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Modelling and Simulation of Water Level Control in The Tank with The Cascade Control System

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Abstract:

Simulators for measurement and control systems in the process industry have been made at the Research Center for Calibration, Instrumentation and Metrology, Indonesian Institute of Sciences. In this paper, simulate water level control in the tank with a cascade control system using simulink. By first making mathematical modelling for the components and instruments used in the simulator. For water flow rate measurement modelling using orifice plates and differential pressure transmitters, the gain obtained is 50508. The simulation results show that at water level control using a cascade control system, the change in water flow rate of 1 liter/minute to the tank does not affect the water level in the tank, or the water level in the tank remains stable.

Keywords — Mathematical model, simulation, water level control in the tank, cascade control system, water level stable.

I. INTRODUCTION

The simulator for industrial process measurement and control has been created in the research center for Calibration, Instrumentation and Metrology - Indonesian Institute of Sciences, the simulator can perform several simulations of measurement system and control system, that is, measurement of water flow rate, measurement of water level in the tank, water. Then, water flow control, water level control in the tank – single loop and using cascade control system. Furthermore, also the simulator can be used as a field device on a SCADA system. The simulator for measurement and control in the process industry is used for training for technicians or engineers in the process industry, as well as for research [1].

The liquid level control in the tank or in the container is widely used in industries, because among its purposes is, to know the number of raw materials, semi-finished products or finished products in a container by checking and adjusting the balance between input and output materials . also to monitor the production process or liquid level inside the container to ensure its quality and quantity [2].

The strategy for controlling the liquid level in the tank in industrial processes, which have long been done is to use a single loop feedback control system, using the Proportional Integral Derivative (PID) controller [3].

Furthermore, to enhance or improve of the conventional water level control results, to keep the water level in the tank fixed at the set point, due to the parameters of the changed plant, or the effect of the disturbance variables on the plant, several studies have been undertaken namely by Hong Ying Cao and Deng conduct research to control the water level with cascade control system using PLC (Programmable Logic Controller)[2]. Ashish Singh Thakur, Himmat Singh, and Sulochana Wadhwani make simulations of controlling water levels using fuzzy logic [4]. Shiro Masuda conducted research on PID controller gain tuning so that the water level in the tank following the disturbance reference model output [5]. Then, Jiri Vojtesek and Petr Dostal, controlling the volumetric flow rate of water that enters the tank via solenoid valves, using adaptive approach control with recursive identification [6].

II. THE SIMULATOR OF WATER LEVEL CONTROL USING THE CASCADE CONTROL SYSTEM

The simulator of cascade control system level-flow (LC-FC) in the industrial process as shown in Fig. 1 and illustrated by Piping & Instrumentation Diagram (P&ID) as shown in Fig. 2.

Fig. 1. The Instrumentation for measurement and control in industrial process simulator [1,7].

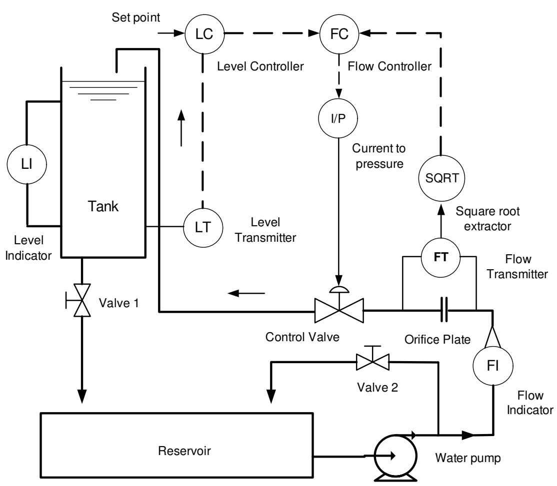


Fig. 2. P&ID of water level control using cascade control system, on the simulator [1,8].

As shown in Fig. 2, as well as figure 3, the cascade control system uses two PID controllers that is, the primary controller is the level controller (LC), and the slave controller is the flow controller (FC). There is also two processor loop that is, the primary process or the primary loop is the water level in the tank, and secondary process or secondary loop is the flow of water, where the process characteristics of the secondary process have a faster response than the primary process. [9,10,11].

The workings principle of the LC-FC cascade control system as shown in Fig. 2 and the block diagram of Fig. 3 are as follows:

The water level in the tank is categorized as the measured output variable or, the controlled output variable is measured by the level transmitter (LT). Then the output from LT becomes the input for LC, where the input value of LT will be set aside with the LC set point. If the result of the difference between the LC set point value and the input value of LT is not equal to zero, then the LC will feed the flow controller (FC), the input from the LC becomes the set point for the FC, then the FC will perform an action called the manipulated variable, due to an error between the FC set point value and the input value of the FT, where FT measures the flow rate that occurs. FC action is a command to the Control Valve (CV) to open or close the valve, then the result of the opening or closing of the valve, resulting in a decrease or increase in the flow rate of water, so that the water level in the tank will rise or fall, until the water level in the tank the same as the LC set point [8].

A. Modelling

The mathematical modelling of the process tank, level transmitter, and control valves have been described by the authors in a paper entitled characterization of a simulator for water level control in the tank - single loop [7].

Furthermore, Fig. 3 shows the water level control block diagram using the LC-FC cascade control system and using PID controller. The mathematical modelling for each component of the block diagram in Fig.3, based on the basic parameters of the components, as well as the specifications of the simulator instruments, as shown in Table 1.

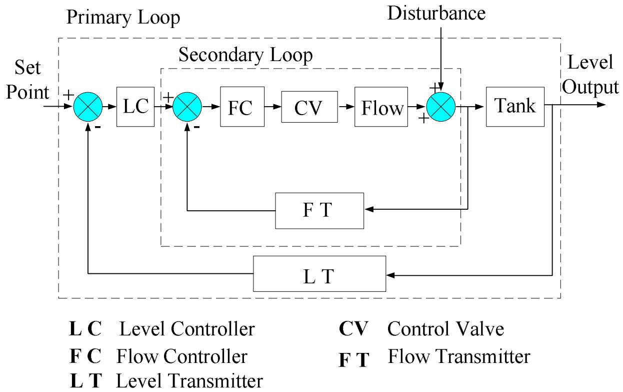


Fig. 3. Block diagram of water level control using cascade control system [1,8,9,10].

TABLE 1
BASIC PARAMETERS AND INSTRUMENTS SPECIFICATION OF THE SIMULATOR [1,7]

Components	Specification
Tank high	1.25 meter
Maximum height measurements of water level (LH)	0.8 meter
Minimum height measurements of water level (LH)	0.2 meter
The diameter of the tank (D)	0.25 meter
The maximum water flow rate into the tank (Q)	19 liters/minute
The diameter of pipe and water valve out tank (d)	± 0.5 inch
Level Transmitter (LT)	Input 0 - 100 IN H_2O Output 4 – 20 mA
Flow Transmitter (FT)	Input 0 - 150 IN H_2O Output 4 – 20 mA
Curren to pressure (I/P)	Input 0,2 – 1 bar Output 4 – 20 mA
Control valve	Diameter 0,5 inch
The inner diameter of the orifice plate (d)	0.34 inch

B. *Process Tank*

Process tank is a representation of the water level changes in the tank. The tank input is the water flow rate, q_{in} (m^3/s), while the output is the water level in the tank, h (m). The maximum q_{in} is 19 liters/minute or 0.0003154 m^3/s, and the maximum water level in tank h (m) is determined as high as 0.8 m. The relationship between q_{in} and h is shown in the block diagram in Fig. 4 [1,7],

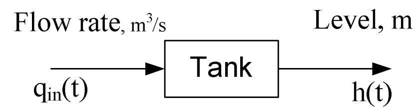


Fig. 4. Block diagram of the process tank [7,12].

Furthermore, the process tank as shown in Fig. 2 is modeled with a gravity tank model, then the modelling results in Laplace transform as shown in Fig. 5,

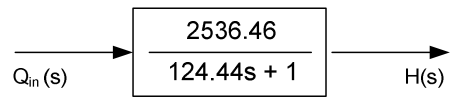


Fig. 5. Block diagram of the model of the process tank [7].

C. *Level Transmitter (LT)*

Level Transmitter (LT) is an instrument to measure water level in the tank. As for the type of LT used in the simulator is differential pressure transmitter as shown in Fig. 6,

Fig. 6. Differential pressure transmitter for level measurement in the tank on simulator [1].

The differential pressure transmitter measures the level h by measuring the pressure difference P between the pressure inside the tank caused by the water level with the relative pressure to the atmosphere, and the output signal of measurement of differential pressure transmitter of is 4 – 20 mA, as shown in Fig. 7 [3,13],

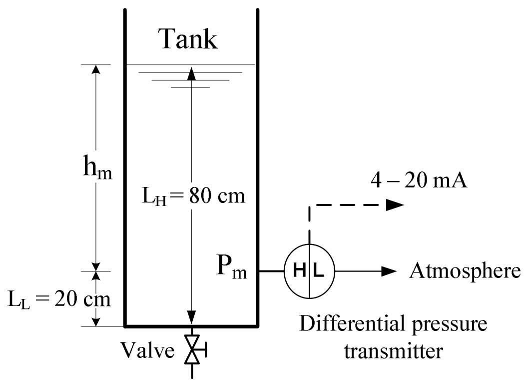


Fig. 7. Measuring the water level in the tank on the simulator [1,7].

Fig. 7 shows the LT of the simulator measuring the water level in the tank between 0.2 - 0.8 meter, or the water level in the tank measured by LT between 0 - 0.6 meter.

Then, the result of level measurement modelling using a differential pressure transmitter is represented in the block diagram as shown in Fig. 8, and the modelling results in Laplace transform as shown in Fig. 9,

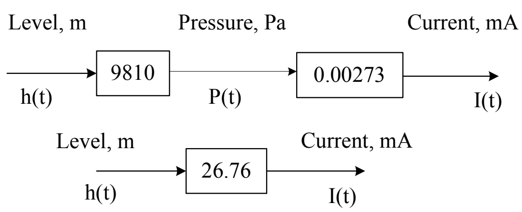


Fig. 8. Block diagram of the level measurement model on the simulator [7].

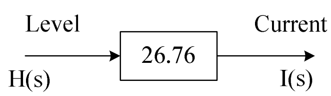


Fig. 9. Block diagram of the level measurement model on the simulator in Laplace transform [7].

Then based on Fig. 9, gives water level input 0 - 0.6 meter and output plus offset 4 mA, using excel then the result of the relation between level measurement input, with output current as shown in Fig. 10,

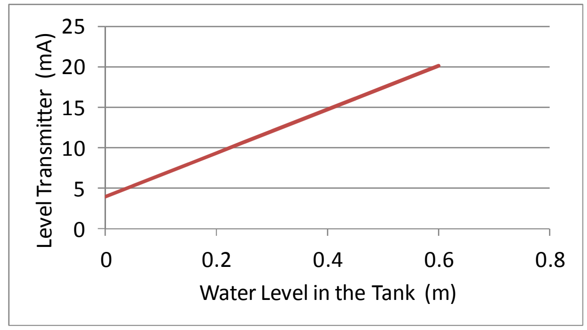


Fig. 10. Relationship curve between level measurement and current output of level measurement using LT.

Or, the relationship between the level measurement with the output current, on the measurement level using LT, using Eq. 1, [1,3]

$$LT_{out} = \left(\frac{L - L_{min}}{L_{max} - L_{min}}\right)(LT_{max} - LT_{min}) + LT_{min} \quad (1)$$

Where, L is the water level in the tank, L_{max}= 0.8 m, L_{min} = 0.2 m, LT_{out} = LT output in mA, LT_{min} = 4 mA, LT_{max} = 20 mA.

D. Control Valve

The control valve as an actuator to control the flow rate of water into the tank, as shown in Fig. 11. The valve is mounted to the pipe where water flows through the valve body. The size of the opening that the liquid flows through is given by the position of the valve stem. This is controlled by changing the pressure on one side of the diaphragm which causes a change in the position of the plug. It can be done because it is controlled by the pressure changes that occur in the diaphragm, it causes the position of the plug changed. The pressure signal to the diaphragm is obtained from the current to pressure converter (I/P), it is a device that converts an electrical signal 4 - 20 mA to a proportional pressure signal output 0.2 - 1 bar or 20 - 100 kPa, as shown in the block diagram in Fig. 12, as well as the modelling results for each block [7,12],

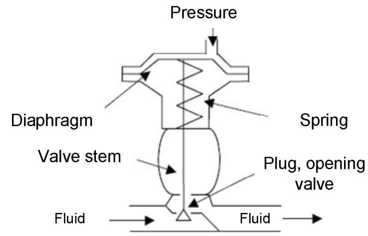


Fig. 11. Diagram of Control Valve [7,12].

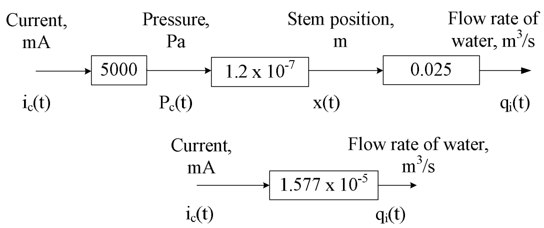


Fig. 12. Block diagram of the control valve component values [7].

And, modelling results in Laplace transform as shown in Fig. 13,

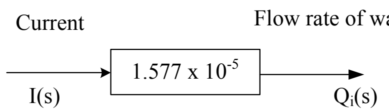


Fig. 13. The block diagram of the control valve model in the simulator in Laplace transform [7].

E. Flow measurement

Measurement of water flow in the simulator using the principle of the pressure difference, using orifice plate mounted on the pipe, the flow rate of water flowing in the pipeline, when passing through the orifice plate would cause a pressure difference [1,3,13].

The pressure difference occurs is between on the flow of water into the plate orifice, with at the flow of water out of the plate orifice, the pressure on the side of inflows to the plate orifice is higher than the pressure in the flow out of the plate orifice, respectively given notation H (high) and L (Low), as shown in Fig. 16.

Furthermore, the pressure difference that occurs is measured using an FT type of pressure difference, with the output of the FT is 4-20 mA. Then, because the relationship between the flow rate by the output pressure difference that occurs is quadratic, then used a Square Root Extractor, where the Square Root Extractor is a function of the roots so that the output of the FT into linear [13], as shown in Fig. 15 and 16.

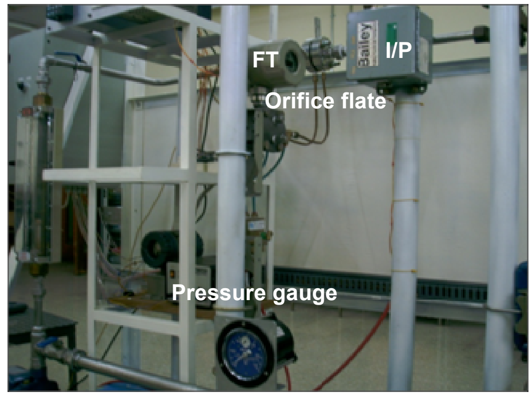


Fig. 14. Water flows measurement using orifice plate and flow transmitter [1].

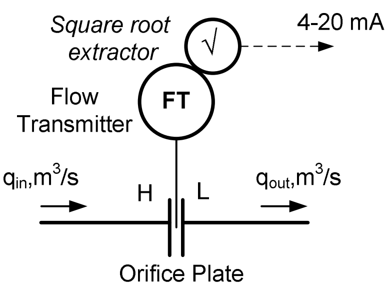


Fig. 15 . P&ID of water flow measurement using orifice plate and flow transmitter.

Furthermore, from Fig. 15 for modelling the flow measurements based on Eq. 2,

$$Q = 5.667\ SD^2 \sqrt{\frac{h}{s.g}} \qquad (2)$$

Where Q is the flow rate in GPM, h is the pressure difference that occurs between the H side and the L side in IN H_2O, s.g is the specific gravity of water =1 [3,13], then, in the block diagram as shown in Fig. 16,

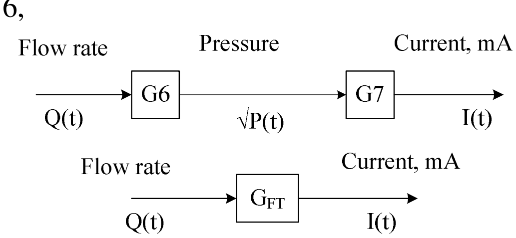


Fig. 16. Block diagram of the flow measurement using orifice plate and flow transmitter

Furthermore, from Eq. (2) defining K as shown in Eq. (3),

$$K = 5.667\ SD^2 \quad (3)$$

Where D is the diameter of the pipe in inch and S is the sizing factor.
Since the diameter of the pipe used in the simulator is 0.5 inches with the schedule of 10, so, D is obtained in table A-4. Standard dimensions for welded or seamless steel pipe, page 452 [3], D = 0.674 inch.
And, the sizing factor is obtained by calculating the ratio of beta β, as shown in Eq. (4) [3],

$$\beta = \frac{d}{D} \quad (4)$$

Where d is the diameter of the hole of the orifice plate, d = 0.34 inch.
Then, by substituting the d and D values to Eq. (4), so, the beta ratio is obtained,
β = 0.504.
Then, for β = 0.504, so, sizing factor of the orifice plate is obtained by using table 4.2. Sizing factor, page 104 [3],
S = 0.1600.
Then, by substituting the values of S and D into Eq. (3), so, K is obtained,
K = 0.4118.

Furthermore, to simplify the Eq. (2), the Eq. (3) is substituted into the Eq. (2), its results as shown in Eq. (5),

$$Q = K\sqrt{\frac{h}{S.g}} \quad (5)$$

Thus, using Eq. (5), G6 of the block diagram of Fig. 16 as shown in Eq. (6),

$$G6 = \frac{1}{K} \quad (6)$$

And, the block diagram in Fig. 16 becomes as shown in Fig. 17,

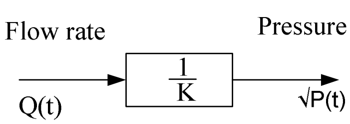


Fig. 17. Block diagram of the flow measurement model

using orifice plate

Then, since the value of K that has been obtained through the calculation process by involving imperial unit, Then, calculate the value of K through the calculation process by using the units of the International System (SI). Calculation of the value of K using excel, based on Eq. (3) as shown in table 2.
The calculation process in table 2 described as follows:

a. Determine the flow rate (Q) from 0 - 19 liters/min, then convert Q to m^3/s and GPM.
b. Substitute each value of Q in GPM and the value of K = 0.4118 to Eq. (2), so the pressure values (h) in IN H_2O are obtained.
c. Convert each h value in IN H_2O to Pascal, then substitute each h value in Pascal and each Q in m^3/s into Eq. (2), so that K is obtained,
K= 1.6460 x 10^{-6}

TABLE 2
CALCULATION PROCESS TO OBTAIN K VALUES FROM SI UNITS

Flow rate (Q)			**Pressure ($\sqrt{h}$)**		**K**
Liter/ minute	m^3/s	GPM	IN H_2O	Pascal	
0	0	0	0	0	0
5	0.000083	1.316	3.195	15.957	1.646 x 10^{-6}
7	0.0001162	1.842	4.472	70.594	1.646 x 10^{-6}
9	0.0001494	2.368	5.753	90.764	1.646 x 10^{-6}
11	0.0001826	2.894	7.029	110.934	1.646 x 10^{-6}
13	0.0002158	3.421	8.307	131.104	1.646 x 10^{-6}
15	0.000249	3.947	9.586	151.274	1.646 x 10^{-6}
17	0.0002822	4.473	10.863	171.444	1.646 x 10^{-6}
19	0.0003154	4.999	12.141	191.613	1.646 x 10^{-6}

Then, substitute the value of K= 1.6460 x 10^{-6} to Eq. (6), G6 is obtained, G6 = 607525.
And, the block diagram for G6 becomes as shown in Fig. 18,

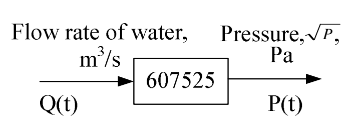


Fig. 18. Block diagram of the modelling result of flow rate measurement using an orifice plate

Furthermore, calculating the value of G7 of Fig. 16, rewrite the equation (5) by replacing the notation, so that as shown in equation (7),

$$Q_{\max\_FT} = K\sqrt{P_{\max\_FT}} \tag{7}$$

Where Q_{max_FT} is maximum flow rate that can be measured by the FT and P_{max_FT} is the maximum pressure output of FT measurement.
Then, based on the FT specification in table 1, the maximum pressure output of FT measurement is P_{max_FT} = 150 IN H_2O or P_{max_FT} = 37363.34 Pa.
Then, substitution P_{max_FT} = 37363.34 Pa and K = 1.646 x 10^{-6} to Eq. (7), thus, the maximum flow rate that can be measured by the FT is obtained,
Q_{max_FT} = 0.00031817 m^3/s.

Then, the maximum pressure output of the FT, from the measurement of the flow rate, is obtained when the maximum flow rate occurs, as shown in Eq. (8),

$$P_{max} = \frac{P_{\max\_FT}}{Q_{\max\_FT}}\, Q \tag{8}$$

Where, Q = 0 – 19 liters/min or 0 - 0.0003154 m^3/s, thus P_{max} is obtained,
P_{max} = 37038.05 Pa.

Then, the value of G7 is obtained by using (9),

$$G7 = \frac{I}{\sqrt{P}} = \frac{I_{max}-I_{min}}{\sqrt{P_{max}-P_{min}}} \tag{9}$$

Where P_{min} = 0, I_{max} = 20 mA and I_{min} = 4 mA, So, G7 is obtained,
G7 = 0.083 mA/Pa.

Furthermore calculate the G_{FT}, based on Fig. 16, G_{FT} is obtained through the Eq. (10),

$$G_{FT} = G6 \; x \; G7 \tag{10}$$

So, G_{FT} is obtained,
G_{FT} = 50507.9586 ≈ 50508 mA/ m^3/s.
And, the block diagram in Fig. 16 becomes,

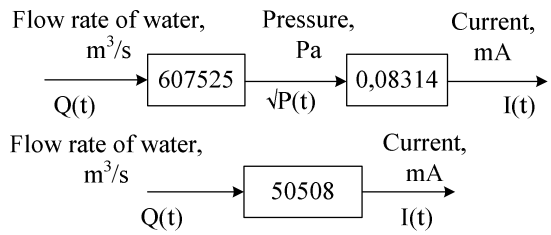


Fig. 19. Block diagram of the flow rate measurement model on the simulator

Then, the flow measurement model in Laplace transforms as shown in Fig. 22,

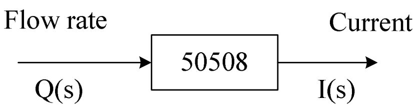


Fig. 20 . Block diagram of the flow measurement model on the simulator in Laplace transform

Furthermore, from the block diagram of Fig. 19, the simulation of flow measurement using excel, with the input water flow rate of 0 - 0.0003154 m^3/s and offset 4 mA is added for the FT output, the simulation result as shown in Fig. 21,

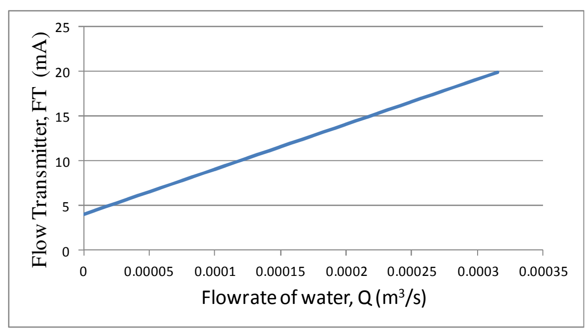


Fig. 21. The curve of relationship between flow rate with output current from the flow measurement

Rewriting the Eq. (3) by replacing the notation, so the equation obtained the relationship between the input flow rate, with the output current, as shown in Eq. (11),

$$FT_{out} = \left(\frac{Q-Q_{min}}{Q_{max}-Q_{min}}\right)(FT_{max} - FT_{min}) + FT_{min} \tag{11}$$

Where, Q is the flow rate of water flowing into the tank, Q_{max}= 0.0003154 m^3/s, Q_{min} = 0.
FT_{out} = FT output in mA, FT_{min} = 4 mA, FT_{max} = 20 mA.

III. SIMULATION OF THE WATER LEVEL CONTROL AND DISCUSSION

Simulation using simulink of water level control results using a cascade control system, compared to the simulation results of a water level control - single loop. Each system will be compared if there is no disturbance and if given a disturbance that is, the increase and decrease of the flow rate of water flowing into the tank.

Then, as the modelling results for the process tank, LT, FT, flow and control valve, are subsequently substituted into the block diagram of the cascade control system of a level-flow in Fig. 3, the results as shown in Fig. 22,

Fig. 22.Block diagram of the level-flow cascade control system with the modelling results on the simulator

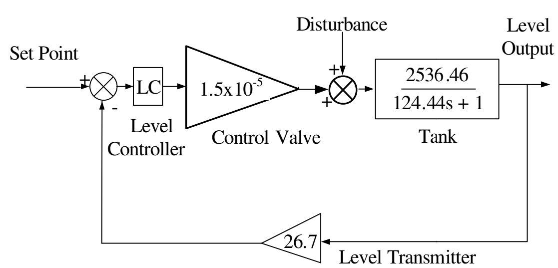


Fig. 23. Block diagram of the level control-single loop with the modelling results on the simulator

Simulation by tuning first, to Level Controller (LC) and Flow Controller (FC) of the cascade control system. Likewise for Level Controller (LC) of water level control single-loop [3,8,9,11].

Then, the simulation is done by giving the set point to LC input step, with an amplitude of between 4-20 mA, while the relationship between the set point with the water level occurring in the tank using the Eq. 12,

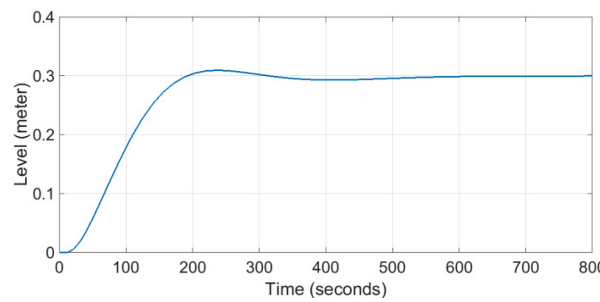
$$L_o = \left(\frac{SP - SP_{min}}{SP_{max} - SP_{min}}\right)(L_{max} - L_{min}) + L_{min} \quad (12)$$

Where, SP is *set point*, SP_{max} = 20 mA, SP_{min} = 4 mA, L_o is water l*evel* in the tank, L_{min} = 0, L_{max} = 0.6 meter.

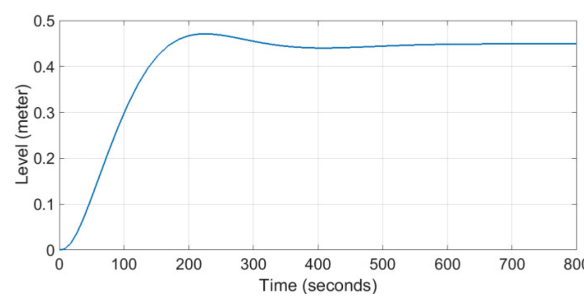
F. Simulation without disturbance

In this paper, simulation by giving the water level set point in the tank, as high as 0.3 m and 0.45 m, then using Eq. (12) obtained the set point of step input at LC are 12 mA and 16 mA respectively.

The simulation results for water level control using cascade control system as shown in Fig. 24, while for water level control - single loop as shown in Fig. 25,



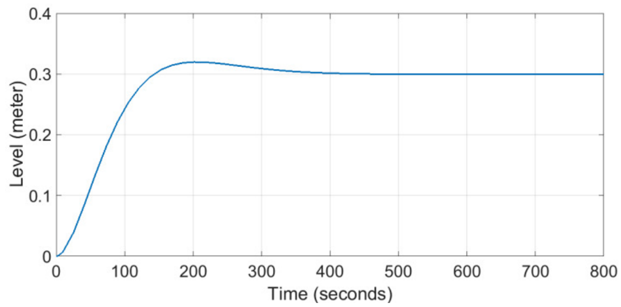
a. Set point water level in the tank, as high as 0.3 m.



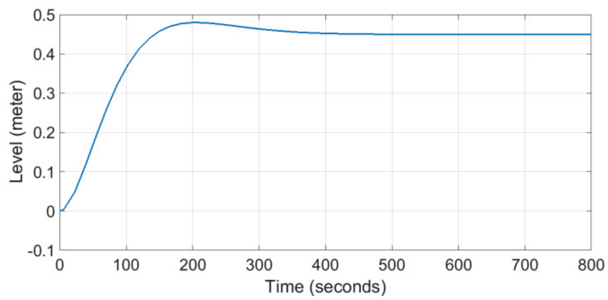
b. Set point water level in the tank, as high as 0.45 m.

Fig. 24 . Response curve of water level control using cascade control system, no disturbance.

Based on Fig. 24.a. for set point 12 mA it is known that the time required by water to reach a height of 0.3 m in the tank, or the settling time is about 600 seconds, and there is lag about 12 seconds. As for the 16 mA set point in Fig. 26.b. the time required by the water to reach a height of 0.45 m in the tank, also about 600 seconds, and there is a lag of about 2 seconds.



a. Set point water level in the tank, as high as 0.3 m.



b. Set point water level in the tank, as high as 0.45 m.

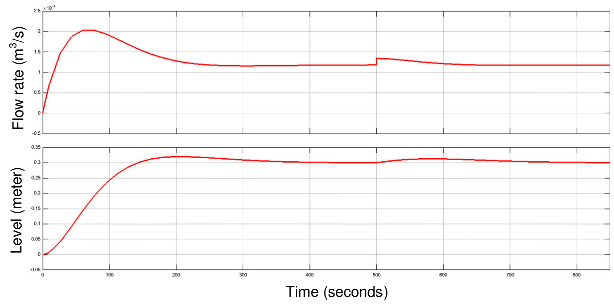
Fig. 25 . Response curve of water level control – single loop, no disturbance.

Then, in Fig. 25.a. for 12 mA set point it is known that the time required by the water to reach a height of 0.3 m in the tank is about 450 seconds, and there is a lag of about 0.06 seconds. While in Fig. 25.b. for set point 16 mA the time required by water reaches a height of 0.45 m in the tank, also about 450 seconds, and there is lag about 0.05 seconds.

G. Simulation with disturbance

The water level in the tank is given disturbance, assuming there are an increase and a decrease in flow rate of water into the tank.

To simulate the increase or decrease of the flow rate of water into the tank, based on Fig. 22 and 23, and by using simulink, the disturbance is given by step input for water level control – single loop, with amplitude is 0.000016, that is assuming increasing flow rate of water equal to 0.0000166 m^3/s or equal to 1 liter/minute, then, step input with amplitude is –0.000016, that is assuming of decrease flow rate of water to the tank is equal to 0.0000166 m^3/s, the simulation results as shown in Fig. 26. Then, for the simulation of water level control using cascade control system with disturbance, the disturbance is given by pulse generator input, amplitude are 0.000016 m^3/s and -0.000016 m^3/s, simulation results for the cascade control system as shown in Fig. 27,



a. Increase the flow rate of water to the tank

b. Decrease the flow rate of water to the tank

Fig. 26 . Response curve of water level control – single loop, with disturbance

Fig. 26. a. showing an increase in the flow rate of water to the tank in the seconds to 500, the increase in the flow rate of water causes the water level in the tank to rise for about 300 seconds or about 5 minutes, the level changes from 0.3 m to a maximum of about 0.3126 m.

Likewise, as shown in Fig. 26.b. when a decrease in the flow rate of water to the tank occurs, the resulting drop in water causes the level of water in the tank to decrease, for about 320 seconds or about 5.3 minute, altitude changes from 0.3 m to a maximum of about 0.2867 m.

Fig. 27. Response curve of water level control using cascade control system, with disturbance.

Fig. 27 shows, if the water level in the tank stabilizes at 0.3 m, then, seconds to 500 there is an increase in the flow rate of water to the tank, as a result of increased water flow rate into the tank, it appears that the water level in the tank does not change, just like in the seconds to 650, a decrease in the flow rate of water to the tank, consequently not changing the water level in the tank, also for the next seconds.

IV. CONCLUSIONS

By comparing the results of the simulation of water level control in the tank on the simulator, between the cascade control method with single-loop, it is obtained:

For the simulation without disturbance, it is known that, for water level control-single loop, the time required to achieve settling time at the desired set point is faster than the water level control system by using the cascade method.

Then, for a simulation by providing a disturbance of the increase and decrease of the flow rate of water to the tank as much as 1 liter/minute, it is known that, on water level control- single loop, there is an increase or decrease of water level in the tank, about 5 minutes and 5.3 minutes. While on the water level control system by using the cascade method, does not affect the water level in the tank.

Thus, if the desired level of liquid in the tank remains stable, to the disturbance caused by the increase or decrease of the flow rate of the liquid to the tank, it is preferable to use a liquid level control with a cascade control system.

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