

## RESULTS AND DISCUSSION

The results can be divided into three parts. The first part is the calibration of sensors and/or transmitters. The second part is applications of LabVIEW for control this process. And the third part comprised of dynamics study of the proposed system.

### 1. Calibration curves

Calibration is necessary for the communication of equipment and program. In this work, there are three sensors, two differential pressure transmitters and one thermocouple type K. Those would need the correct signals from process because the accuracy in control is necessary. The calibration curves are shown as follow

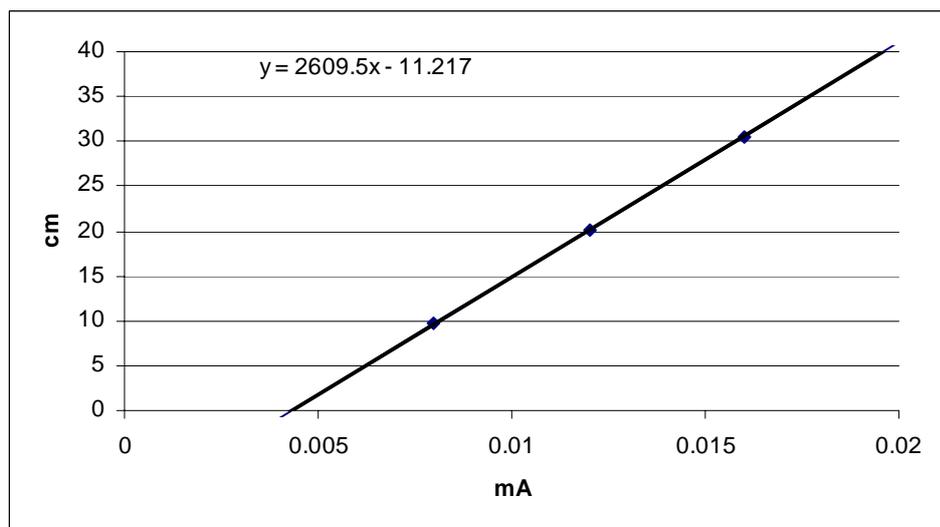


Figure 17 The calibration curve of YOKOGAWA EJA110 DP CELL

Figure 17 shows the calibration curve of Yokogawa EJA 110 DP cell. The x axis is analog signal output of this sensors and/or transmitters, mA, and y axis is the high of liquid in the tank, cm. The characteristic of this curve is linear. It means that the relationship of this curve can be used to read the liquid level directly when the program obtained the analog signal from sensors and/or transmitters.

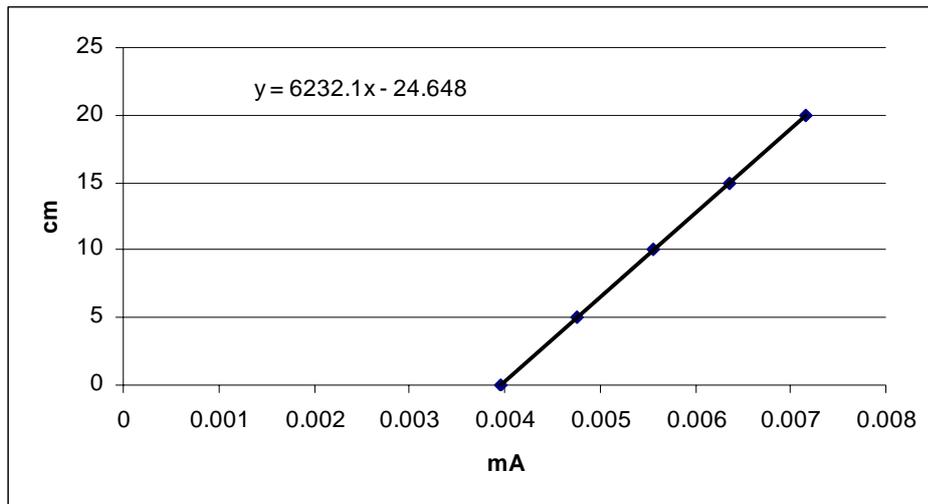


Figure 18 The calibration curve of Nagano ADZ-SMX-10.0 Pressure Transmitter

Figure 18 shows the calibration curve of Nagano ADZ-SMX-10.0 pressure transmitter. The x-y axis is similar with Yokogawa DP call. The characteristic of this curve is linear. It means that the relationship of this curve can be used to read the liquid level directly when the program obtained the analog signal from sensors and/or transmitters.

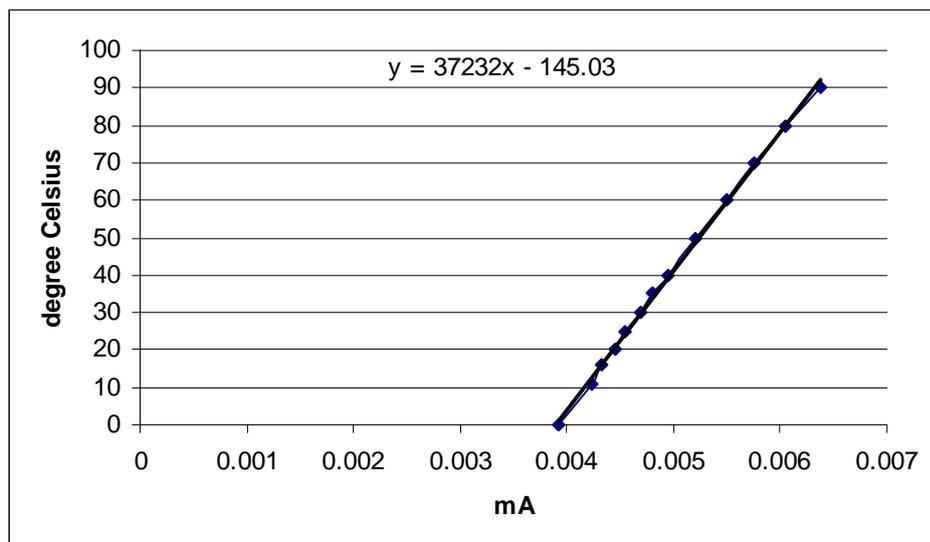


Figure 19 The calibration curve of a thermocouple type K

Figure 19 shows the calibration curve of thermocouple type K. The x axis is analog signal output of this sensors and/or transmitters, mA, and y axis is the temperature of liquid in the tank, degree Celsius. The characteristic of this curve is linear. It means that the relationship of this curve can be used to read the temperature directly when the program obtained the analog signal from sensors and/or transmitters.

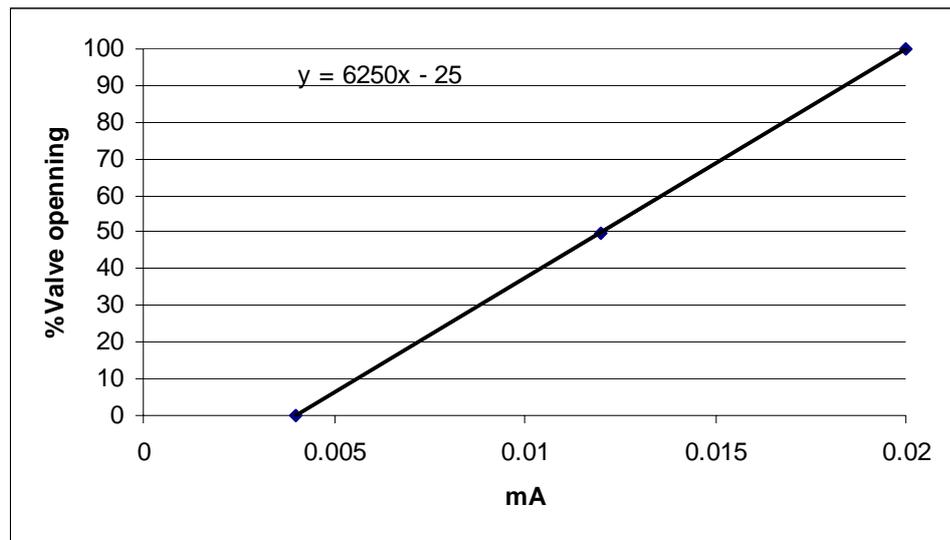


Figure 20 The calibration curve of control valve

Figure 20 shows the calibration curve of control valve. The x axis is analog signal output of this sensors and/or transmitters, mA, and y axis is the percent valve opening. The characteristic of this curve is linear. It means that the relationship of this curve can be used to read the liquid temperature directly when the program obtained the analog signal from sensors and/or transmitters.

Figure 21 shows the calibration curve of inverter. The x axis is pump speed, rpm, and y axis is the analog output, mA. The characteristic of this curve is linear. It means that the relationship of this curve can be used to control the pump speed directly when the program needed the speed from user.

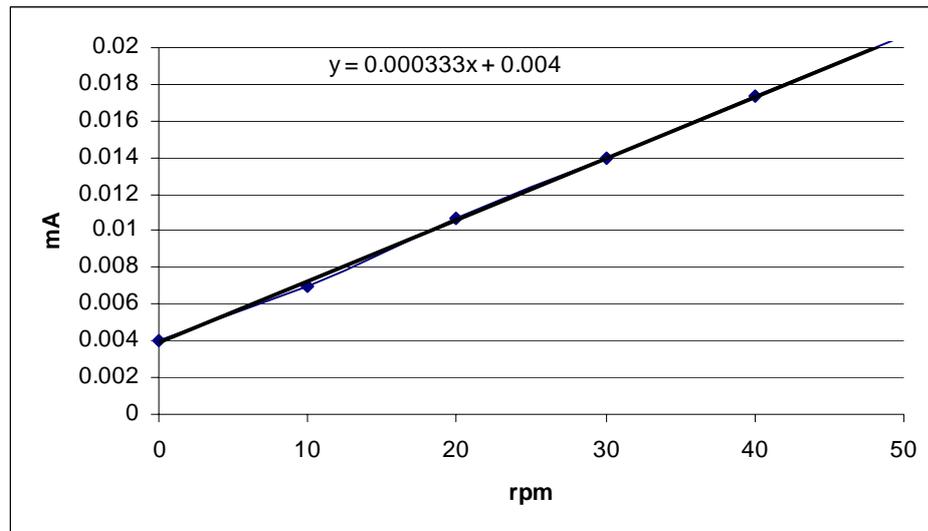


Figure 21 The calibration curve of inverter

## 2. LabVIEW programming

In previous topic, sensors and/or transmitters are calibrated. We will now apply LabVIEW to control this process. Before looking at these details, however, it would be helpful to look the structure of control. A number of mathematical models that describe the dynamic operation of one tank process and two-interacting tank process were developed. Solving such model, that is, finding the output variables as functions of time for some change in the input variable (s) requires either analytical or numerical integration of the differential equation. From these equations, mathematical models are helpful to design the various controllers. This work has proposed two well known model based controllers; IMC and GMC, in order to control this process. In this part, LabVIEW program is used in order to develop the control structure based on proposed models. In addition, PID and Fuzzy control were also applied to study.

There are three parts. The first programs are sub VIs which is a group of functions to support the control. The second part is a DAQ assistant setting. And the third part is GUI controlling with these process.

## 2.1 Sub Virtual Instruments

There are 11 sub VIs used in these applications.

- 2.1.1 Tank 1 calibration VI
- 2.1.2 Tank 2 calibration VI
- 2.1.3 Temperature calibration VI
- 2.1.4 Valve calibration VI
- 2.1.5 In-range 4-20 mA VI
- 2.1.6 PID controller VI
- 2.1.7 IMC controller (level) VI
- 2.1.8 IMC controller (temp) VI
- 2.1.9 GMC controller (level) VI
- 2.1.10 GMC control (temp) VI
- 2.1.11 Integral Absolute Error (IAE) VI

### 2.1.1 Tank 1 calibration VI

This VI is built from the relationship in Figure 17. The input obtains data from DAQmx read VI and output send out to show the level of tank 1 in centimeter unit. Figure 22 is shown the feature of tank 1 calibration VI.

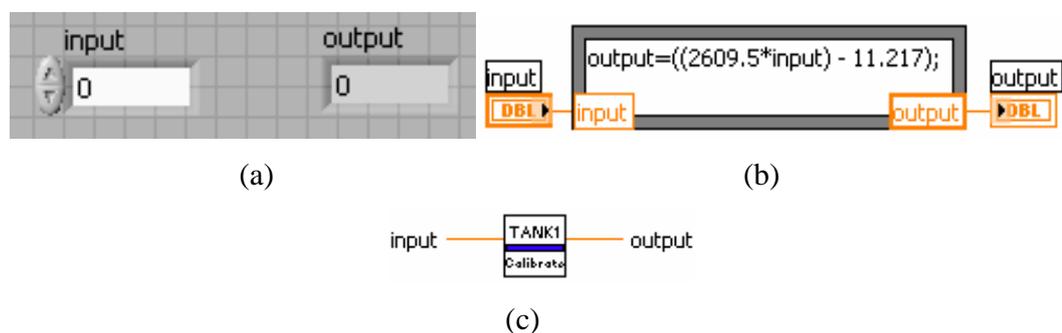


Figure 22 Tank1 calibration VI: (a) front panel, (b) block diagram, (c) icon

### 2.1.2 Tank 2 calibration VI

Tank 2 calibration VI is built from the relationship in Figure 18. The input obtains data from DAQmx read VI and output send out to show the level of tank 1 in centimeter unit. Figure 23 is shown the feature of tank 2 calibration VI.

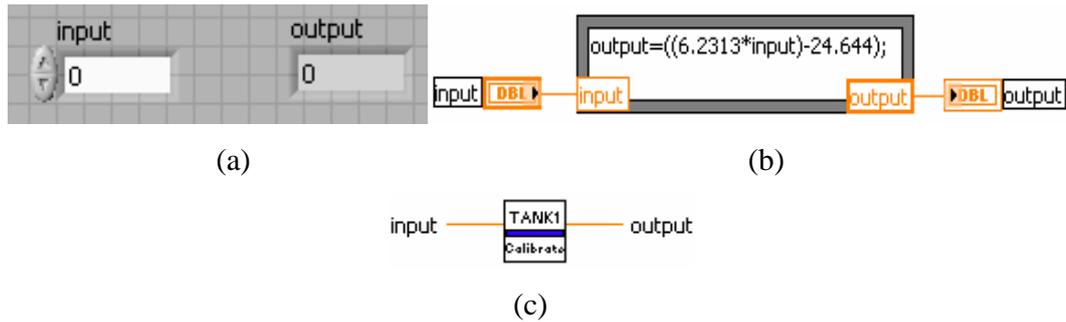


Figure 23 Tank 2 calibration VI: (a) front panel, (b) block diagram, (c) icon

### 2.1.3 Temperature calibration VI

Temperature calibration VI is built from the relationship in Figure 19. The input obtains data from DAQmx read VI and output send out to show the level of tank 1 in centimeter unit. Figure 24 is shown the feature of temperature calibration VI.

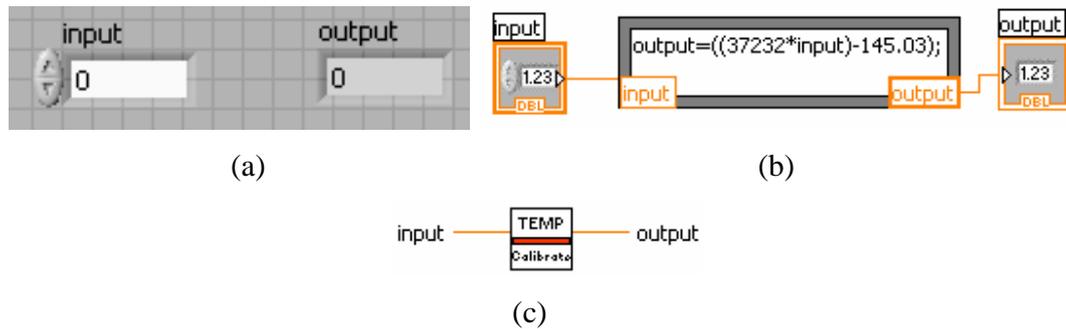


Figure 24 Temperature calibration VI: (a) front panel, (b) block diagram, (c) icon

2.1.4 Valve calibration VI

Valve calibration VI is built from the relationship in Figure 20. The input obtains data from DAQmx read VI and output send out to show the level of tank 1 in centimeter unit. Figure 25 is shown the feature of temperature calibration VI.

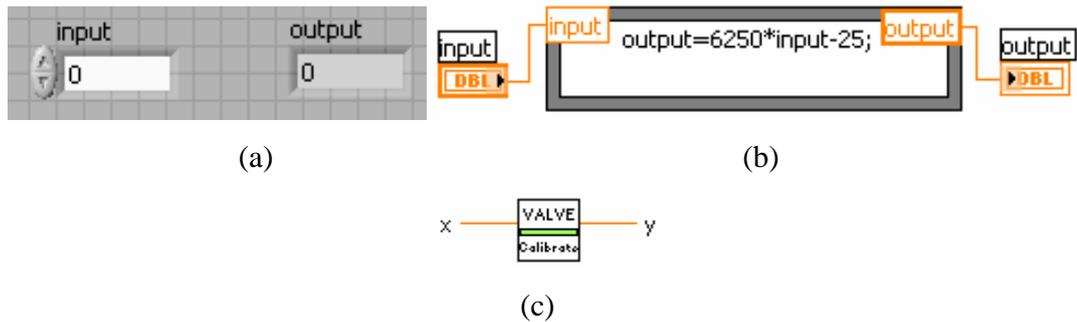


Figure 25 Valve calibration VI: (a) front panel, (b) block diagram, (c) icon

2.1.5 In-range 4-20 mA VI

In range 4-20 mA VI is built for control the range of controller output which is in the 4-20 mA range. The input obtains data from controller and output sends data to the final control element. For the example, if the controller output is too high (upper 0.02 mA), the the maximum of controller output is 0.02 mA and *vice versa*. Figure 26 shows the feature of in-range 4-20 mA VI.

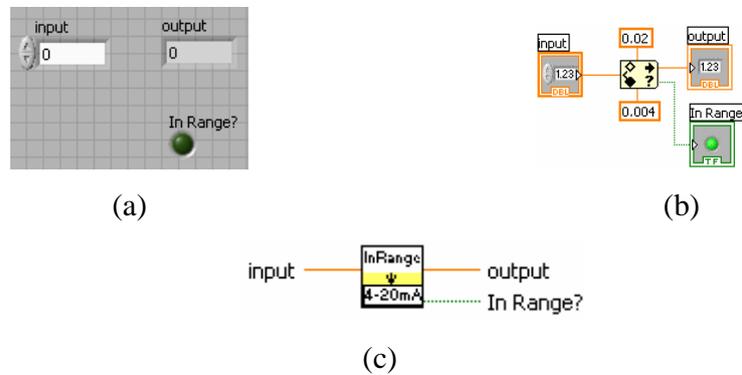


Figure 26 In-range 4-20 mA VI: (a) front panel, (b) block diagram, (c) icon

### 2.1.6 PID controller VI

PID controller VI is built from Equation 40. The input obtains error from the different between variable input and set point. Sampling time (dt) is set for sampling. PID controller has three tuning parameters, Kc, Ti, and Td. The PID VI uses an integral sum correction algorithm that facilitates anti-windup and bumpless manual to automatic transfers. Windup occurs at the upper limit of the controller output, for example, 100%. When the error, e, decreases, the controller output decreases, moving out of the windup area. The integral sum correction algorithm prevents abrupt controller output changes when you switch from manual to automatic mode or change any other parameters. The default ranges for the parameters SP, PV, and output correspond to percentage values. Figure 27 is shown the feature of PID controller VI.

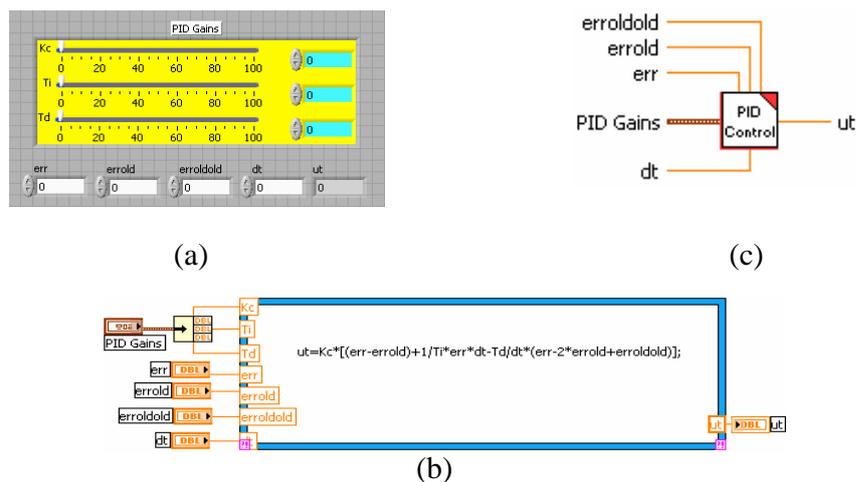


Figure 27 PID controller VI: (a) front panel, (b) block diagram, (c) icon

### 2.1.7 IMC controller (level) VI

IMC controller VI is built from Equation 51. The input obtains error from the different between variable input and set point. Sampling time (dt) is set for sampling. IMC controller has only one tuning parameters, Kc. Figure 28 shows the feature of IMC controller (level) VI.

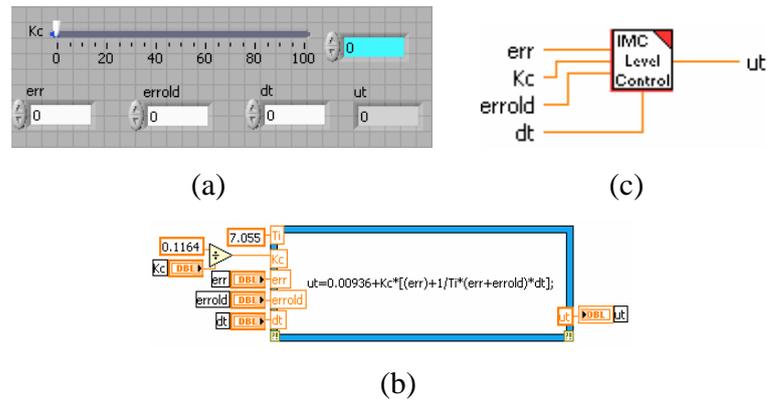


Figure 28 IMC controller (level) VI: (a) front panel, (b) block diagram, (c) icon

### 2.1.8 IMC controller (temp) VI

This VI is similar with IMC controller (level) VI. Kc. Figure 29 shows the feature of IMC controller (temp) VI.

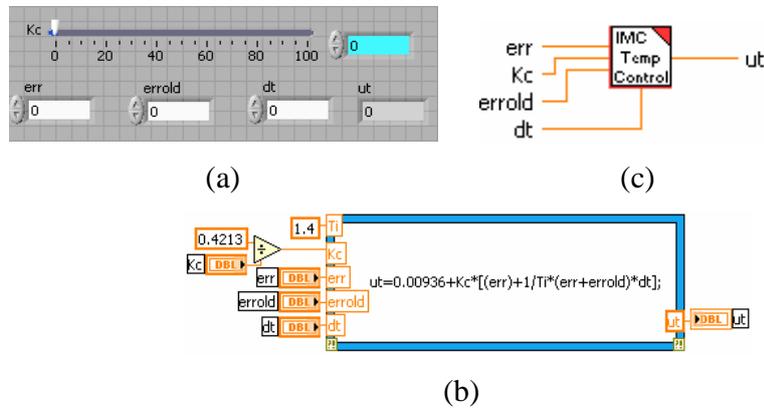


Figure 29 IMC controller (temp) VI: (a) front panel, (b) block diagram, (c) icon

### 2.1.9 GMC controller (level) VI

GMC controller VI is built from Equation 62. The input obtains error from the different between variable input and set point. Sampling time (dt) is set for sampling. GMC controller has only one tuning parameters, Kc. Figure 30 shows the feature of GMC controller (level) VI.

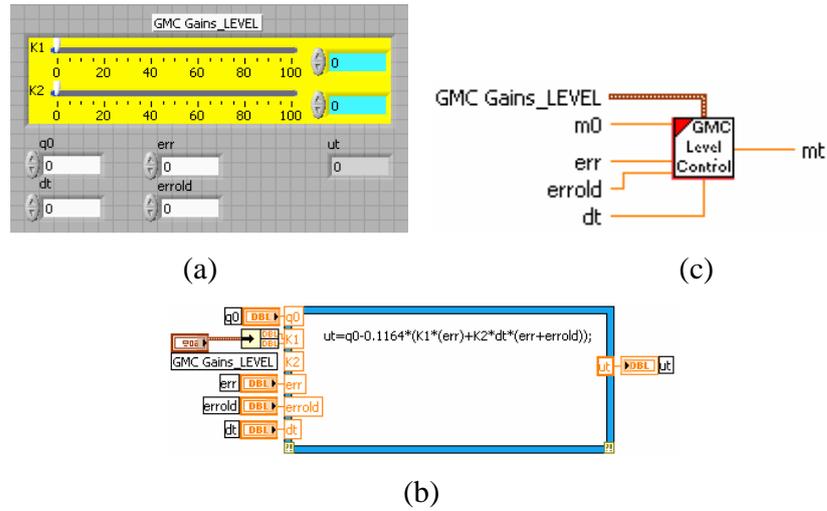


Figure 30 GMC controller (level) VI: (a) front panel, (b) block diagram, (c) icon

### 2.1.10 GMC controller (temp) VI

GMC controller VI is built from Equation 67. The input obtains error from the different between variable input and set point. Sampling time (dt) is set for sampling. GMC controller has only one tuning parameters, Kc. Figure 31 shows the feature of GMC controller (temperature) VI.

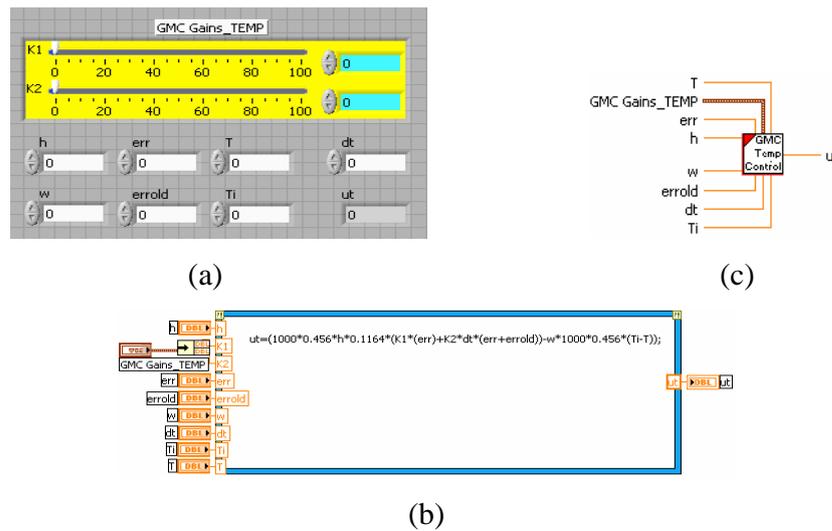


Figure 31 GMC controller (temp) VI: (a) front panel, (b) block diagram, (c) icon

### 2.1.11 Integral Absolute Error (IAE) VI

IAE VI is built to check the error of process response. The IAE VI should put out of the loop because the final result of run should be shown the total error. The IAE VI feature is shown in Figure 32.

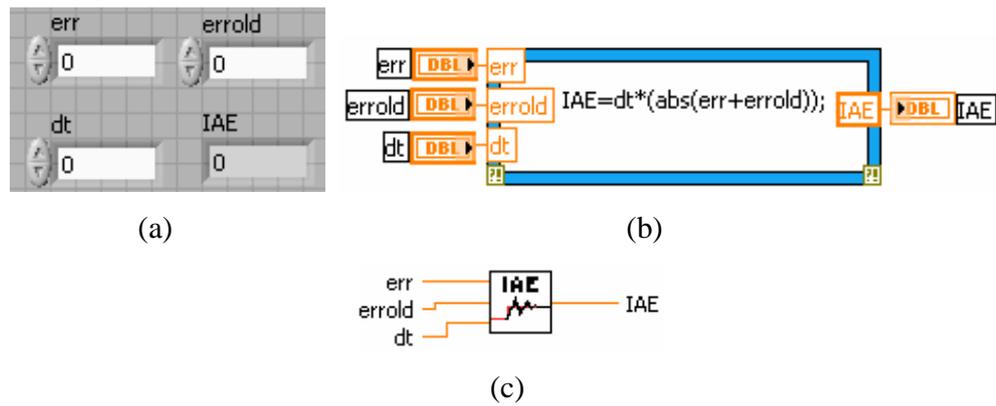


Figure 32 IAE front panel VI: (a) front panel, (b) block diagram, (c) icon

This work, each control program has a similar implement for control. The measured variable signals are measured from sensor/transducer. All analog signals, 4-20 mA, will be sent into SCXI-1322 terminal box simultaneously which is represented

by DAQmx read VI () (TAN). Note that this block has been set in APPENDIX C. Then,

the signal will be sent to the index array () that returns the element or sub array of n-dimension array at index. After that, the signals will be sent to calibration block sub

VI, tank 1 calibration, tank two calibrations, and temperature calibration ( )

and () (TEMP Calibrate). The output of calibration blocks are the correct value of process. Next, the error value is determined by the different of process variable and set point

( and ). Then, the signals will go to controller blocks sub VIs, PID, IMC,

GMC, and FLC (     ). Note that Fuzzy controller block is a function in LabVIEW program toolkit. This block must create the rule based for process control. The procedures are described in APPENDIX B. Then, the controller

output signals will be sent into In-Range 4-20 mA () (InRange 4-20mA). This block will help to save the FCE from damage. The outputs of this block will be sent to DAQ assistant VI

(). Then, the signal will be sent to SCXI-1325 terminal. Finally, these signals will be sent to FCE in order to adjust the actuator to open or to close the valve. It does until the process output has no error. The control programs are shown in Figures 33 to 37.

## 2.2 Manual control two-interacting tank

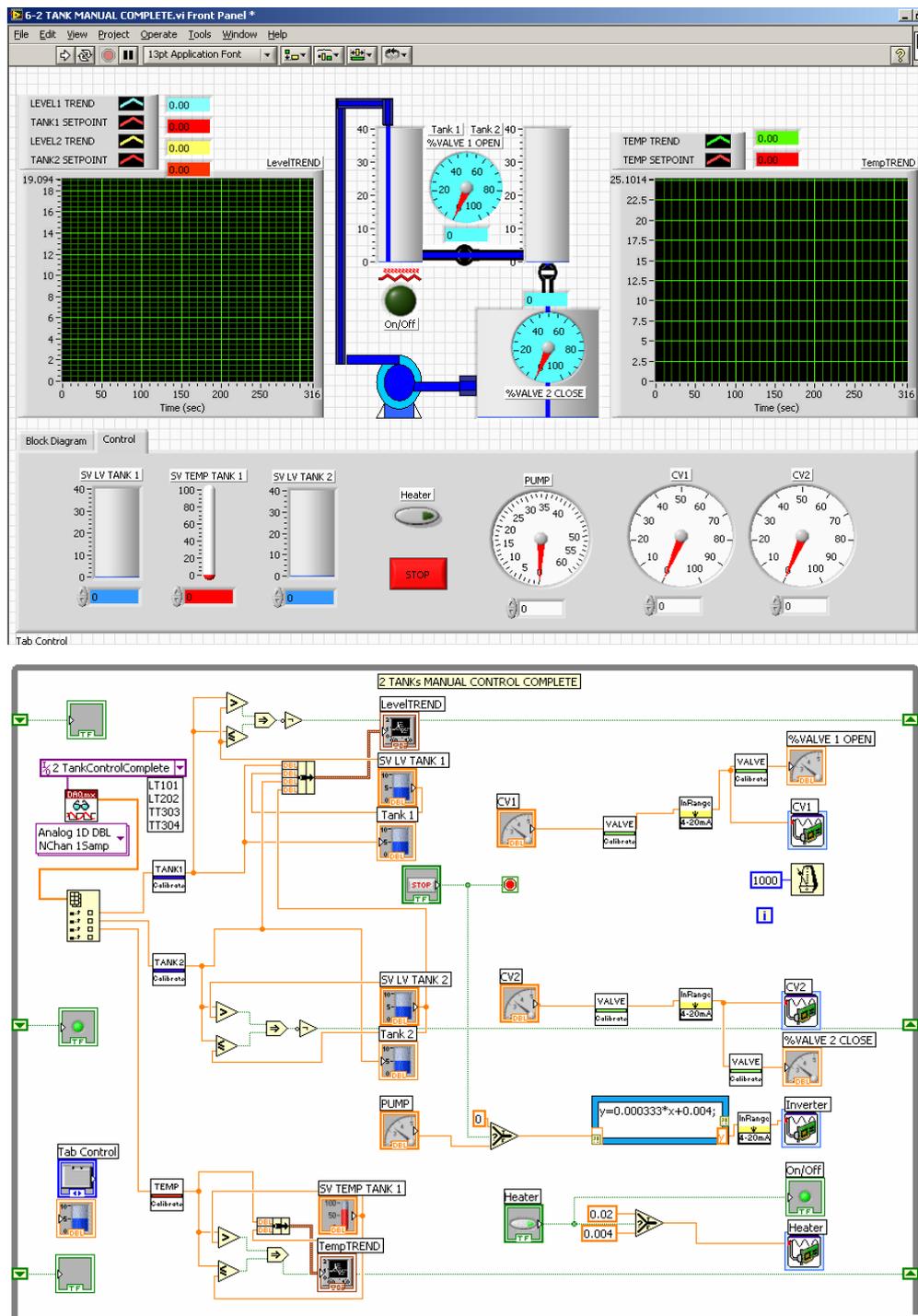


Figure 33 Two-interacting tank system is controlled by Manual control: front panel (above), block diagram (below)

## 2.3 PID control two-interacting tank

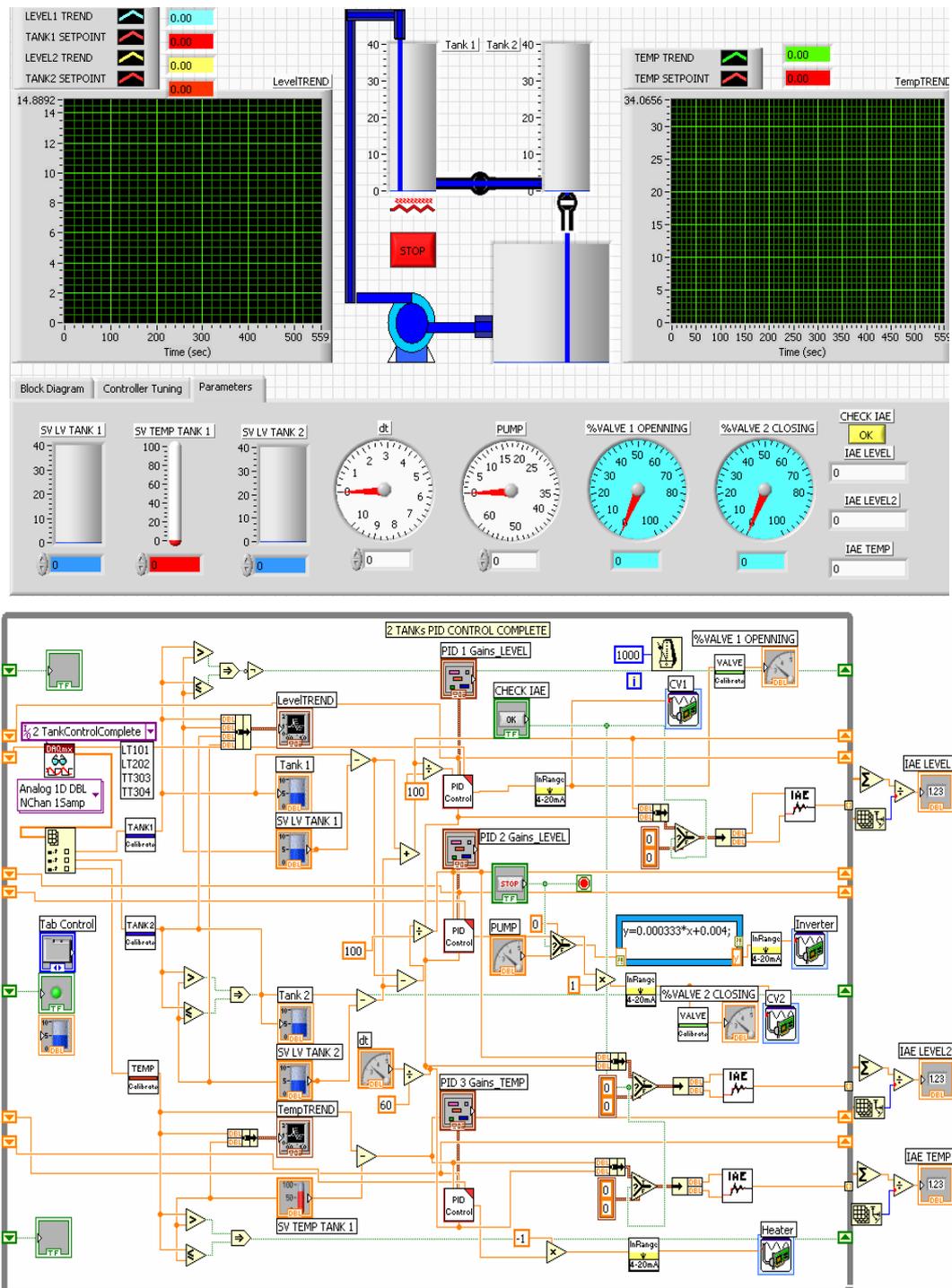


Figure 34 Two-interacting tank system is controlled by PID controller: front panel (above), block diagram (below)

## 2.4 IMC control two-interacting tank

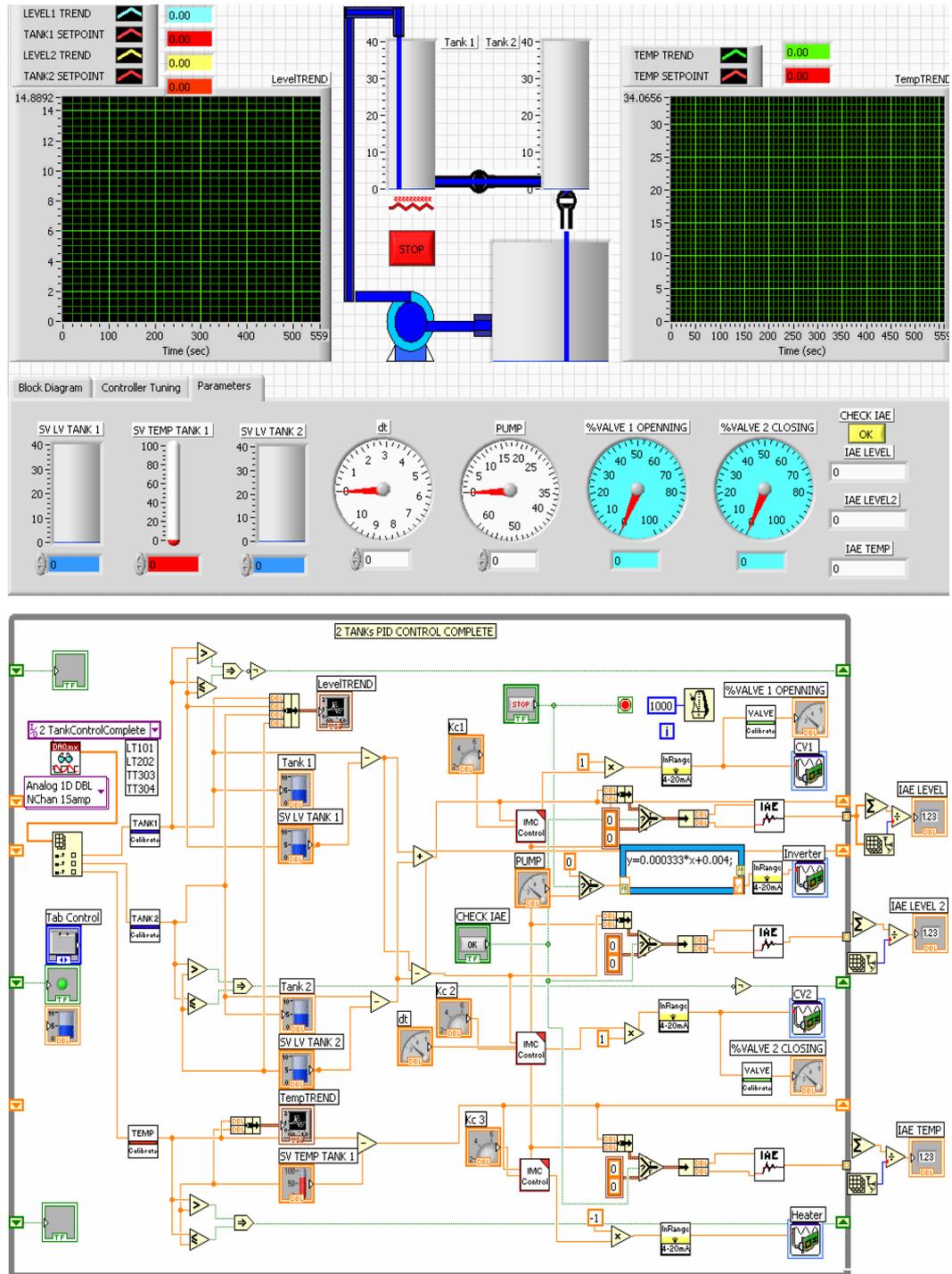


Figure 35 Two-interacting tank system is controlled by IMC controller: front panel (above), block diagram (below)

## 2.5 GMC control two-interacting tank

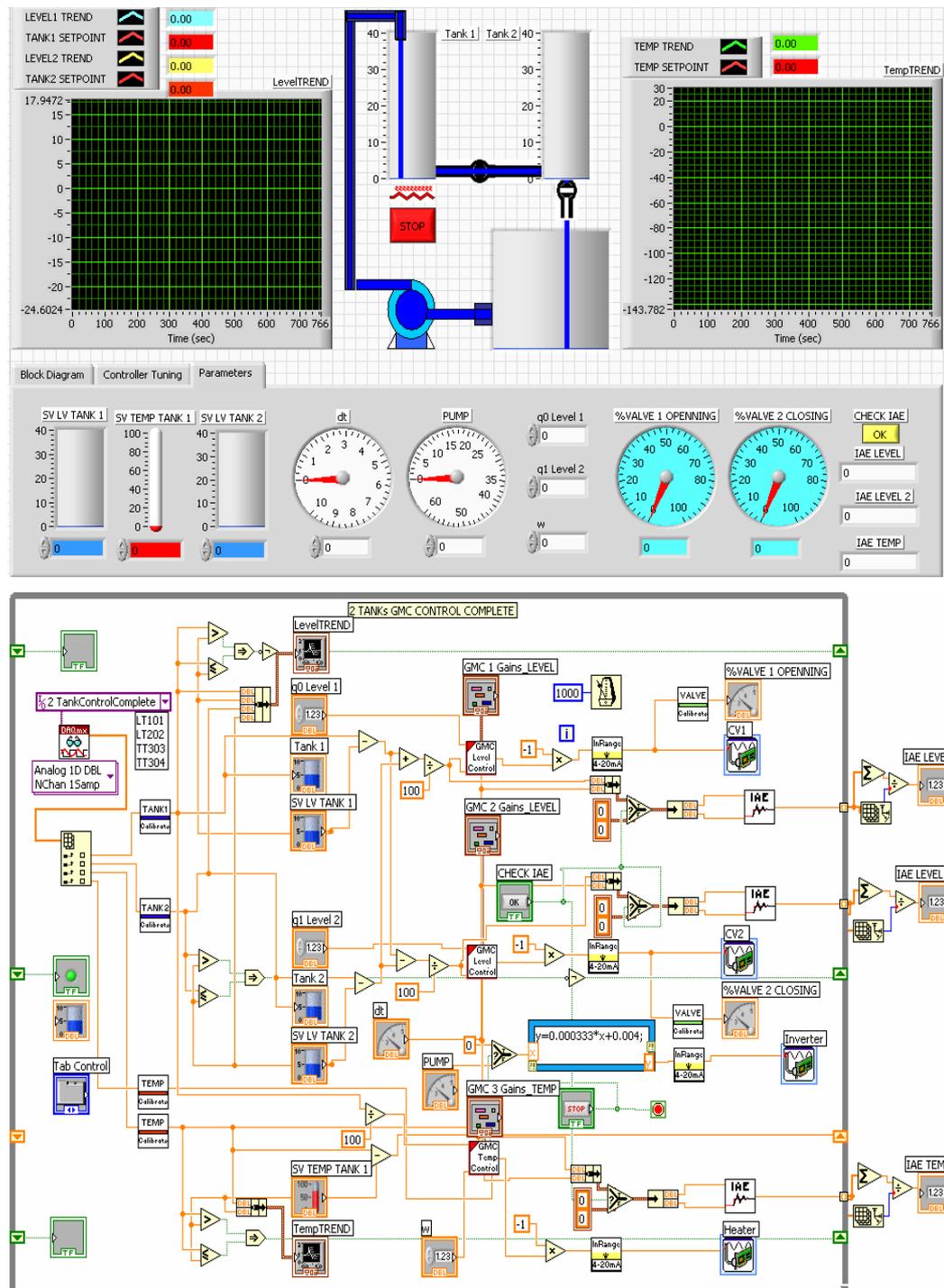


Figure 36 Two-interacting tank system is controlled by GMC controller: front panel (above), block diagram (below)

## 2.6 FLC control two-interacting tank

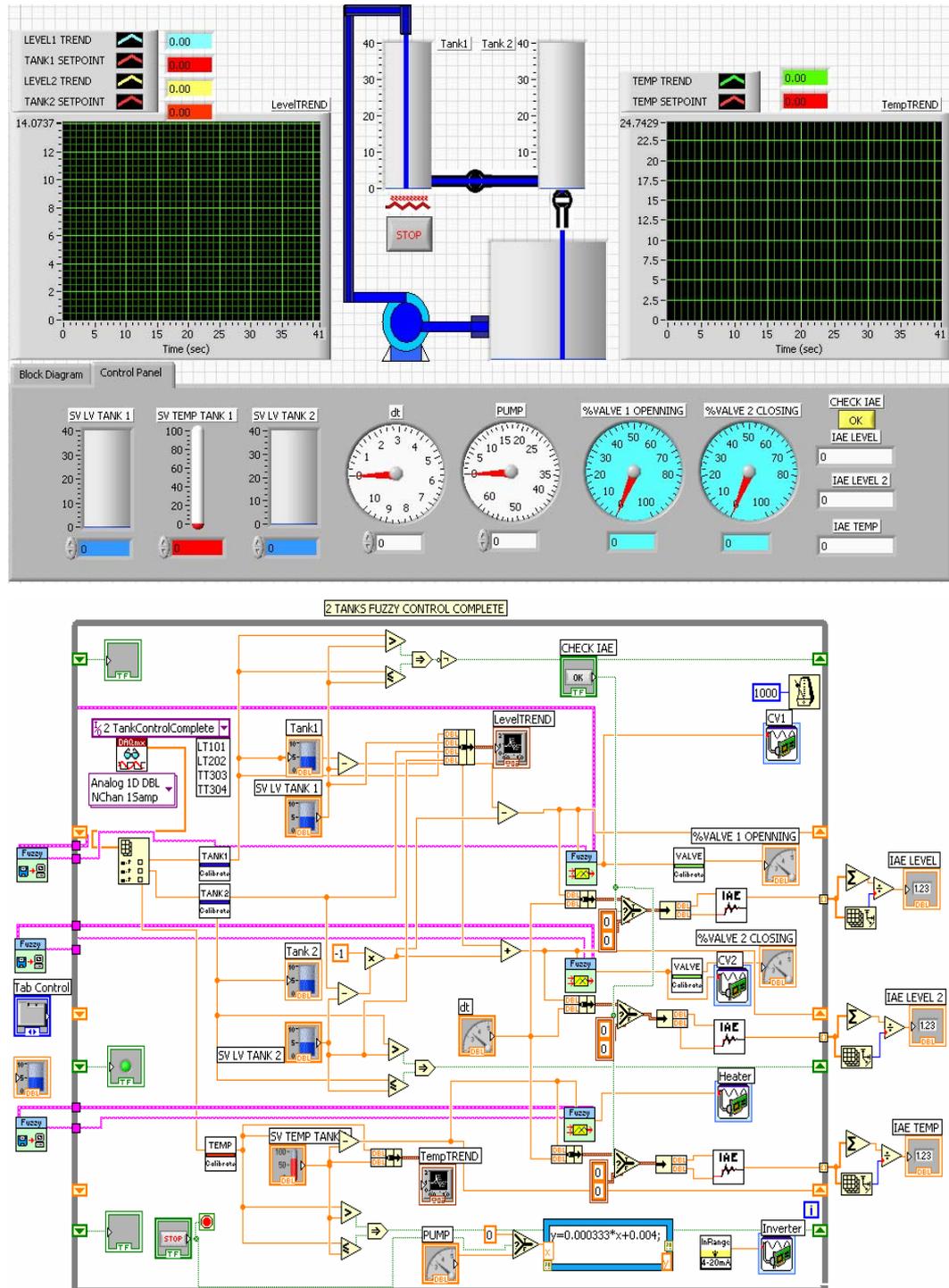


Figure 37 Two-interacting tank system is controlled by FLC controller: front panel (above), block diagram (below)

### **3. Dynamics responses**

All experiment results given here are based on variety designed controller. The objective in this part is to find the best controller such that the accuracy control of level and temperature in the tank. In this case study will be divided into two parts. The first part is one tank process system which can be divided into two cases and the second part is the two interacting tank system which can be divided into four cases. Both parts are controlled by several designed controller such as PID, IMC, GMC, and FLC. In this work, level and temperature are key parameters to control on web-based via LabVIEW program.

LabVIEW acquire the data from data acquisition card. In the control loop used while loop to control this system. The sampling rate depends on the user, in this experiment used one second.

#### 3.1 One tank process system

In order to observe the control response of level and temperature, one tank process system can be divided to study into two cases as follow.

1. The first case is level set point increasing 3 cm and temperature set point increasing 1 °C, which the specified final time of 150 sec was used.
2. The second case is level set point decreasing 3 cm and temperature set point increasing 1 °C, which the specified final time of 250 sec was used.

The steady state of this process is level at 13 cm and temperature at 30 °C because temperature is hard to control, this experiment attempt to control start up temperature in range  $\pm 0.5$  °C. The feed flow rate  $0.0033 \text{ m}^3/\text{min}$  is used in this work. These results in the maximum accuracy can be compared by IAE with results obtained from proposed controller design strategy. The speed of response can be considered by rising time.

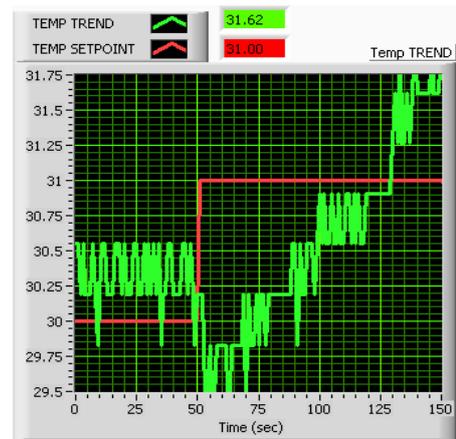
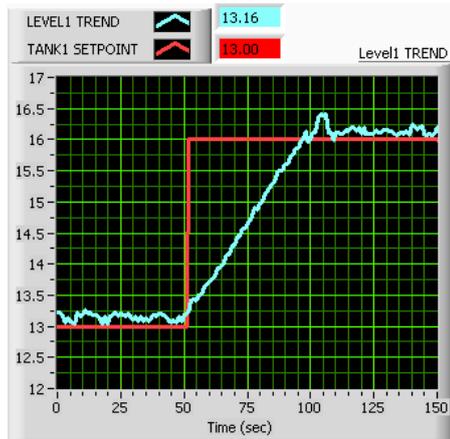


Figure 38 PID control response in the first case

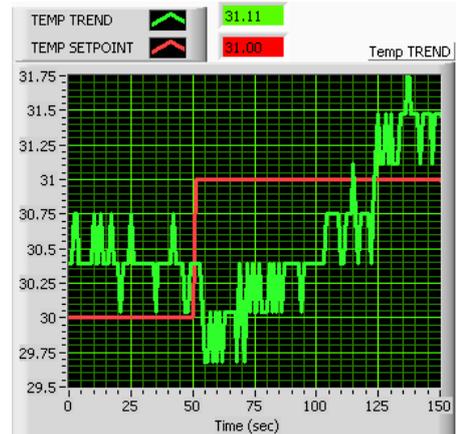
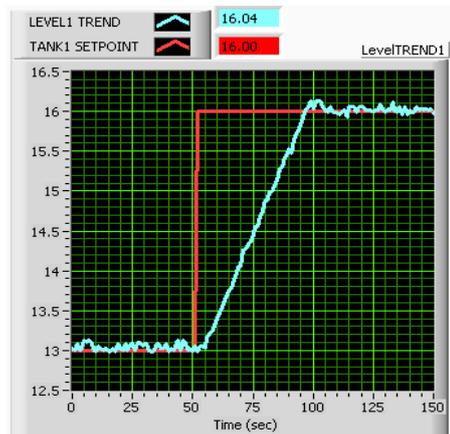


Figure 39 IMC control response in the first case

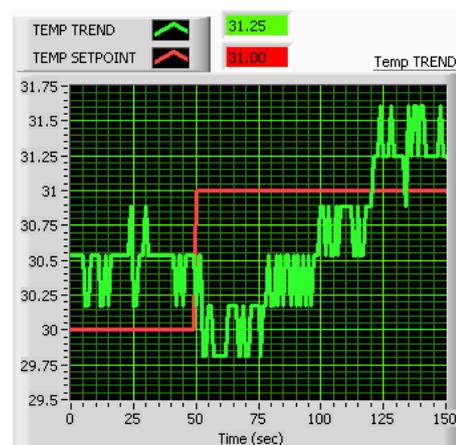
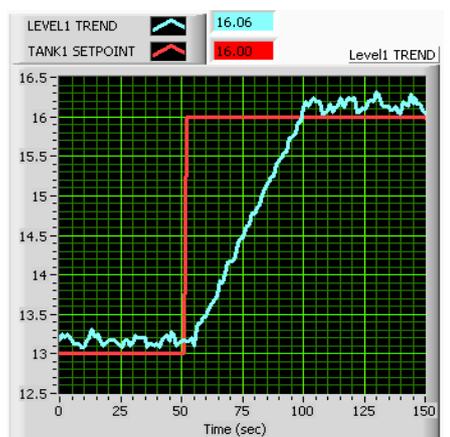


Figure 40 GMC control response in the first case

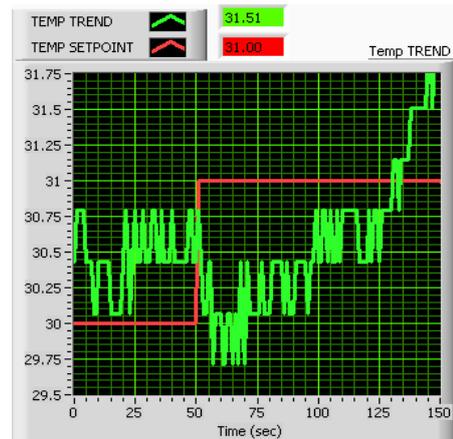
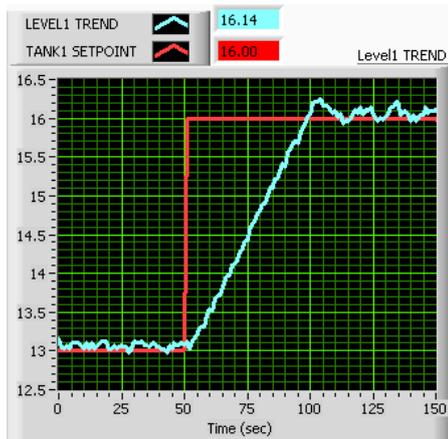


Figure 41 FLC control response in the first case

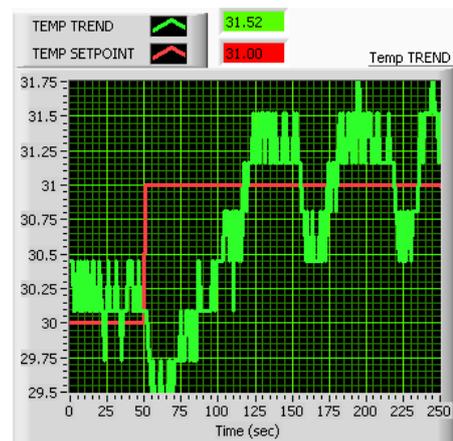
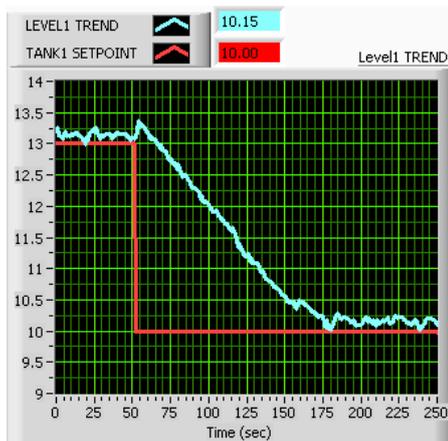


Figure 42 PID control response in the second case

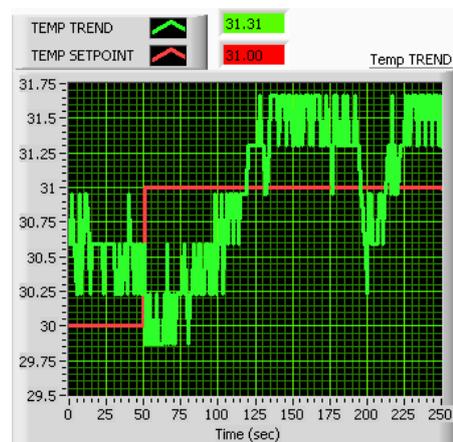
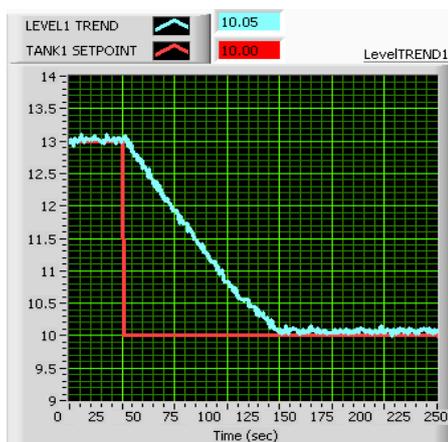


Figure 43 IMC control response in the second case

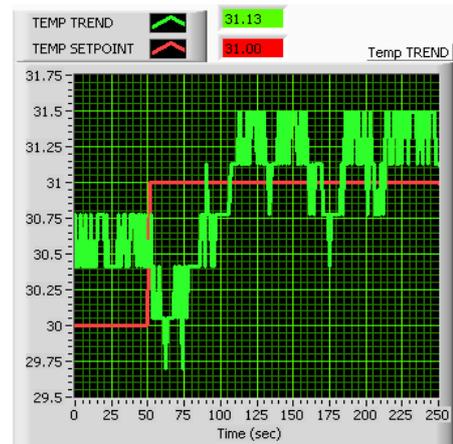
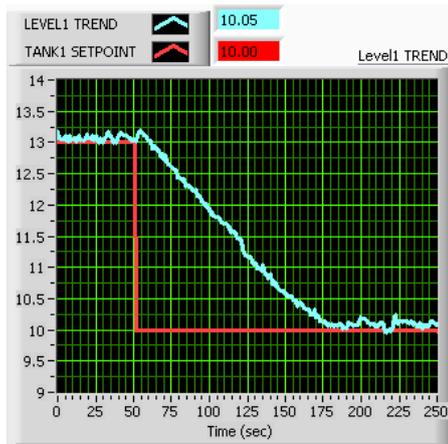


Figure 44 GMC control response in the second case

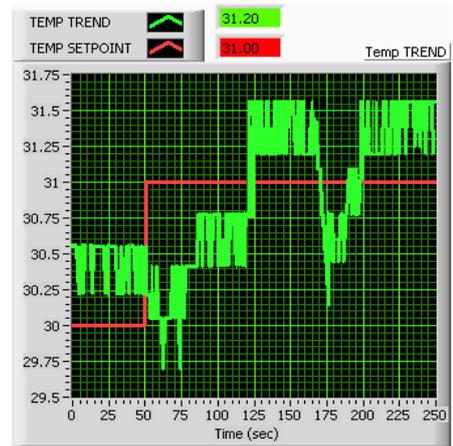
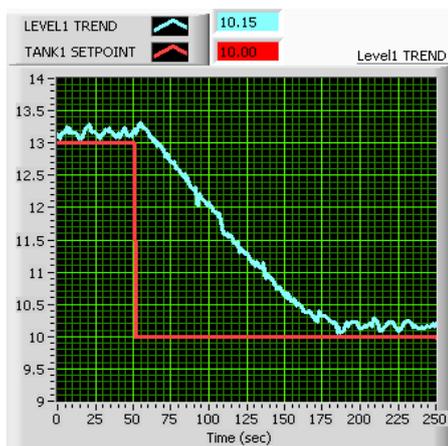


Figure 45 FLC control response in the second case

The result can be concluded in the following section.

Table 2 Comparison of the results obtained from one tank control system

Controller Sub VIs	Level (cm)	Temp (°C)	IAE of Level	IAE of Temp.	Level Rise Time (sec)	Temp Rise Time (sec)
PID	+3	+1	7.5898E-5	0.0059490	99	130
IMC			5.7557E-5	0.0048721	99	124
GMC			6.7645E-5	0.0053564	99	120
FLC			0.0026078	0.0315564	99	130
PID	-3	+1	0.0001317	0.0057389	177	116
IMC			0.0001141	0.0055895	179	119
GMC			0.0001284	0.0043642	180	105
FLC			0.0051329	0.0156698	200	120

As shown in Table 2, IMC and GMC controller have IAE less than PID controller because the model base is correct and they are easy to tune than PID controller. The rise time is very close because this model is basic for control. When temperature loop is considered, it was found that GMC controller is the best. As shown in Table 2, the time response of GMC is very shortest when compared with other controllers. FLC controller is an alternative controller which has low accuracy than other controllers. As the results, the error is very small size. Thus, all designed controllers can be used for easily control one tank process system. One tank process system is represented MIMO system because level has effect with temperature. As shown in Table 2, the temperature can adapt to the new set point for a few time when the volume of liquid in a tank is reduced.

### 3.2 Two-interacting tank process

In order to observe the control response of level, two interacting tanks process system can be divided to study into four cases as follow.

1. The third case is level of tank one and two set point increasing 5 cm.
2. The fourth case is level of tank one and two set point decreasing 5 cm.
3. The fifth case is only level of tank 1 set point decreasing 5 cm.
4. The sixth case is only level of tank 2 set point increasing 5 cm.

The steady state condition of this process is level of tank 1 at 25 cm and level of tank 2 at 15 cm.

The third case is a servo problem with both tanks. It is similar the one tank control linear process. When the process is disturbed by set point change, tank one from 25 to 30 cm and tank two from 15 to 20 cm, the first tank will keep the liquid for tank two also. It means that control valve will close until the level in tank one is equal the level set point of tank one and tank two combined together. After that control valve one will extremely open in order to flow the liquid into tank two. Then, the level of both tank are at the new set point. Finally, each control valve will control the level in each tank around the set point. The error is about  $\pm 0.5$  cm.

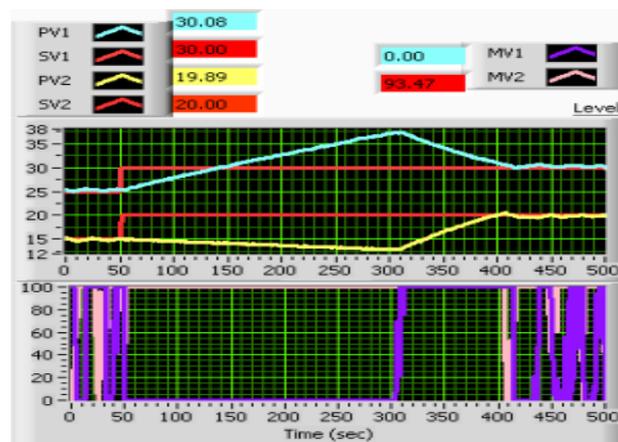


Figure 46 PID control response in the third case

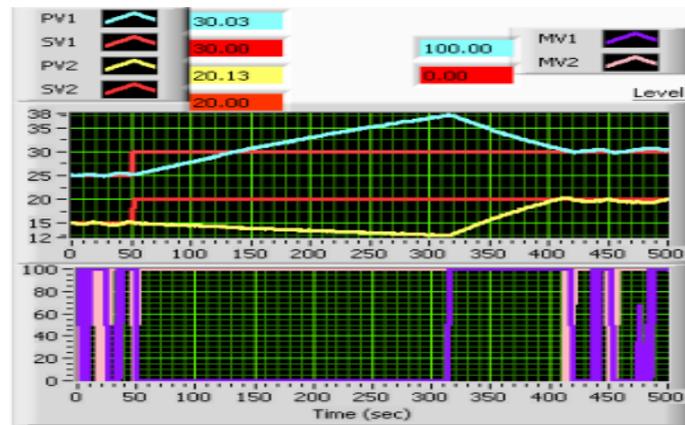


Figure 47 IMC control response in the third case

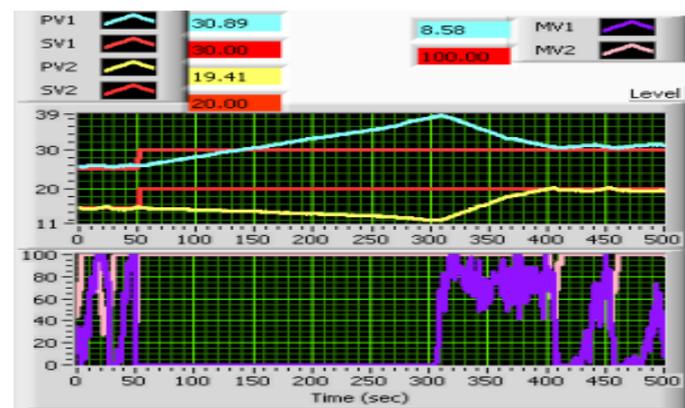


Figure 48 GMC control response in the third case

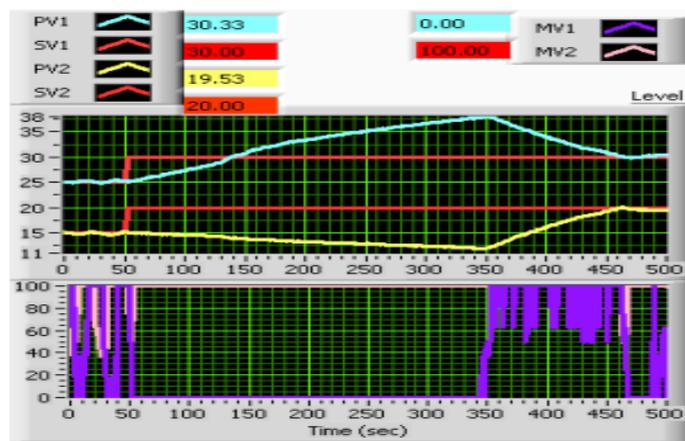


Figure 49 FLC control response in the third case

The fourth case is a servo problem with both tanks. It has the interacting effect between tank one and two when the level of tank one decreases from 25 to 20 cm and tank two decreases from 15 to 10 cm. The interacting effect in this case is not much because both tanks reduce the set point together. The outflow of tank one has the effect with the liquid level of tank two. Therefore, each control valve will adjust the level at the same decreasing rate until the response approaches the new set point. PID and IMC controllers use the high range in control the process while GMC and IMC use low range in control outflow of each tank.

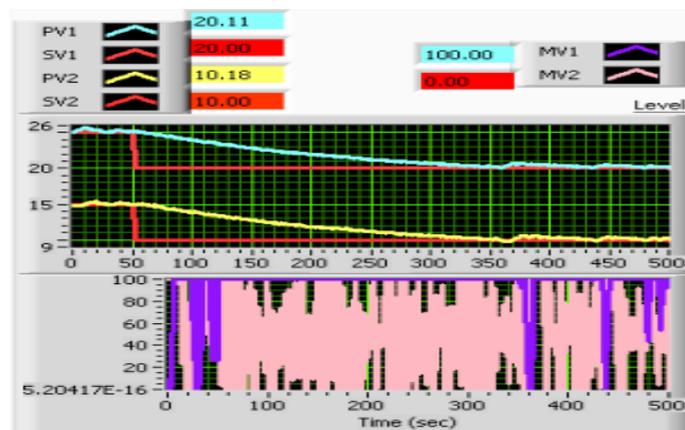


Figure 50 PID control response in the fourth case

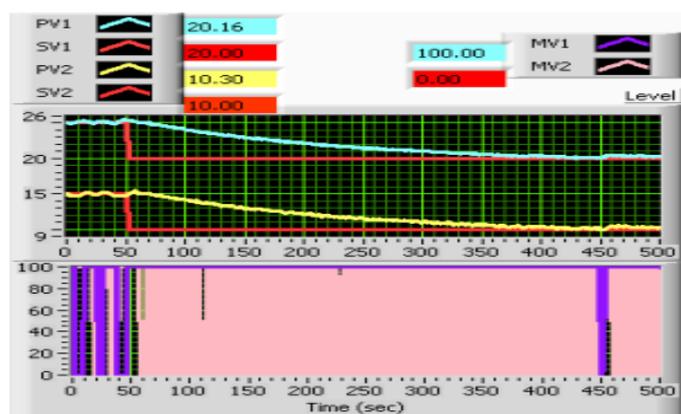


Figure 51 IMC control response in the fourth case

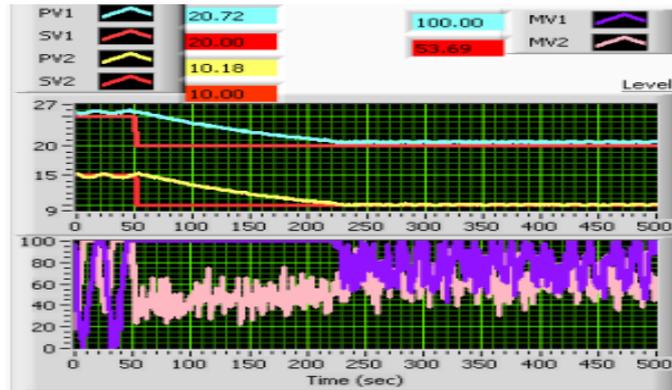


Figure 52 GMC control response in the forth case

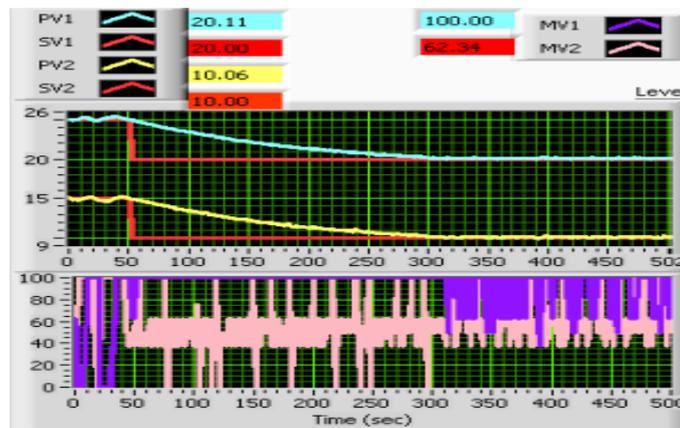


Figure 53 FLC control response in the forth case

The fifth case is a servo-regulatory problem. It means that the level of tank one is a servo problem and tank two is a regulatory problem. This case is a strong interacting system because the level from tank one flows through out to tank two that no the set point change. The flow pattern can describe as follow. When the set point of tank one decreases from 25 to 20 cm, the level of tank two increases until the response has the same error. Then, the response will increase at the same decreasing rate until the response approaching the new set point. The error in this case is about  $\pm 0.5$  cm.

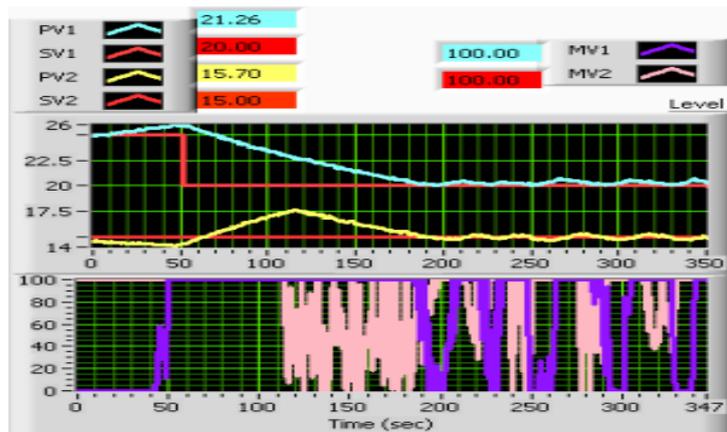


Figure 54 PID control response in the fifth case

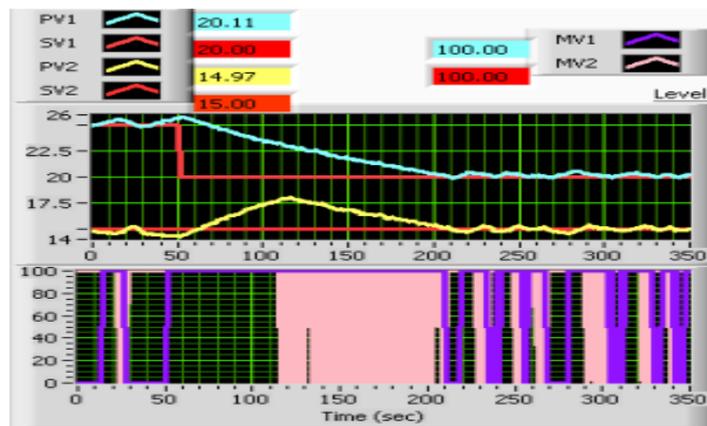


Figure 55 IMC control response in the fifth case

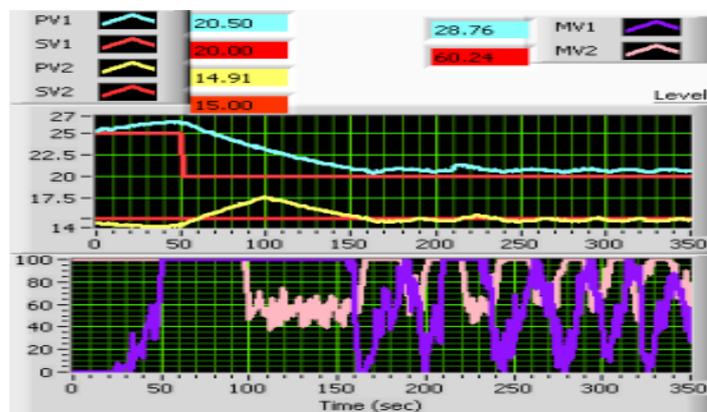


Figure 56 GMC control response in the fifth case

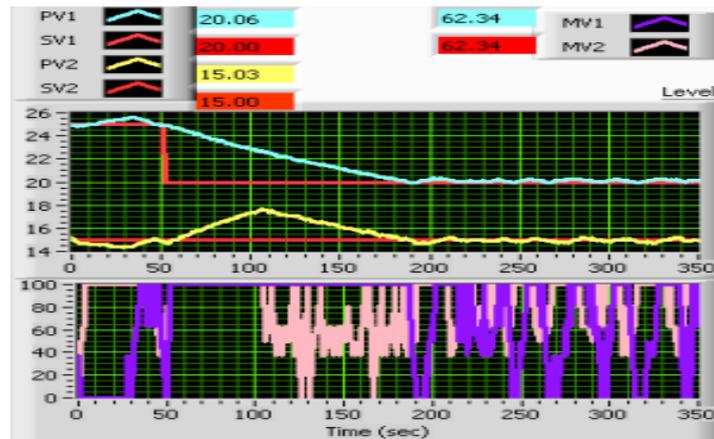


Figure 57 FLC control response in the fifth case

The sixth case is a regulatory-servo problem. It means that tank two is changed set point from 15 to 20 cm. and tank one has no change set point. It is similar with the third case but the set point of tank one does not change. Tank one will keep the liquid sufficiently for tank two set point.

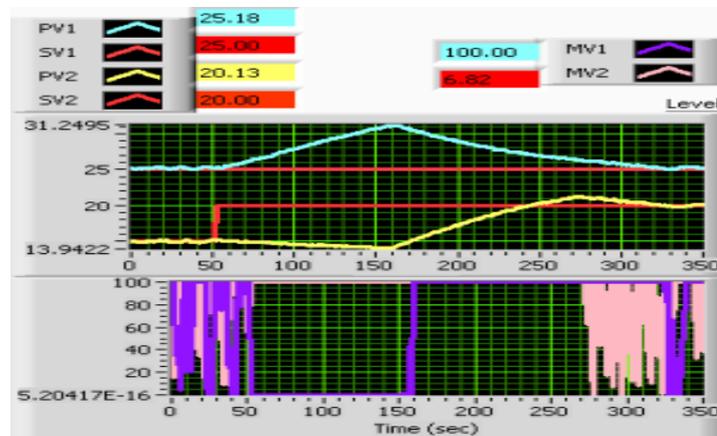


Figure 58 PID control response in the sixth case

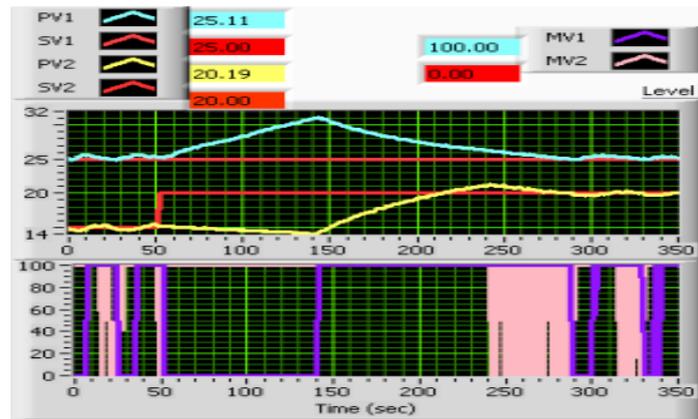


Figure 59 IMC control response in the sixth case

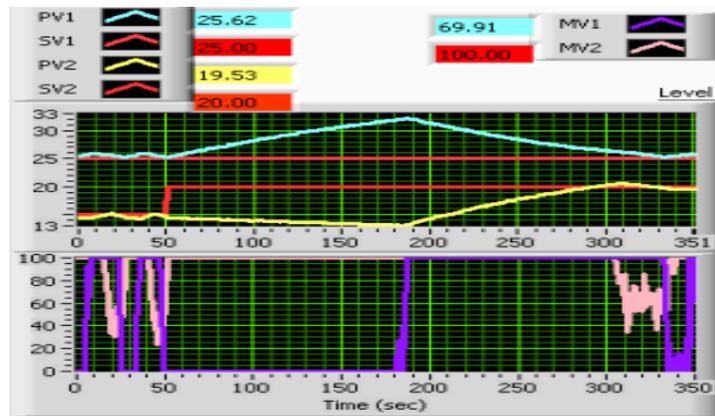


Figure 60 GMC control response in the sixth case

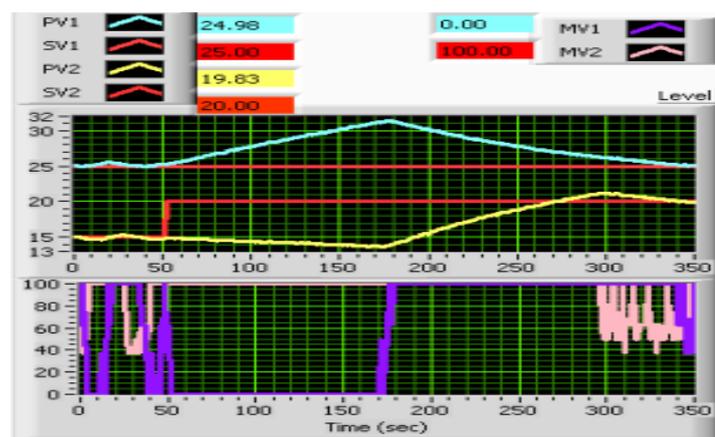


Figure 61 FLC control response in the sixth case

All results of two interacting tanks system are collected in Table 3 for the convenient analysis. The model based controllers have high accuracy than PID controller which is a conventional controller because the IAE value is smaller than PID. While, a FLC can control this process but it has much error than other controller. GMC controller spends a fewest time to adapt the response to a new set point.

Servo and regulatory problem in cases fifth and sixth are used for this study. It was found that GMC controller can implement this system efficiently.

**Table 3** Comparison of the results obtained from two-interacting tank system

Controller Sub VIs	Level 1 (cm)	Level 2 (cm)	IAE of Level 1	IAE of Level 2	Level Rise Time (sec)
PID	+5	+5	0.022547	0.000486	410
IMC			0.022654	0.053421	410
GMC			0.197535	0.046787	410
FLC			1.949123	1.604422	460
PID	-5	-5	0.032694	0.001421	360
IMC			0.014919	0.003442	300
GMC			0.017252	0.003980	230
FLC			2.643571	0.060090	420
PID	-5	+0	0.024761	0.000115	190
IMC			0.010717	0.003753	190
GMC			0.006517	0.007932	160
FLC			1.611564	0.576997	210
PID	+0	+5	0.019611	0.000602	320
IMC			0.009531	0.028904	280
GMC			0.005062	0.024192	330
FLC			1.127631	1.921952	350

Since all LabVIEW programs are controlled on web-based, next, the graphic user interfaces (GUI) are shown for each controller which controls one tank and two interacting tanks system respectively. Before control, set point is the firstly known in which process and each GUI has difference functions or buttons because each controller need difference data. For example, PID needs 3 tuning parameters and sampling time, IMC needs one tuning parameter and sampling time, GMC needs two tuning parameters, volumetric flow rate in of each tank, mass flow rate, and sampling time and FLC does not need anything.

Since each controller has different advantages and disadvantages. Therefore, this work, the advantages and disadvantages can be concluded into Table 4

Table 4 Comparison of all controllers

Controllers	Advantages	Disadvantages
PID	Wide-spread acceptance	Hard to tune
IMC	Have only one tuning parameter	Depend on mathematic model
GMC	Suitable for non-linear process	Depend on mathematic model
FLC	Does not need the tuning parameters	Low accuracy

In this work, the computer IP address 158.108.43.207 was used as a server computer. The other computer can control process on web-based when the server computer turned on. The procedure has been discussed in APPENDIX D. The following figure will show LabVIEW control on web-based with one tank and two-interacting tank system.

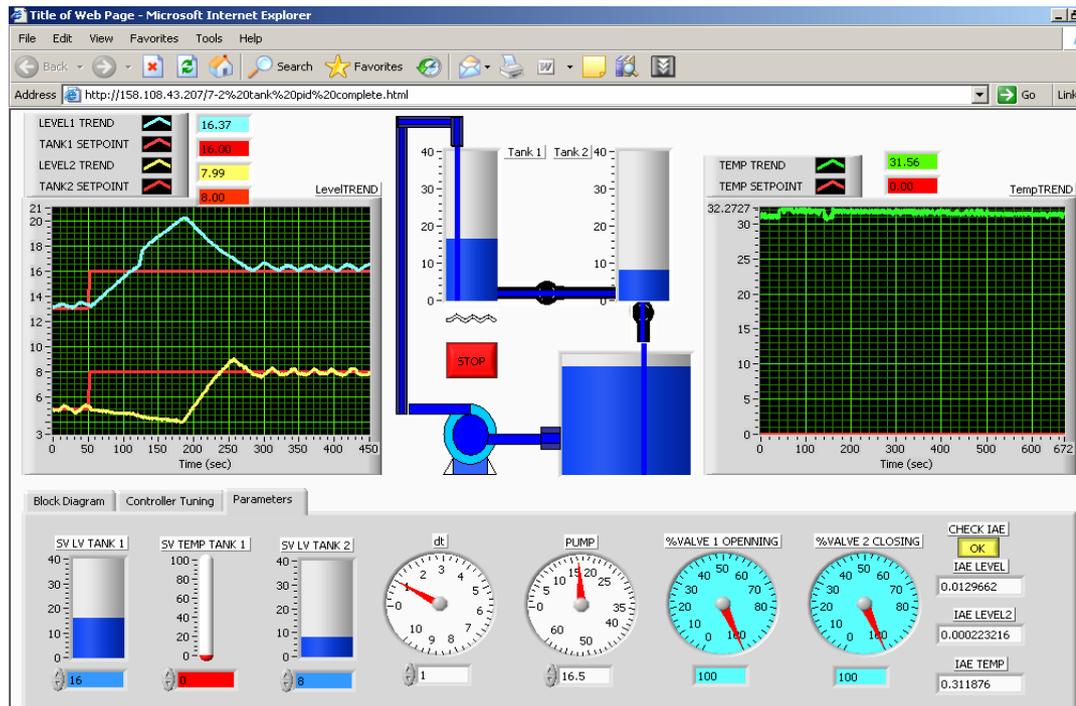


Figure 62 PID controls two-interacting tank on web-based

For the Block Diagram tab, it shows a PID close-loop control diagram

For the controller Tuning tab, there are three controllers to control process variable. The first controller controls the level of the first tank. The second controller controls the temperature of the first tank. The third controller controls the level of the second tank. Each controller has three parameters,  $K_c$ ,  $T_i$ , and  $T_d$ , must be tuned for the good response of control.

For the Parameter tab, Left graph shows level trends and them set points respectively. Right graph shows the temperature trend and its set point. This work set the level of tank one at 13 cm and tank two at 5 cm. Temperature is set at 30 degree Celsius. For the identical flow rate, the pump speed is set at 16.5 rpm ( $0.0033 \text{ m}^3/\text{min}$ ). Sampling time is set at 1 second. The valves opening and closing are shown on this tab. Check IAE button is used for when the accuracy of process is needed. Finally, Push stop button when the user wants to stop the operating.

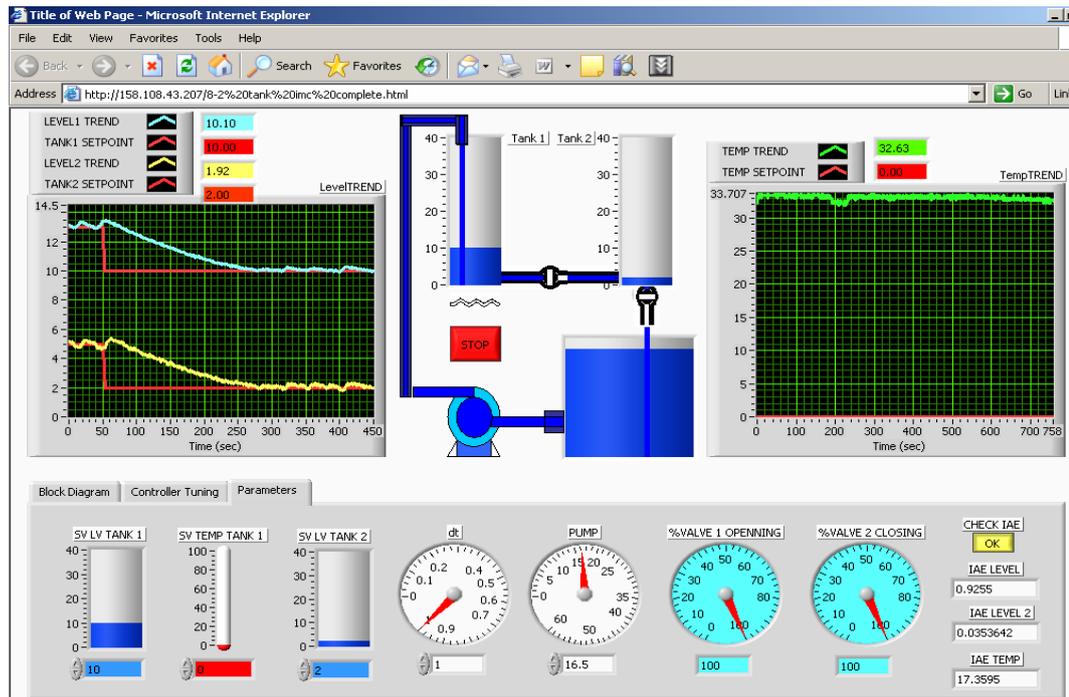
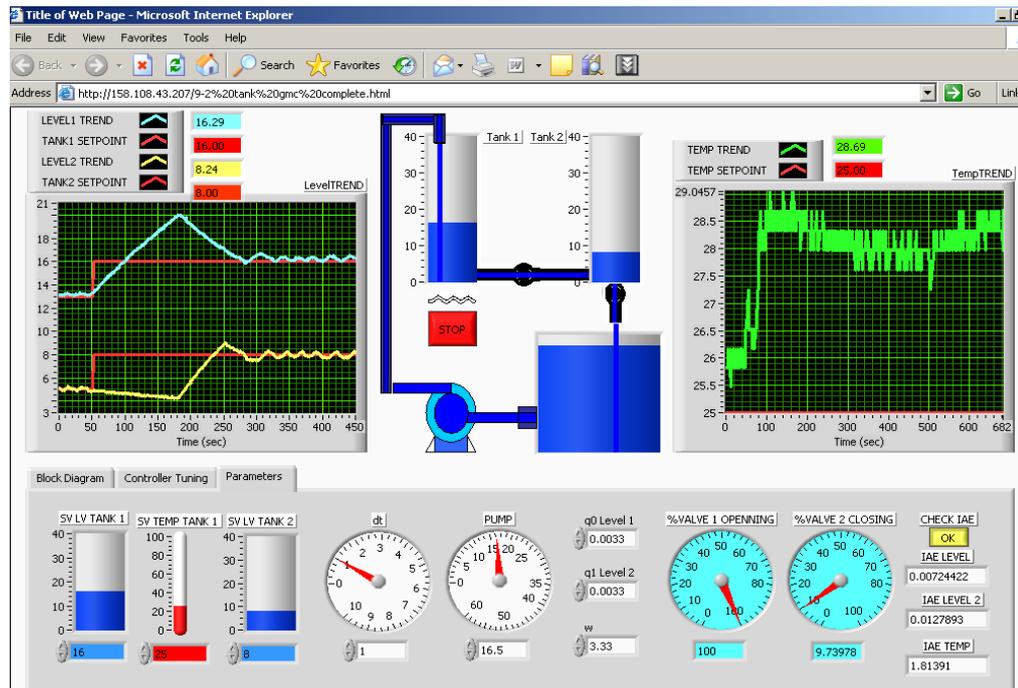


Figure 63 IMC controls two-interacting tank on web-based

For the Block Diagram tab, it shows a IMC close-loop control diagram

For the controller tuning tab, there are three controllers to control process variable. The first controller controls the level of the first tank. The second controller controls the temperature of the first tank. The third controller controls the level of the second tank. Each controller has only one parameter,  $K_c$ , must be tuned for the good response of control.

For the Parameter tab, Left graph shows level trends and them set points respectively. Right graph shows the temperature trend and its set point. This work set the level of tank one at 13 cm and tank two at 5 cm. Temperature is set at 30 degree Celsius. For the identical flow rate, the pump speed is set at 16.5 rpm ( $0.0033 \text{ m}^3/\text{min}$ ). Sampling time is set at 1 second. The valves opening and closing are shown on this tab. Check IAE button is used for when the accuracy of process is needed. Finally, Push stop button when the user wants to stop the operating.



**Figure 64** GMC controls two-interacting tank on web-based

For the Block Diagram tab, it shows a GMC close-loop control diagram

For the controller Tuning tab, there are three controllers to control process variable. The first controller controls the level of the first tank. The second controller controls the temperature of the first tank. The third controller controls the level of the second tank. Each controller has two parameters, K1 and K2, must be tuned for the good response of control.

For the Parameter tab, most GUI is same with PID and IMC. It is difference from flow rate, q0 level 1, q1 level 2, w, in this tab. These flow rates obtained from doing the experiments. Thus, all flow rates are shown as follow.

$$q_0 = 0.0033 \text{ m}^3/\text{min}$$

$$q_1 = 0.0033 \text{ m}^3/\text{min}$$

$$w = 3.33 \text{ kg}/\text{min}$$

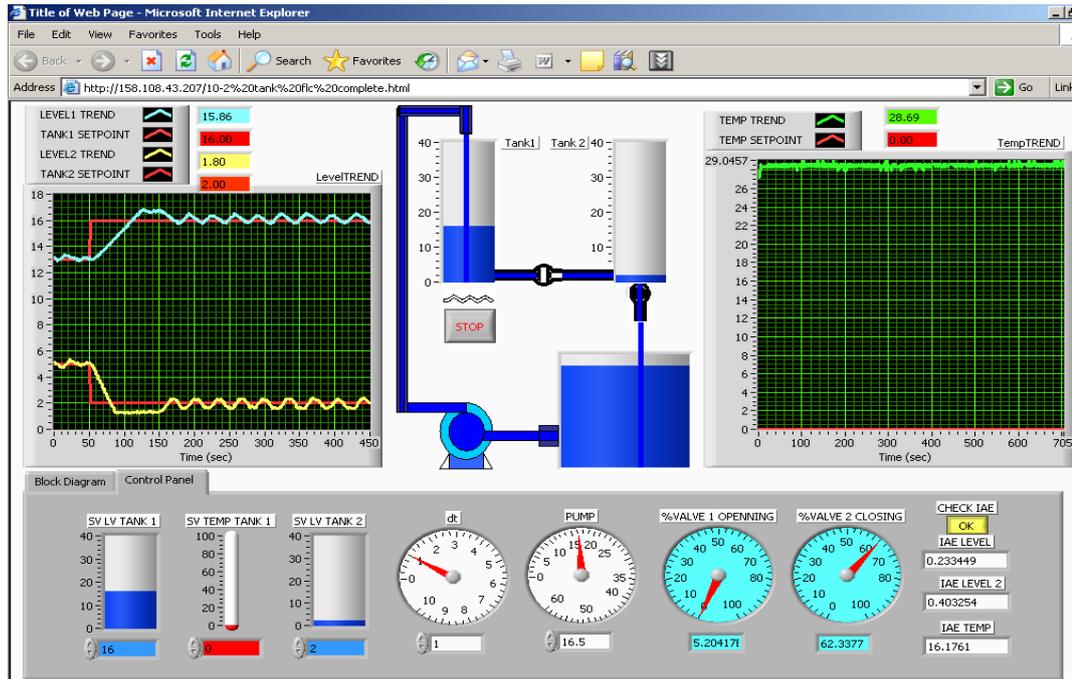


Figure 65 FLC controls two-interacting tank on web-based

For the Block Diagram tab, it shows a FLC close-loop control diagram

For the Control Panel tab, Left graph shows level trends and their set points respectively. Right graph shows the temperature trend and its set point. This work set the level of tank one at 13 cm and tank two at 5 cm. Temperature is set at 30 degree Celsius. For the identical flow rate, the pump speed is set at 16.5 rpm ( $0.0033 \text{ m}^3/\text{min}$ ). Sampling time is set at 1 second. The valves opening and closing are shown on this tab. Check IAE button is used for when the accuracy of process is needed. Finally, Push stop button when the user wants to stop the operating.

FLC control does not tuning parameter for control.

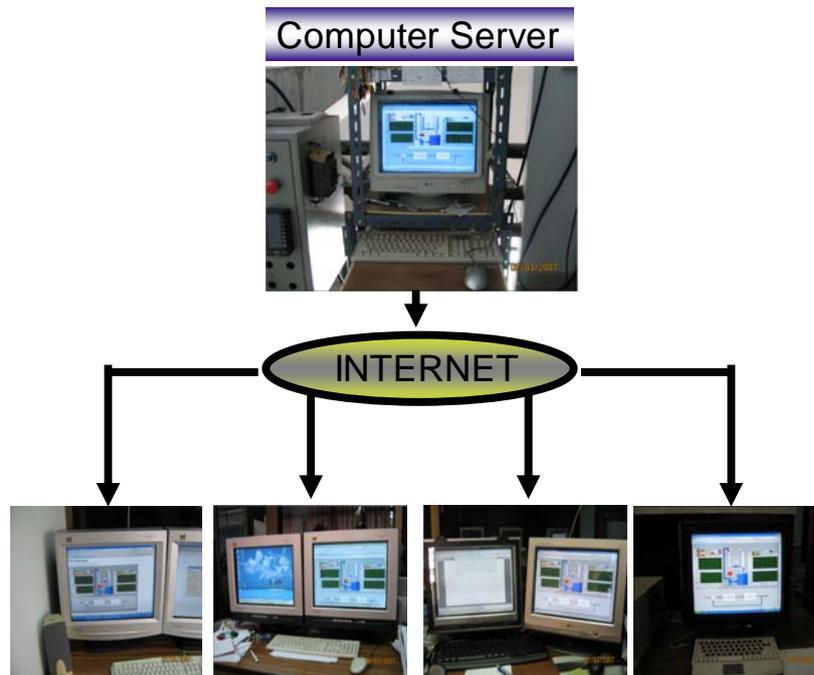


Figure 66 LabVIEW controls system via internet

The plant can be controlled by another computers at any place via the computer sever. Each computer can show the control response. The web based control does not have transport lag time in control. This program cannot be applied by another computer. The program can only be applied at the computer server. Therefore, the program should be general. This figure shows that the process can be controlled from anywhere that has internet.

It was found from these results that the PID controller is a reference controller. Since PID controller is an acceptably widespread implement in many industries for a long time. IMC and GMC controller is model based controller which want the validity of the model to be able efficient control. Furthermore, it is known well that IMC and GMC controller are derived from PI controller.

Level loop is easy to control because it has no transport lag time. The model of level loop is a linear that equation is not complicated. The model of temperature loop is non-linear because the effects of heat transfer. As the results, the energy balance around the tank is a non-linear model. GMC controller can be efficiently used in this system because GMC solve the manipulated variable directly thus the model cannot be linearized.

LabVIEW can control on web-based which has no transport lag time in control. If the tuning method is considered, PID controller has three tuning parameters, IMC controller has only one tuning parameter, GMC controller has two tuning parameters, and FLC has no tuning parameter but FLC has rule based for control instead. It depends on characteristic of the work what need in accuracy of control. PID is suitable for general case. IMC is better than PID but IMC needs the correctly model and IMC comfortable to tune. GMC is suitable for non-linear system and needs correctly model too. Finally, FLC needs rule based for control which no waste a time for tuning but the obtained response has accuracy less than other controllers.