Laboratory 3
Capacitive circuit voltage control with an industrial controller

1 Introduction

This third and last laboratory deals the implementation of a control law in an industrial controller to control of a voltage at the terminal of an analog electronic circuit.

Each pair of students have 2 time slots of 2 hours (i.e. 4 hours) to perform the experimental part of the laboratory.

The two main interests of this lab are :
– The use of an industrial controller ;
– To deal with a system modelled with a nomminimum phase transfer function.

FIGURE 1 – Experimental setup

Given the importance of some literal calculation, **it is imperative to have prepared the items requested before beginning the laboratory session** dedicated to the experiments with the experimental setup. A printed document with the solutions of the requested calculations will be available in the lab room.

As a reminder, the mastery of the document titled ***General manual for the labs and the tutorials sessions*** is a **prerequisite for performing the laboratories**.

2 Presentation of the industrial controller

2.1 General considerations

Different types of industrial controllers are presents in the industrial environment.

In some cases, as part of some modern industrial processes, controllers of type PID are presents as algorithms computed in an Programmable Logic Controller (PLC).

In other cases for more simple or more specific processes, controllers exist as preprogrammed equipment, with fixed inputs and/or outputs or partially configurable. It is this type of controller which will be used for this laboratory.

From a "packaging" point of view, PLCs as partially configurable controllers are in the form of a case, meeting the applicable standards, containing the electronics to compute the command code or the value of the command signal. These cases usually only have as user interface some lights indicators and alpha-numeric displays. Computers or specific consoles are then necessary to program these devices, as well as the supervision of the processed data.

2.2 The selected PID controller

The controller selected for this lab is a partially configurable PID type controller designed by OMRON. It is simply representative of the market offer in this type of devices. When the experimental system of the laboratory has been designed, it was one of the most general models, i.e. it accepts as I/O unspecified electronic signals (voltage between 0 and 10 Volts, and currents between 0 or 4 and 20 mA). Other models offered more oriented I/O such that thermocouple inputs, relays or triacs output.

Beside its PID controller function, the selected device is also equipped with threshold alarm and a list of other customizable functions, scale changes, signal filtering and more. All the parameters of these functions have to be encoded via a front panel consisting of a digital indicator and some push buttons (a drop down menu is supposed to simplify the task of the user...).

For this laboratory, a command and supervision software has been developed to enable students to communicate with the controller. So to simply set the important parameters and graphically display the signals of process value and command. The synoptic of the software is largely inspired by the front panel of the controller.

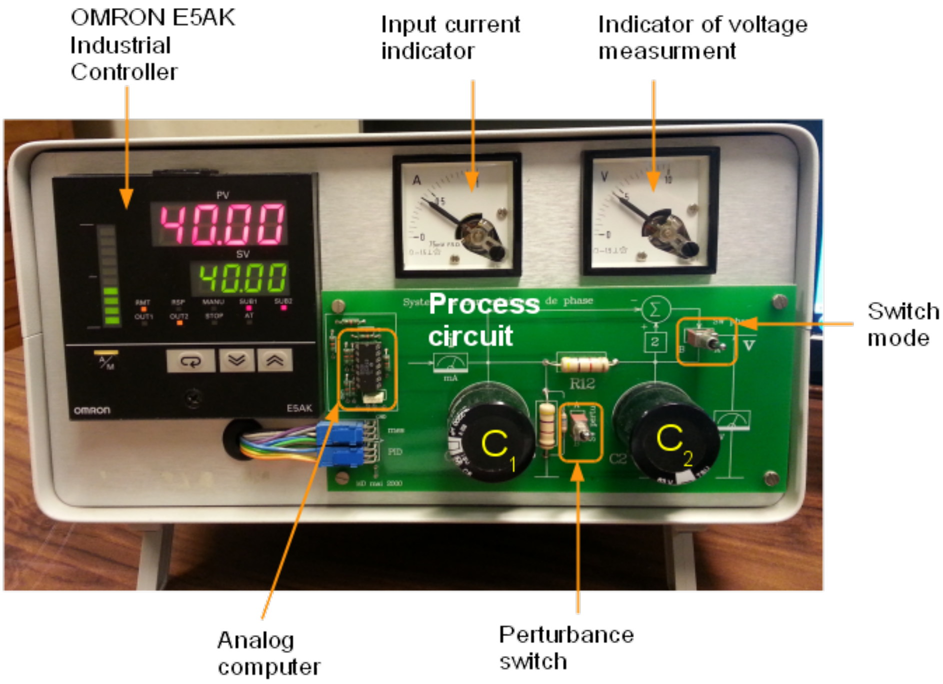

FIGURE 2 – Case containing the OMRON controller and the process circuit

2.3 The supervision and command software

This software has to be downloaded from the *Moodle* site of this course (file `Labo_Omron-app.zip`).

For a proper operation of the software, it is recommended to follow the procedure below :

1. Select the file `Labo_OMRON-app.zip`, and download it ;
2. Save it on the disk `Z:` ;
3. Right click on the file `Z:\Labo_Omron-app.zip` and select "*Extract all*". Windows will extract all the `.zip` file in a new file `Z:\Labo_Omron-app` that it will create ;
4. To run the software of the lab, you must double click on `Z:\Labo_Omron-app\OMRON.exe`.

To communicate with the industrial controller (with the right communication parameters), the software needs the 3 other files that come with it.

When the software is running, the three panels presented must be active, and one of them gets the data displayed on the front panel of the controller.

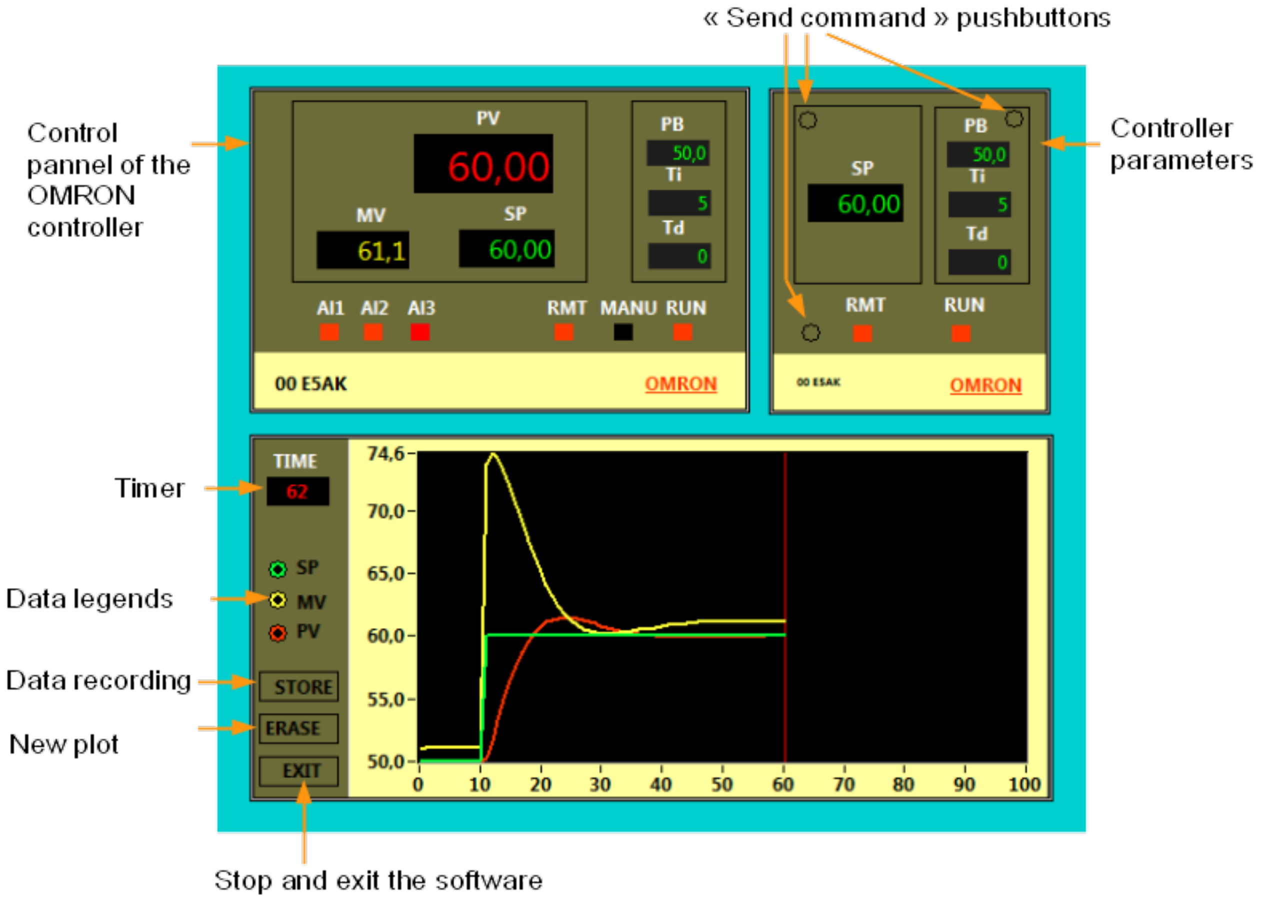

FIGURE 3 – View of the user interface of the supervision and command software used for this lab

2.3.1 Front panel of the controller

This panel of the software (see figure 3) reflects the state of the main information stored and displayed by the industrial controller on its front panel :

– **PV** : Process Value
  State of the measure, expressed in % of the scale (0 - 10 V).

- **SP** : Set Point
  Value of the setpoint , expressed in % of the scale (0 - 10 V ou 0 - 20 mA). **If the feedback loop is activated (the indicator `RUN` is ON), it is the setpoint, else, it is the command signal, directly applied on the process.**
- **MV** : Manipulated Variable
  State of the command, expressed in % of the scale (0 - 20 mA).
- **PB** : Proportional Band
  Inverse of the proportional gain of the controller, without unit.
- **Ti** : Integral Time
  Integration constant, in seconds.
- **Td** : Derivative Time
  Derivative constant, in seconds.
- **Al1, Al2, Al3** : Alarm indicators. Not used.
- **RMT** : ReMoTe
  Indicator of remote control. ON if the the controller can be programmed via a RS-232 connexion with the computer (not used, and forced to active state).
- **MANU** : Manual
  Indicator ON if the controller is in manual mode (not used and forced to inactive state).
- **RUN** : Indicator of feedback control (i.e. closed loop), ON if the feedback control loop is active (the system is in open loop if the indicator is OFF).

2.3.2 Remote control panel

This panel allows to modify the control parameters used for this lab, and to communicate them to the controller. This panel is devide in 3 different sections and separately changeable :
- One section for the setpoint (SP) ;
- One section for the control parameters (PB, Ti et Td) ;
- And one section for the operating mode (RUN).

To modify one parameter and to send it to the industrial controller, students must first change the value in the digital control in the lab software. And to send it to the controller, students must click on the associated **"Send command" pushbuttons**.

2.3.3 Panel of the graphical plot

This last panel contains a graphical plotter that shows the evolution of the data with the time. The different data can be identified with the associated legend.

The graphical plotter runs in scan mode on a time scale of 100 seconds. The display is scanned two times before being cleared to restart. For a good view, the most significant changes will have to occur in the first 100 seconds of an experiment.

The software store 200 seconds of data in buffer that can be recorded in a file for a later examination.

Beside the graphic plotter itself, the panel also contains :
- A timer with a resolution of one second. This timer is automatically reset after 200 seconds.
- A `STORE` button that active the record procedure of the buffer in which the data are stored. The data are then recorded as an `ASCII` array organized in columns separated by tab characters. In order, the columns show the time [s] and the variables SP [%], MV [%] et PV [%]. The procedure provides a classic *Windows* recording menu. **Warning :** The data can only be recorded on the drive `Z:` or on

a USB memory stick. All the other memory locations of the computers can be cleared at the next reboot.
– An `ERASE` button that clear the plotter, reset the data memory buffer and restart an observation of 200 seconds.
– An `EXIT` button to stop and exit the session.

3 The process used for this laboratory

3.1 The electronic circuit

The process used for this lab is a simple capacitive circuit which the diagram is shown on figure 4.

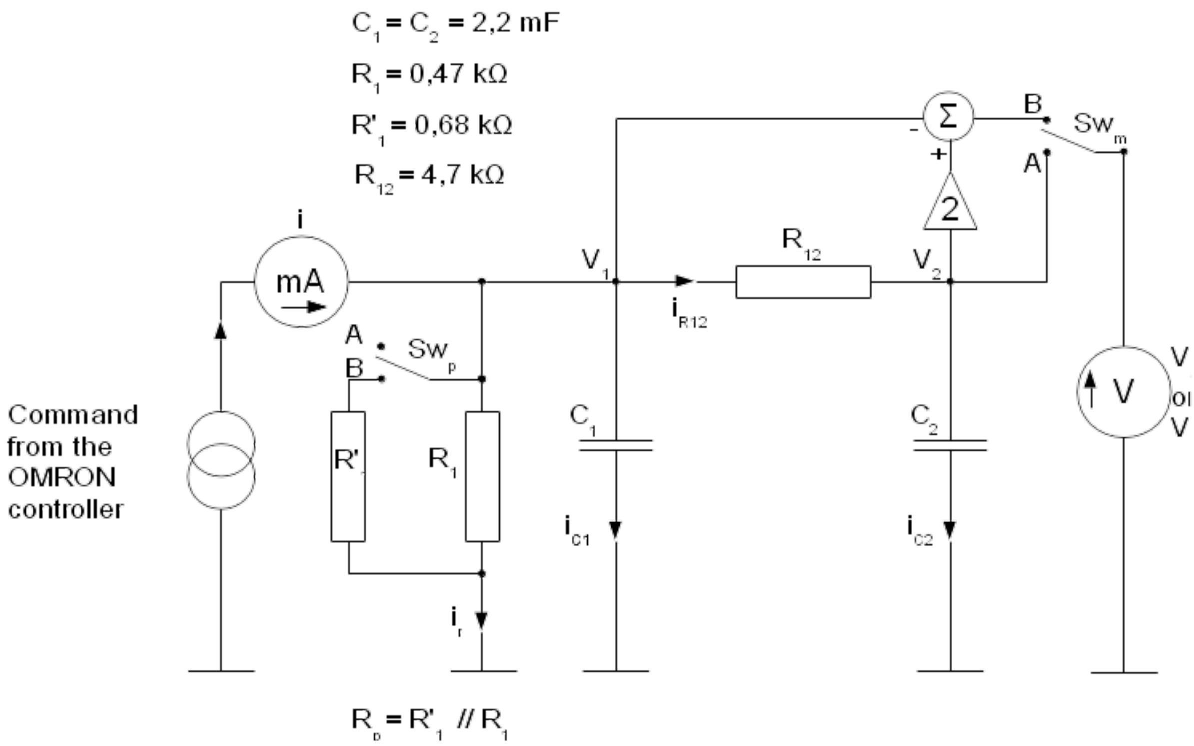

FIGURE 4 – Electronic circuit of the lab process

The command signal from the OMRON controller is a current (i) between 0 and 20 mA, and the output is an analog voltage (V_A or V_B) between 0 and 10 V.

The printed circuit board contains 3 resistors, 2 capacitors and a small analog circuit that computes the arithmetic operation shown as a block diagram on figure 4.

The Sw_m switch selects the output voltage, either the "natural" voltage of the capacitive circuit (V_A [V]), or the voltage from the analog computing (V_B [V]). This is the position of this switch that introduce the unstable zero in the process' transfer function.

The Sw_p switch allows for it to connect in parallel or not two resistors, which serves to disrupt the process.

3.2 Equations of the circuit

The behaviour of the circuit can be fully modelled using the equations of electrodynamics.

Balance of currents :

$$i_{C1} = i - i_{rp} - i_{R12} \tag{1}$$
$$i_{C2} = i_{R12} \tag{2}$$

Components equations :

$$\frac{dV_1}{dt} = \frac{1}{C_1} i_{C1} \tag{3}$$
$$i_{R12} = \frac{V_1 - V_2}{R_{12}} \tag{4}$$

With the equations (1), (2), (3) and (4), we can find :

$$\frac{d_{V1}}{dt} = \frac{-1}{C_1}\left(\frac{1}{R_p} + \frac{1}{R_{12}}\right) V_1 + \frac{1}{C_1}\frac{V_2}{R_{12}} + \frac{i}{C_1} \tag{5}$$
$$\frac{dV_2}{dt} = \frac{1}{C_1}\frac{1}{R_{12}} V_1 - \frac{1}{C_2}\frac{1}{R_{12}} V_2 \tag{6}$$
$$V_a = V_2 \quad \textbf{ou} \quad V_B = -V_1 + 2V_2 \tag{7}$$
$$\tag{8}$$

3.3 Scaling

The OMRON controller expresses its I/O variables in% of full scale. This facilitates the fact that the same device can be equipped with several electronic adaptation modules for different physical quantity (temperature, voltage, current, impedance, ...). In our case, we have to proceed the following changes :
The command parameter :

$$[0mA; 20mA] \Leftrightarrow [0\%; 100\%] \tag{9}$$
$$\textbf{d'où :} \quad i_{[mA]} = i_{\%}\frac{20}{100} \tag{10}$$

Output :

$$[0V; 10V] \Leftrightarrow [0\%; 100\%] \tag{11}$$
$$\textbf{d'où :} \quad V_{A \textbf{ ou } B[V]} = V_{A \ ou \ B\%}\frac{10}{100} \tag{12}$$

From equations (5), (6) et (7) it is now possible to write the equations of state in the form :

$$\frac{d_{V1}}{dt} = \frac{-1}{C_1}\left(\frac{1}{R_p} + \frac{1}{R_{12}}\right) V_1 + \frac{1}{C_1}\frac{V_2}{R_{12}} + \frac{0,2}{C_1} i_{\%} = f_1\left(i_{\%}; R_p; V_1; V_2\right) \tag{13}$$
$$\frac{dV_2}{dt} = \frac{1}{C_1}\frac{1}{R_{12}} V_1 - \frac{1}{C_2}\frac{1}{R_{12}} V_2 = f_2\left(V_1; V_2\right) \tag{14}$$
$$V_{a\%} = 10V_2 \quad \textbf{ou} \quad V_{B\%} = -10V_1 + 20V_2 \tag{15}$$

3.4 Linearised state equations

The disturbance is the resistor R_p $[\Omega]$. Thereby the state equations are not linear. It is therefore necessary to find an operating point (= equilibrium) $\left(\bar{i_\%}; \bar{R_p} \Rightarrow \bar{V_1}; \bar{V_2}\right)$ in the neighbourhood of which the system can be considered linear.

Thereafter, the usual notations will be used, namely :

$$\bar{i_\%} \to u \tag{16}$$
$$\bar{R_p} \to v \tag{17}$$
$$\bar{V_1} \to x_1 \tag{18}$$
$$\bar{V_2} \to x_2 \tag{19}$$
$$\bar{V_{A\ \mathbf{ou}\ B\%}} \to y \tag{20}$$
$$\tag{21}$$

and the positive counted parameters $a_{11}; a_{12}; a_{21}; a_{22}; b; d$, given by :

$$a_{11} = \left.\frac{\delta f_1}{\delta V_1}\right|_{\bar{V_1}} = \frac{1}{C_1}\left(\frac{1}{\bar{R_p}} + \frac{1}{R_{12}}\right) \qquad a_{12} = \left.\frac{\delta f_1}{\delta V_2}\right|_{\bar{V_2}} = \frac{1}{C_1 R_{12}} \tag{22}$$
$$a_{21} = \left.\frac{\delta f_2}{\delta V_1}\right|_{\bar{V_1}} = \frac{1}{C_1 R_{12}} \qquad a_{22} = \left.\frac{\delta f_2}{\delta V_2}\right|_{\bar{V_2}} = \frac{1}{C_2 R_{12}} \tag{23}$$
$$b = \left.\frac{\delta f_1}{\delta i_\%}\right|_{\bar{i_\%}} = \frac{0,2}{C_1} \qquad d = \left.\frac{\delta f_1}{\delta R_p}\right|_{\bar{R_p}} = \frac{\bar{V_1}}{C_1 \bar{R_p}^2} \tag{24}$$

These parameters are those of the general equations given below :

$$\dot{x_1} = -a_{11}x_1 + a_{12}x_2 + bu + dv \tag{25}$$
$$\dot{x_2} = a_{21}x_1 - a_{22}x_2 \tag{26}$$
$$y = 10x_2 \quad \mathbf{ou} \quad (-10x_1 + 20x_2) \tag{27}$$

For reasons of **digital simplifications**, it is adviced for students to work with electrical quantities expressed in $k\Omega$ and in mF.

4 Structure of the OMRON controller

The manufacturer of the controller used in the context of this lab acquaints the PID structure of the controller shown on figure 5.

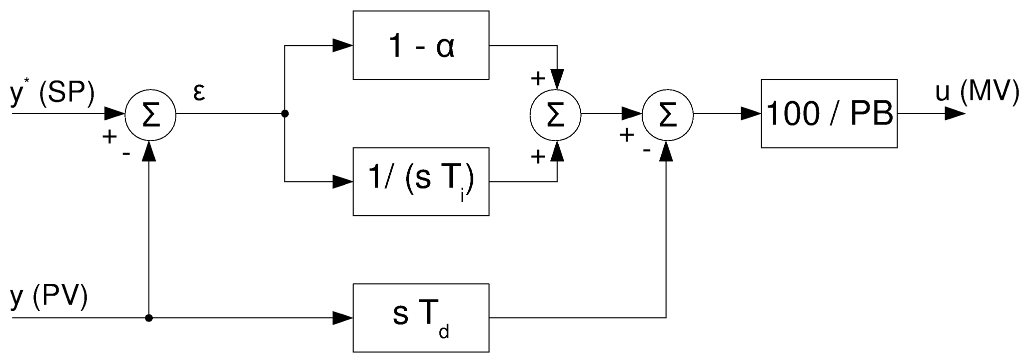

FIGURE 5 – PID sturcture of the OMRON controller

The command signal is given by :

$$u = \frac{100}{PB}\left(\left((1-\alpha) + \frac{1}{s.T_i}\right)\epsilon - s.T_d.y\right)$$

The users of this PID controller must note that :
- The proportional gain has the form of $\frac{100}{PB}$. The acronym `PB` reads *Proportional Band* ans is expressed in %.
- The integral and derivative gains are expressed in seconds.
- An α factor, without units, has been introduced by the manufacturer. This factor has the effect of reducing the term of the instantaneous response to an abrupt change of setpoint. This setting is tunable in the interval $[0;1]$. Altough this device may be useful, it will be constantly forced to 0 in the context of this lab to keep a conventional structure.
- The PB, T_i and T_d parameters have be bounded by the manufacturer :

$$PB \in [0,1;999,9]\ \ \% \tag{28}$$
$$T_i \in [1;3999]\ \ s \tag{29}$$
$$T_d \in [1;3999]\ \ s \tag{30}$$

5 Experiments to achieve for this laboratory

5.1 Usage restrictions

For this laboratory, the derivative action will not be used. We must therefore ensure that the value $T_d = 0$ is effective. The transfer function of the controller is therefore :

$$C(s) = \frac{100}{PB}\left(1 + \frac{1}{s.T_i}\right)$$

5.2 Linearisation

To linearise the process equations, we must set a reference equilibrium point (later called reference point). It is advised to use the point :

$$\bar{i_{\%}} = 50\ \% \qquad\qquad \bar{R_p} = R_1 = 0,47\ k\Omega \tag{31}$$

All the parameters are now calculable.

Before any other experiment, the system has to be brought to the reference point. To perform this preliminary experiment, you must :

1. Deactivate the `RUN` mode ;
2. Place `SW phase` switch (switch of mode) in position `A` (to disconnect the analog computing module) ;
3. Place the `SW pertu` switch (disturbance switch) in position `A` (only R_1 connected) ;
4. Set a setpoint (`SP`) of 50 % ;
5. Let the process settling down.

5.3 Settling time measurements

Before calculating the parameters d a controller, students must be able to characterize the dynamic of the process. For a naturally stable process like the one which get used while this lab, one of the main characteristic is the settling time or response time.

The goal of the described experiments in this point is to measure the settling time with a step of disturbance and this, for the two mode of operation : without zero ("minimum phase" mode), and with an unstable zero (in "non minimum phase" mode). This experiment will enable to observe that, despite the difference of the transient response, the two versions of the process have the same settling time.

5.3.1 Measure with the "minimum phase" system

To perform this experiment, students have to follow this procedure :

1. Initially place the system in open loop ;
2. Place the system at its reference point ;
3. Click on the `Erase` button ;
4. After 10 seconds, toggle the `SW pertu` switch from position `A` to position `B` ;
5. Let the system evolve and record the transient response of the system while the system is returning to its equilibrium. Subsequently, store the data and measure the response time.

5.3.2 Measure with the "nonminimum phase" system

To perform this second experiment, students have to follow this procedure :

1. Initially place the system in open loop ;
2. Place the system at its reference point ;
3. Toggle the switch `SW phase` from position `A` to position `B` (to connect the analog computer) ;
4. Let the system evolve to its equilibrium (needed given the transfer of energy with the switch off mode) ;
5. Click on the `ERASE` button ;
6. After 10 seconds, toggle the `SW pertu` switch from position `A` to position `B` ;
7. Let the system evolve and record the transient response of the system while the system is returning to its equilibrium. Subsequently, store the data and measure the response time.

5.4 Correction of a step of disturbance

The compensation of a step of disturbance is the main goal of this type of controller. Indeed, the change of setpoint are occasional, and for the most of the time, a controller maintains the process at the fixed setpoint value, despite the disruptive external events.

For the three experiments listed below, students have to calculate the values of the parameters PB and T_i.

5.4.1 "Minimum phase" system

If the transfer function "*disturbance* $\rightarrow$ *output*" has been correctly established, the $T_{vmp}(s)$ transfer function has a 3rd order denominator. Students have to place the poles of the $T_{vmp}(s)$ transfer function (so the controller parameters) to have a settling time similar to the natural settling time (of the system in open loop). In other words, students must fix one of the 3 poles, the value of the slowest pole of the process, and to place the others on the left (with a more negative real part). The response has not to be oscillatory.

To test the response of the closed loop system with the parameters of the controller, students have to follow this procedure :

1. Place the system in open loop ;
2. Place the system at its reference point ;
3. Enter and send the calculated PB and T_i parameters ;
4. Activate the `RUN` mode (that close the loop by computing the error) ;
5. Click on the `ERASE` button ;
6. After 10 seconds, toggle the `SW pertu` switch from position `A` to position `B` to apply a disturbance ;
7. Let the system evolve and record the transient response. Subsequently, store the data and measure the settling time.

5.4.2 "Nonminimum phase" system

To test the parameters tested on the previous paragraph but on the nonminimu phase system,students have to :

1. Stay on the `RUN` mode ;
2. Place the system at its reference point ;
3. Do not change the values PB neither T_i ;
4. Toggle the `SW phase` switch from position `A` to position `B` (to connect the analog computer that generates the unstable zero).

The "nonminimum phase" process controlled with the PB and T_i parameters give an unstable closed loop system. The examination of the transfer function gives the immediate reason ...

5.4.3 Stable "nonminimum phase" system

First, students have to establish the transfer function of the chain "controller - process", without the unit feedback of the output. This chain is the key of the closed loop transfer function "*setpoint* $\leftarrow$ *output*". After a first review, it seems natural to use the zero of the controller to compensate one of the poles of the process.

It is necessary to choose the slowest pole, because its action is leading. This choice is also perfectly justified to set the time of establishment of the system in relation to a setpoint step.

The pole-zero cancellation explained above allows to calculate T_i. The value of PB can be calculated by formulating the followings constraints :
– The disturbance step response of the system must be stable ;
– The disturbance step response of the system must not present any overshoot ;
To test the calculated parameters, it is advised to :

1. Place the system in open loop ;
2. Place the system at its point of reference ;
3. Enter and send the calculated values of the PB and T_i parameters ;
4. Toggle the `SW phase` switch from position `A` to position `B` ;
5. Activate the `RUN` mode ;
6. Click on the `ERASE` button ;
7. After 10 seconds, toggle the `SW pertu` switch from position `A` to position `B` ;
8. Let the system evolve and record the transient response while the system is returning to its equilibrium. Subsequently, store the data and measure the response time.

5.5 Setpoint step response in "nonminimum phase" mode

For completeness, it remains to observe the behaviour of the system reacting to a step applied on the setpoint, with the values of the PB and T_i parameters of the previous paragraph.

Students have to follow this procedure :

1. Let the system in closed loop (`RUN` mode activated) at the point of reference ;
2. The `SW phase` switch must be in position `B` and the `SW pertu` switch in position `A` ;
3. Keep the values of the PB et T_i parameters calculated in the previous paragraph ;
4. Enter a setpoint of `SP` $= 40$ % without sending it ;
5. Click on the `ERASE` button ;
6. After 10 seconds, send the setpoint value to the controller ;
7. Let the system evolve and record the transient response while the system is returning to its equilibrium (correcting the error). Subsequently, store the data and measure the response time.

6 Assessment preparation

Given the complexity of the calculations, it is advised to the students to prepare the followings points before performing the experiments :

1. Calculate the numerical values of the parameters : a_{11} ; a_{12} ; a_{21} ; a_{22} ; b ; d ; $\bar{V_1}$ et $\bar{V_2}$;
2. Calculate the literal (simplified and factorized) and numerical equations of the transfer functions $G(s)$ and $H(s)$ of the "minimum" and "nonminimum phase" process ;
3. Calculate the literal equations (simplified and factorized) of the transfer functions $T_v(s)$ of the "minimum" and "nonminimum" phase process ;
4. Calculate the literal equation (simplified and factorized) of the "nonminimum phase" transfer function $T_r(s)$.

A fix paper will be available at the laboratory.

7 Assessment preparation

For the lab assessment, it is necessary to perform the test with the software `Labo_OMRON_2016_eval_vx.exe`. This software requires the student's FGS number, asks randomly selected questions and returns a numerical key. This **personal key is needed for the individual lab assessment**.

Moreover, to be better prepared for this assessment at the end of the course, it is advised to understand and prepare replies to the following statements :

1. Be able to present all the block diagrams of the controlled systems and be able to show the links with the components of the experimental system ;
2. Be able to present all the literal and numerical calculations of all the expressions used for this lab ;
3. Be able to graphically describe the open loop transient response of the 2 operational modes of the process ;
4. Be able to measure and criticize the values of the different settling time encountered in this lab ;
5. Be able to present and justify all the calculations of the control parameters encountered in this lab ;
6. Be able to justify the failure of control in paragraph 5.4.2 ;