  *Outdoor temperature : 32°C*
  *Outdoor relative humidity: 40%.*

- *Using tuning procedure seen previously:*
  - *Find H parameters: **K, τ, T***
  - *Deduce $TC_R$ P&I parameters allowing a fast indoor temperature response, without any overshoot.*
  - *Test efficiency of parameters making set point step change from 23 to 25°C and vice versa.*
  - *What do you observe?*

Set point step responses

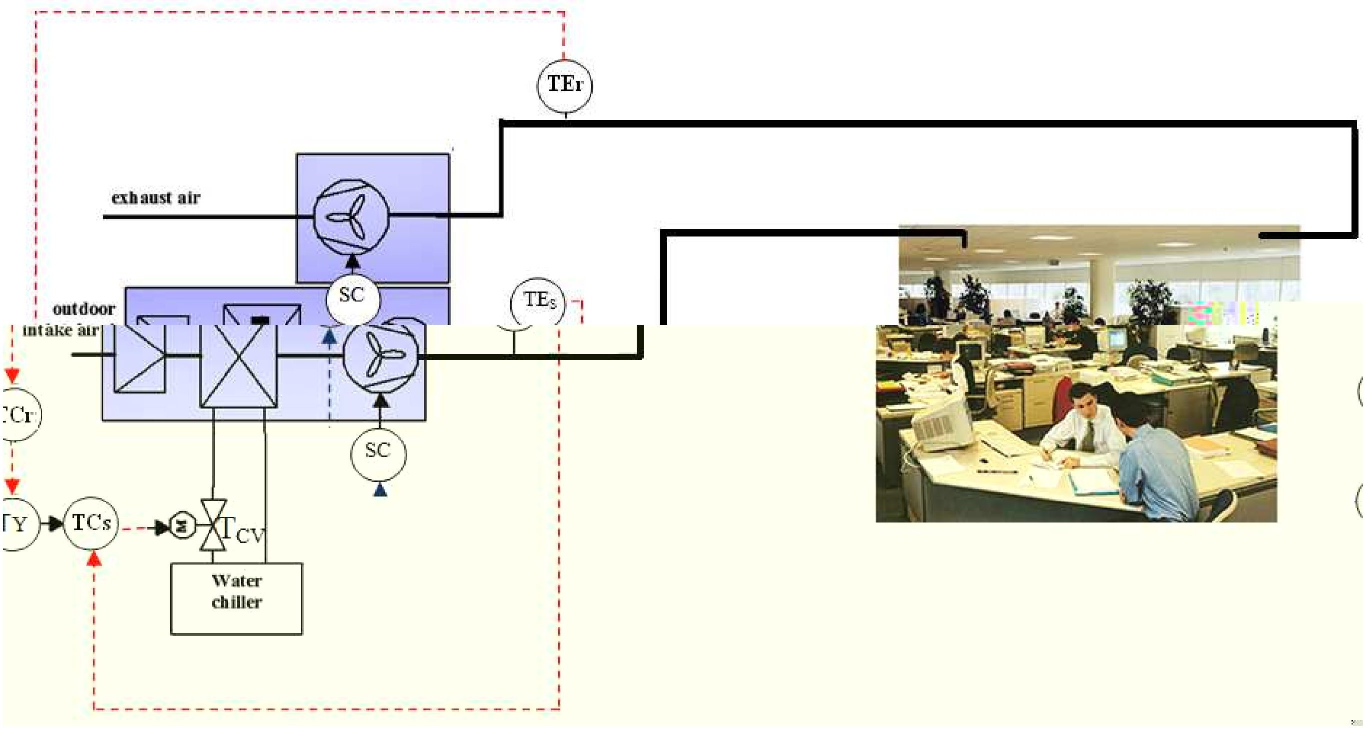


- *Then enter a 24°C set point and vary number of occupants from 0 to 30 and then outdoor temperature from 32 to 26°C. What can you say about control performance? Compare results to those obtained previously with open loop strategy.*



  - This closed loop strategy is more efficient then open loop control, indeed, indoor temperature remains constant whatever disturbances.
  - However, in case of external disturbance:
    - response time is quite long, around 150s
    - $\Delta T_R$=2°C

## IX. Upgrading single loop control strategy to cascade control strategy



A cascade control strategy includes 2 controllers:

- the **"master"** controls indoor air temperature $T_R$
- the **"slave"** controls supply air temperature $T_S$

**How does it work?**

It's 10 o'clock, all staff members arrive at the office and start working really hard, then

- **Master** reads indoor temperature and say: *"hey **slave**! It's getting warmer can you quickly increase cooling"*
- **Slave** receives this information from his **Master** and reply: *"Ok! I reduce supply air temperature"*
- **Master** continues observing indoor temperature and commands: *"Right, stop cooling, it's good now, it's 24°C"*

Suddenly, it's getting cloudy, outdoor temperature drops quickly

- **Slave** says to himself**:** *"Hey! $T_S$ is decreasing, I have to reduce cooling capacity quickly before indoor temperature decreases too much"*

- *Open simulation folder "**office regul cascade**" and run executable file. Verify and change, if necessary, the initial conditions:*

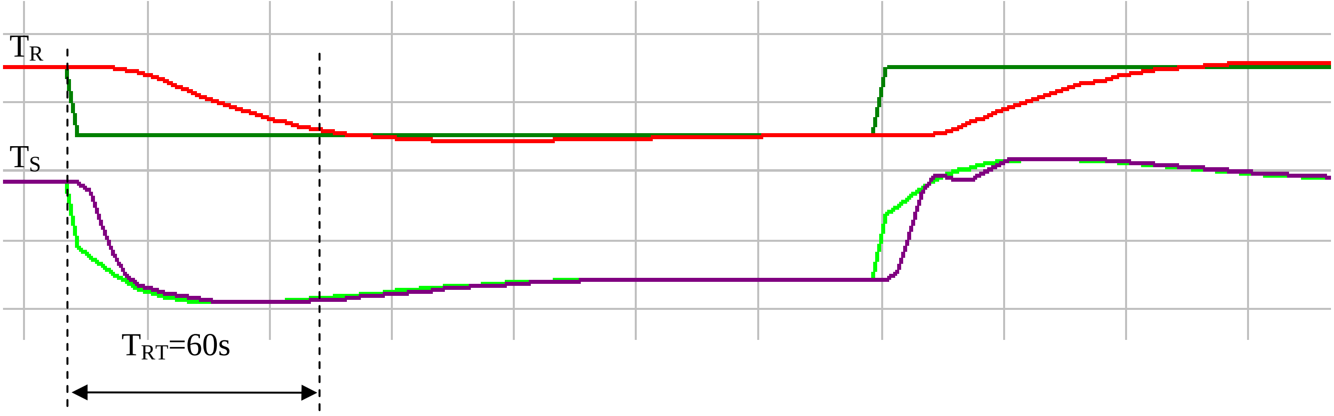
  *Number of occupants: 0*
  *Outdoor temperature : 32°C*
  *Outdoor relative humidity: 40%.*

  *Master* $TC_R$*:*
    *Auto*
    *Internal Set Point*
    *Reverse acting mode*
    *PB=8%*
    *I=3 r/mn*
    *D=0mn*

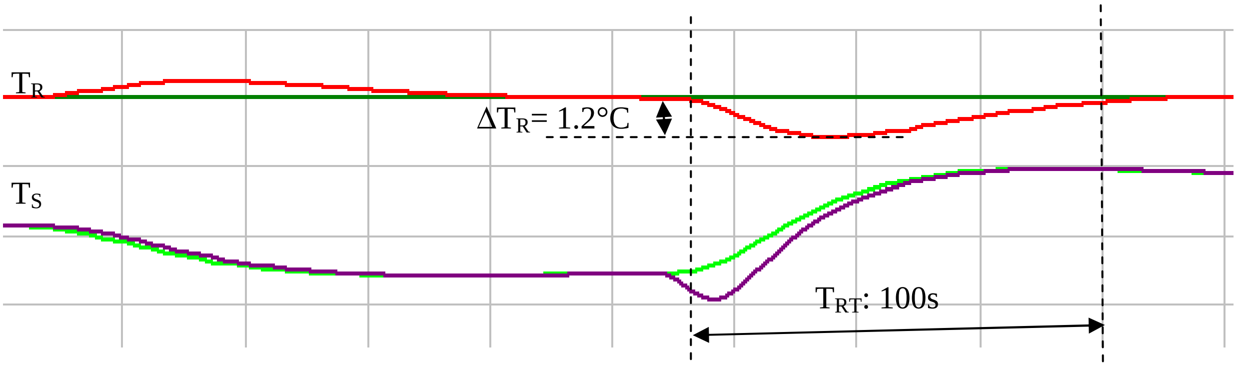
  *Slave* $TC_S$*:*
    *Auto*
    *External Set Point*
    *Direct acting mode*
    *PB=80%*
    *I=8 r/mn*
    *D=0mn*

- *Make set point step change from 23 to 25 and vice versa.*

Set point step responses



- *Then enter a 24°C set point, wait for steady state, and vary number of occupants from 0 to 30 and then outdoor temperature from 32 to 26°C. What can you say about control performance? Compare results to those obtained previously with single closed-loop strategy.*



  - Cascade control strategy reduces Set point and disturbance response time by reacting faster than single closed-loop.