Technology
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Master's in Automation and IT

Instructor: Prof. Dr. Rainer Scheuring

Assignment 3 : Valve Model

Author:	*Student ID*
Bhagyashree Popat Zaware	11160161
Maryam Jahangir	11159172
Muhammad Ali	11160562
Muhammad Munam Farooqui	11160281

Module : Modelling and simulation of continuous systems

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Contents

1 Problem Statement

Develop a simulation model of system with a pipe, a nonlinear valve and a flow controller

Steps:

1: Develop a UniSim model (approximation for reality), where Pipe delta P is bigger than valve delta P.

2: Develop mathematical equations for and identify the parameters of the pipe and the valve.

3: Develop a Scilab (Xcos) model that represents the UniSim model(reality). Focus on pressure flow relations.

4: Develop a PID flow controller for the Scilab (Xcos) model.

5: Do flow control step tests with UniSim and Scilab (Xcos). Compare your results.

6: Optional: Use a linear and an equal percentage valve curve. Compare the closed-loop control behavior of these cases.

Basic valve equation:

$$Flow_{valve} = k_v * \sqrt{density * valve\ \ opening * (Pin - Pout)} \tag{1}$$

Basic pipe equation:

$$\Delta P_{pipe} = \frac{k}{density} * Flow^2 \tag{2}$$

2 Step 1: UniSim Simulation model

We are employing the UniSim simulation for modeling, which includes a system consisting of a pipe and a non-linear (equal percentage) control valve along with a PI flow controller. Our objective is to examine the behavior of this continuous process, analyze the different elements of the system, and develop a mathematical model within the Simulink simulation environment in next steps.

UniSim model is as shown in *Fig. 1*

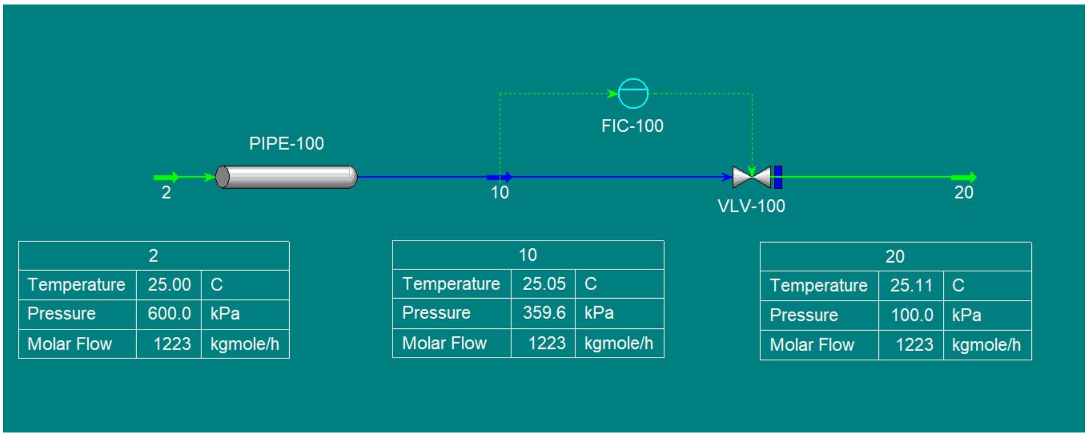

Figure 1: Simulation Model

The design parameters of the main components in the UniSim model are listed below.

Item	Parameter	Value	Unit
Material input stream 2	Pressure	600	kPa
Material output stream 20	Pressure	100	kPa
Fluid	Mass density	1008	kg/m^3
Pipe PIPE-100	Length	20	m
	Outer diameter	40	mm
	Inner diameter	35	mm
	Material	Mild steel	-
	Pipe flow model	Simple pipe friction model methoc	-
	Pipe friction model	Turbulent	-
Valve VLV-100	Operating Characteristic	Equal percentage	-
	Actuator dynamics	first order	-
	Actuator time constant	10	s
	K_v	To be calculated	
Controller	PV min	0	kg/h
	PV max	24580	kg/h
	Kc	1	-
	Ti	10	-
	Td	-	-

Figure 2: Design Parameters in UniSim

2.1 Pipe details used in model:

The physical specifications and dimensions of the pipe define the pressure drop through it as the fluid flows through it. The design of the pipe consists of selecting the internal diameter, the external diameter, the thickness and the length of the pipe. These parameters are chosen in such a way that the pressure drop in the pipe is bigger than the pressure drop in the valve.

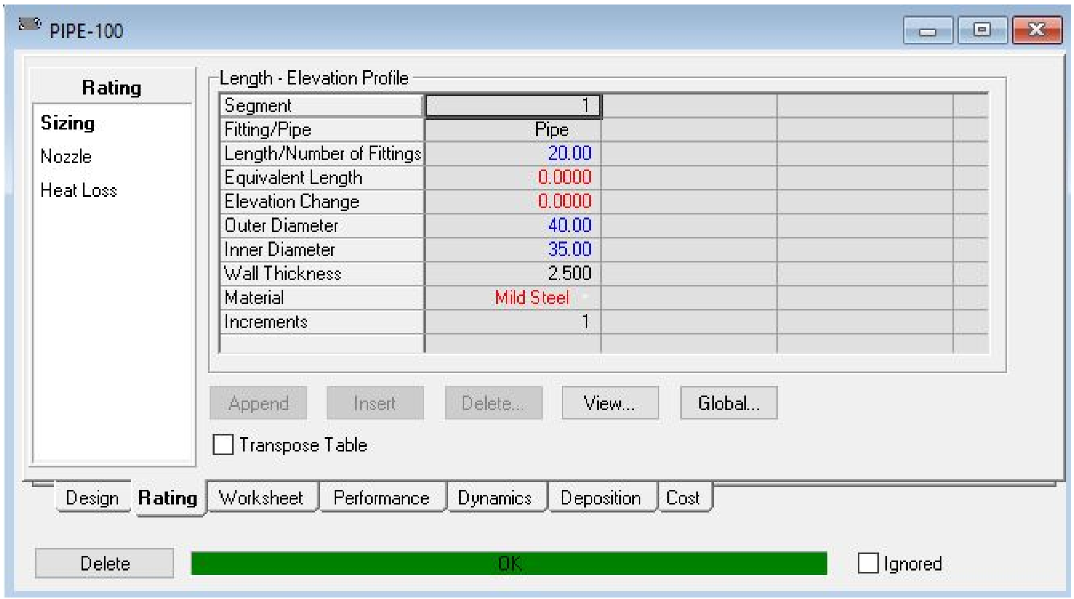

Figure 3: Pipe specifications

We consider to work with turbulent flow and the model chosen was a "Simple Pipe Friction Model Method" for fluid flow dynamics in the pipe.

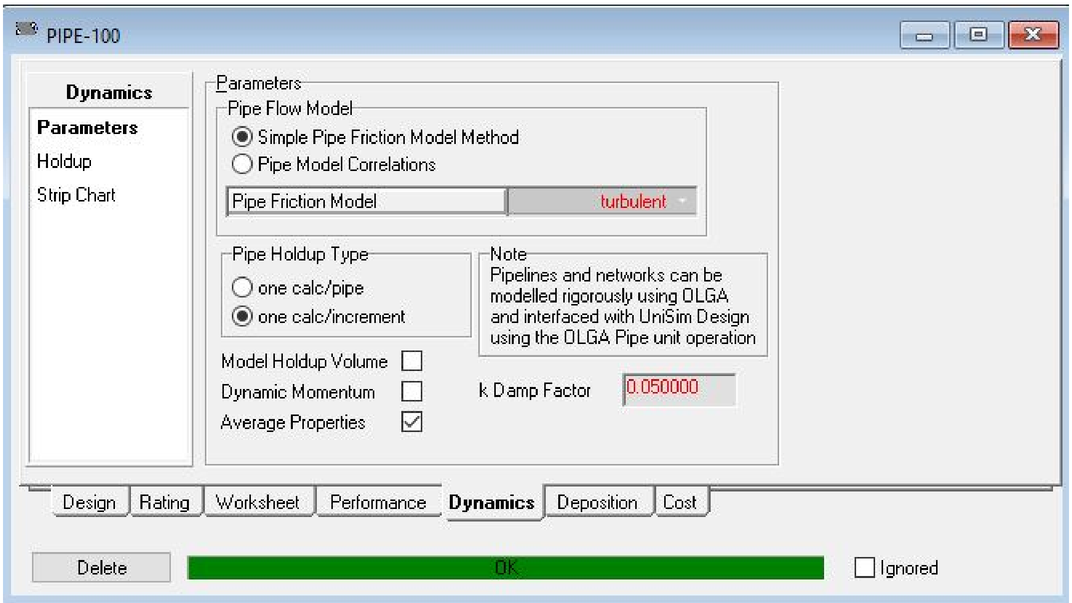

Figure 4: Pipe dynamics

2.2 Valve details used in model:

For the valve specifications, the manufacturer chosen was "Universal Gas Sizing". The first experiment will be performed using the equal percentage valve with a Cv value of 20. At the later stage, the linear valve will also be used.

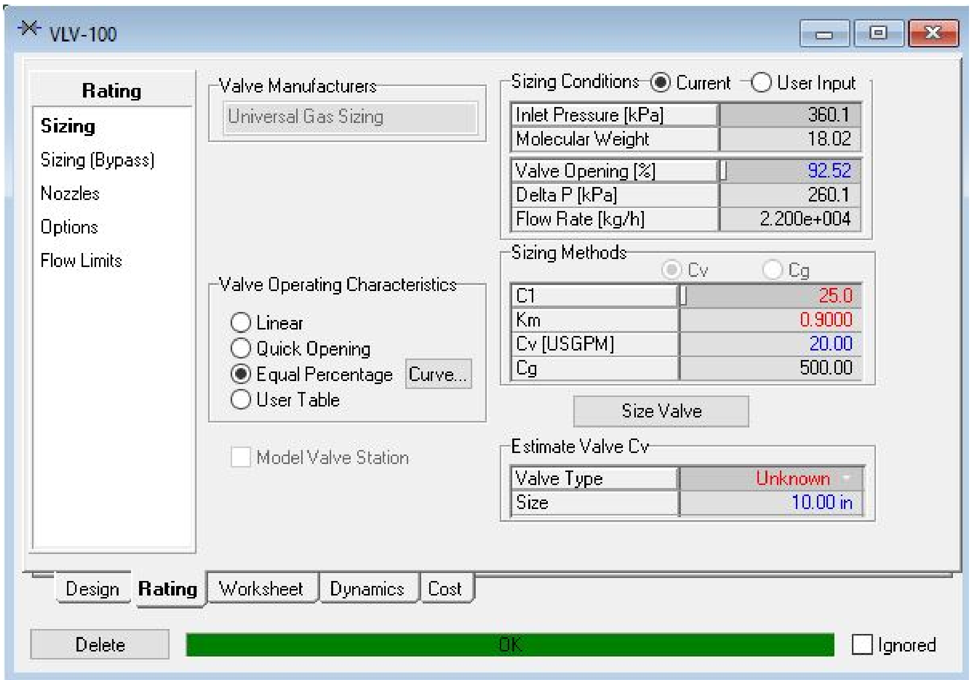

Figure 5: Valve specifications

The following illustration demonstrates how Kv, which is also known as Cv, is a function of OP. As a result, Kv has a different value depending on the valve opening. The curve describes how the equal percentage valve will behave.

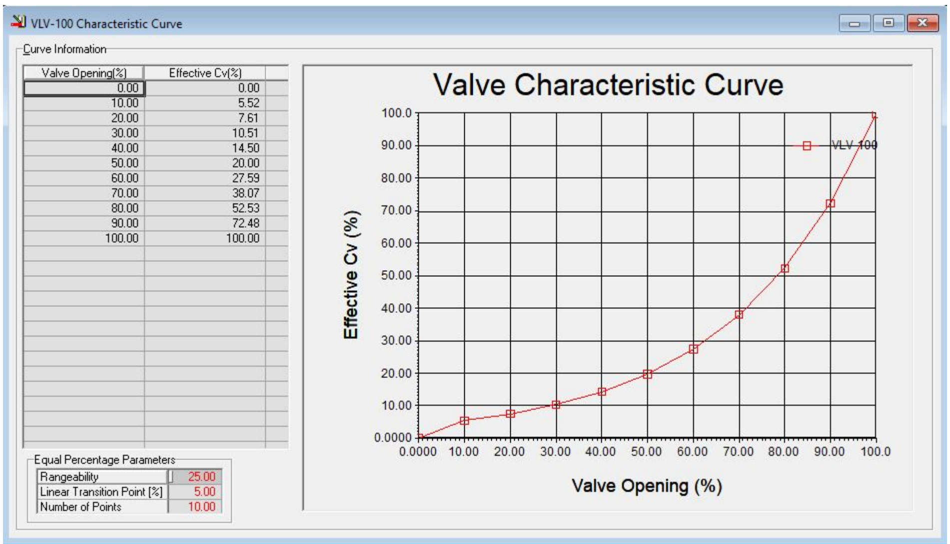

Figure 6: Valve curve

2.3 Controller used in model:

Following are the parameters of PI controller used in UniSim model.

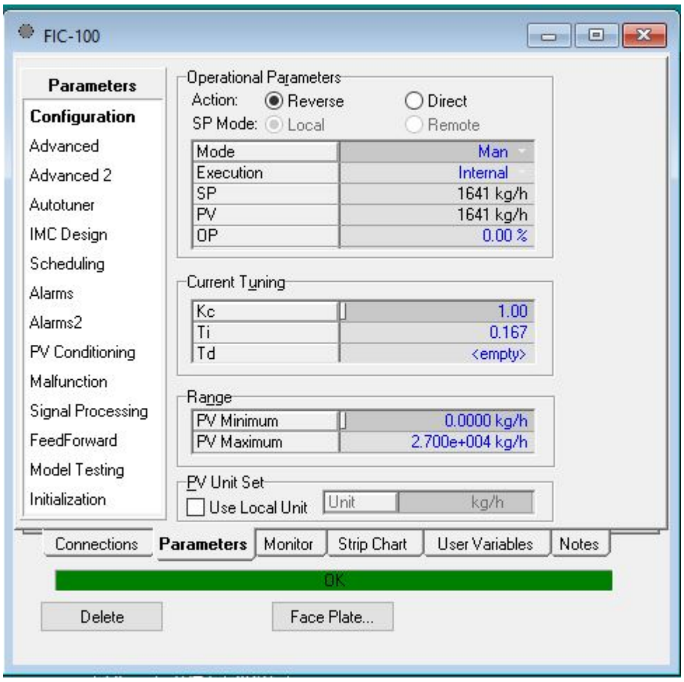

Figure 7: Actuator dynamics

As seen in the following figure, the actuator's dynamic was chosen to be First Order behavior with a time constant of 10s.

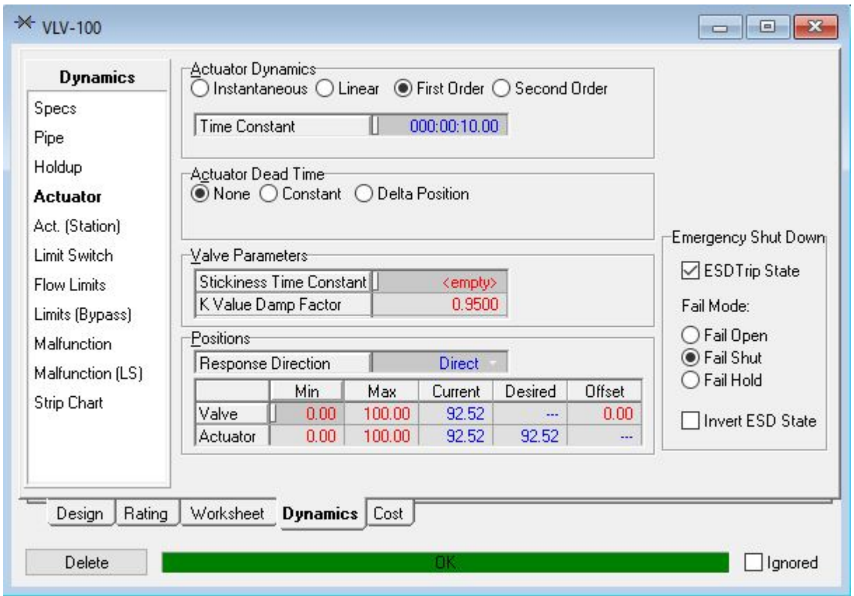

Figure 8: Actuator dynamics

3 Step 2: Mathematical Modelling

3.1 Flow Equation

We will start the modelling from the two basic equations for pipe and valve as stated in problem statement.

$$F = K_v * \sqrt{\rho * \Delta P_v} \tag{3}$$

This can be reformulated as:

$$\Delta P_v = (\frac{F}{K_v})^2 * \frac{1}{\rho} \tag{4}$$

The second basic equation is for pipe, which is as follows:

$$\Delta P_p = \frac{K_p}{\rho} * F^2 \tag{5}$$

Since,

$$\Delta P_{sys} = P_1 - P_3 \tag{6}$$

And,

$$\Delta P_{sys} = \Delta P_p + \Delta P_v \tag{7}$$

Substituting *eq. 4*, *5* and *6* in *eq. 7*, we get,

$$P_1 - P_3 = \frac{K_p}{\rho} * F^2 + (\frac{F}{K_v})^2 * \frac{1}{\rho} = \frac{F^2}{\rho} * (K_p + \frac{1}{K_v^2}) \tag{8}$$

On re-arranging, we get,

$$F = \sqrt{\frac{\rho * (P_1 - P_3)}{K_p + \frac{1}{K_v^2}}} \tag{9}$$

eq. 9 represents final flow equation used in simulation model.

3.2 Dynamic Equation

The dynamic behaviour in the model due to the actuator current and desired position can be modelled using a First Order Equation.

$$\frac{dx}{dt} = -\frac{1}{\tau} * x + \frac{1}{\tau} * \hat{x} \tag{10}$$

4 Normalization

4.1 Flow Equation

In normalization we substitute following values with the units in *eq. 9* to make it dimensionless equation.

$$F = \tilde{F} * \frac{kg}{h}, \tag{11}$$

$$\rho = \tilde{\rho} * \frac{kg}{m^3}, \qquad P = \tilde{P} * kPa \tag{12}$$

$$K_v = \tilde{K_v} * \frac{\frac{kg}{h}}{\sqrt{kPa * \frac{kg}{m^3}}} \tag{13}$$

$$K_p = \frac{\Delta P_p * \rho}{F^2} = \tilde{K_p} * \frac{kPa * \frac{kg}{m^3}}{\frac{kg^2}{h^2}} = \tilde{K_p} * \frac{kPa * h^2}{kg * m^3} \tag{14}$$

Now, by substituting *eq. 11* to *eq. 14* in *eq. 9*, we get,

$$\tilde{F} * \frac{kg}{h} = \sqrt{\frac{\tilde{\rho} * \frac{kg}{m^3} * (\tilde{P_1} * kPa - \tilde{P_3} * kPa)}{\tilde{K_p} * \frac{kPa*h^2}{kg*m^3} + \frac{1}{(\tilde{K_v} * \frac{\frac{kg}{h}}{\sqrt{kPa*\frac{kg}{m^3}}})^2}}} \tag{15}$$

$$\tilde{F} * \frac{kg}{h} = \sqrt{\frac{\tilde{\rho} * \frac{kg}{m^3} * (\tilde{P_1} * kPa - \tilde{P_3} * kPa)}{\tilde{K_p} * \frac{kPa*h^2}{kg*m^3} + \frac{1}{\tilde{K_v}^2 * \frac{\frac{kg^2}{h^2}}{kPa*\frac{kg}{m^3}}}}} \tag{16}$$

$$\tilde{F} * \frac{kg}{h} = \sqrt{\frac{\tilde{\rho} * \frac{kg}{m^3} * (\tilde{P_1} * kPa - \tilde{P_3} * kPa)}{\tilde{K_p} * \frac{kPa*h^2}{kg*m^3} + \frac{1}{\tilde{K_v}^2 * \frac{kg^2*m^3}{h^2*kPa*kg}}}} \tag{17}$$

$$\tilde{F} * \frac{kg}{h} = \sqrt{\frac{\tilde{\rho} * \frac{kg}{m^3} * (\tilde{P_1} * kPa - \tilde{P_3} * kPa)}{\tilde{K_p} * \frac{kPa*h^2}{kg*m^3} + \frac{1}{\tilde{K_v}^2 * \frac{kg*m^3}{h^2*kPa}}}} \tag{18}$$

$$\tilde{F} * \frac{kg}{h} = \sqrt{\frac{\tilde{\rho} * \frac{kg}{m^3} * (\tilde{P_1} * kPa - \tilde{P_3} * kPa)}{\tilde{K_p} * \frac{kPa*h^2}{kg*m^3} + \frac{kPa*h^2}{\tilde{K_v^2}*kg*m^3}}} \tag{19}$$

$$\tilde{F} * \frac{kg}{h} = \sqrt{\frac{\tilde{\rho} * \frac{kg}{m^3} * (\tilde{P_1} - \tilde{P_3}) * kPa}{\tilde{K_p} * \frac{kPa*h^2}{kg*m^3} + \frac{kPa*h^2}{\tilde{K_v^2}*kg*m^3}}} \tag{20}$$

$$\tilde{F} * \frac{kg}{h} = \sqrt{\frac{\tilde{\rho} * (\tilde{P_1} - \tilde{P_3}) * \frac{kPa*kg}{m^3}}{(\tilde{K_p} + \frac{1}{\tilde{K_v^2}}) * \frac{kPa*h^2}{kg*m^3}}} \tag{21}$$

$$\tilde{F} * \frac{kg}{h} = \sqrt{\frac{\tilde{\rho} * (\tilde{P_1} - \tilde{P_3}) * \frac{kg}{1}}{(\tilde{K_p} + \frac{1}{\tilde{K_v^2}}) * \frac{h^2}{kg}}} \tag{22}$$

$$\tilde{F} * \frac{kg}{h} = \sqrt{\frac{\tilde{\rho} * (\tilde{P_1} - \tilde{P_3})}{\tilde{K_p} + \frac{1}{\tilde{K_v^2}}} * \frac{kg^2}{h^2}} \tag{23}$$

$$(\tilde{F} * \frac{kg}{h})^2 = \frac{\tilde{\rho} * (\tilde{P_1} - \tilde{P_3})}{\tilde{K_p} + \frac{1}{\tilde{K_v^2}}} * \frac{kg^2}{h^2} \tag{24}$$

$$\tilde{F} = \sqrt{\frac{\tilde{\rho} * (\tilde{P_1} - \tilde{P_3})}{\tilde{K_p} + \frac{1}{\tilde{K_v^2}}}} \tag{25}$$

This is the normalized flow equation which will be modelled in the Simulink.

4.2 Dynamic Equation

For normalization, we will substitute following values in equation 10 to make it dimensionless equation.

$$x = \tilde{x}(dimensionless) \tag{26}$$

$$\hat{x} = \tilde{\hat{x}}(dimensionless) \tag{27}$$

$$t = \tilde{t}.sec \tag{28}$$

$$\tau = \tilde{\tau}.sec \tag{29}$$

Now substitude from eq. 26 to eq. 29 into eq. 10.

$$\frac{d\tilde{x}}{d\tilde{t}.sec} = -\frac{1}{\tilde{\tau}.sec} * \tilde{x} + \frac{1}{\tilde{\tau}.sec} * \tilde{\hat{x}} \tag{30}$$

$$\frac{d\tilde{x}}{d\tilde{t}} = -\frac{1}{\tilde{\tau}} * \tilde{x} + \frac{1}{\tilde{\tau}} * \tilde{\hat{x}} \tag{31}$$

This is the normalized dimensionless dynamic equation which will be modelled in Simulink.

5 Step 3: Simulink Model Implementation

We will implement the UniSim model(reality) in Simulink using the Normalized Equations (Eq.25 and Eq.31). To implement the Normalized flow equation we need to calculate Kp and Kv values.

5.1 Calculation of Kp Value

Kp value can be calculated using the formula:

$$K_p = \frac{\Delta P_{pmax} * \rho}{F^2} \tag{32}$$

The maximum pressure difference across pipe is(from UniSim) is:

$$\Delta P_{pmax} = 300KPa \tag{33}$$

and the maximum flow in UniSim simulation is 24580 KPa, so the maximum value of Kp is:

$$K_p = \frac{300KPa * 1008Kg/m^3}{(24580Kg/h)^2} = 0.00050055\frac{KPa * h^2}{kg * m^3} \tag{34}$$

5.2 Calculation of Kv Value

Since we are using Equal percentage valve in our model. The Kv of the value is given by the formula [3]:

$$K_v = K_{vmax} * R^{x-1} \tag{35}$$

where x is the OP value between 0 to 1 and R is the Rangeability which can be found in the UniSim as the design parameter of the valve.

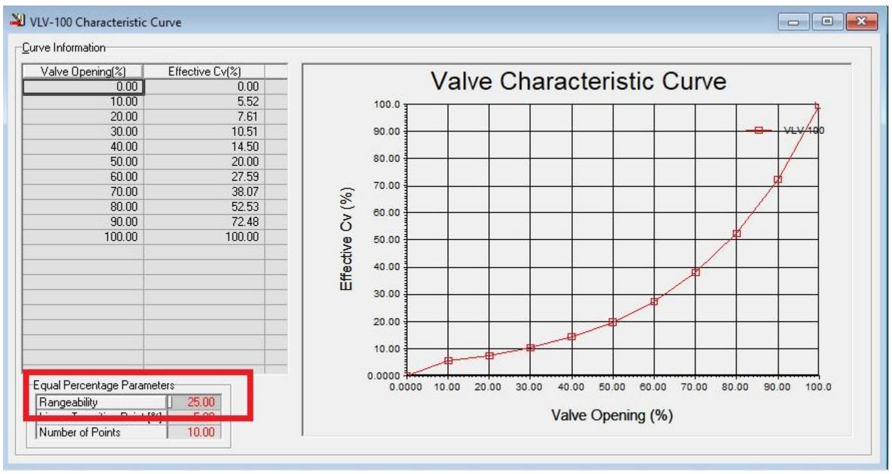

Figure 9: Valve Rangeability

The maximum value of Kv can be calculated using the formula:

$$K_{vmax} = \frac{F}{\sqrt{\rho * \Delta P_{vmax}}} \tag{36}$$

The maximum pressure difference across the valve is(from UniSim) is:

$$\Delta P_{vmax} = 200KPa \tag{37}$$

and the maximum flow in UniSim simulation is 24580 KPa, so the maximum value of Kv is:

$$K_v = \frac{24580Kg/h}{\sqrt{1008Kg/m^3 * 200KPa*}} = 54.6576\frac{kg * m^3}{KPa * h^2} \tag{38}$$

Sine Kv is the function of OP, we can calculate Kv at different OP values using Equation 35.

OP values	Kv
1	54.6576
0.9	39.61471695
0.8	28.71194122
0.7	20.8098311
0.6	15.08254239
0.5	10.93152
0.4	7.922943389
0.3	5.742388245
0.2	4.161966221
0.1	3.016508478

Figure 10: Kv calculation

To implement the relation between OP and Kv in Simulink, the approximation of this Non-linear behaviour of Kv is done. An expression for Kv is determined by applying a third-order regression model which satisfies the Valve characteristics. The approximation shows the linear behaviour of Equal Percentage Valve up to the 10% OP value and shows pure Non-linear behaviour for the OP values higher than 10%. To differentiate this behaviour in the Simulink model, the different polynomial regression is applied for both ranges of OP value.

The linear approximation is done from 0% to 10% OP, which is implemented by the following polynomial.

$$Kv = 3.1650847799999e^1 OP - 2.22e^{-16}$$

The third order polynomial regression model is applied from 10% to 100% of OP value.

$$Kv = 80.2975OP^3 - 55.1571OP^2 + 28.7325OP + 0.1349$$

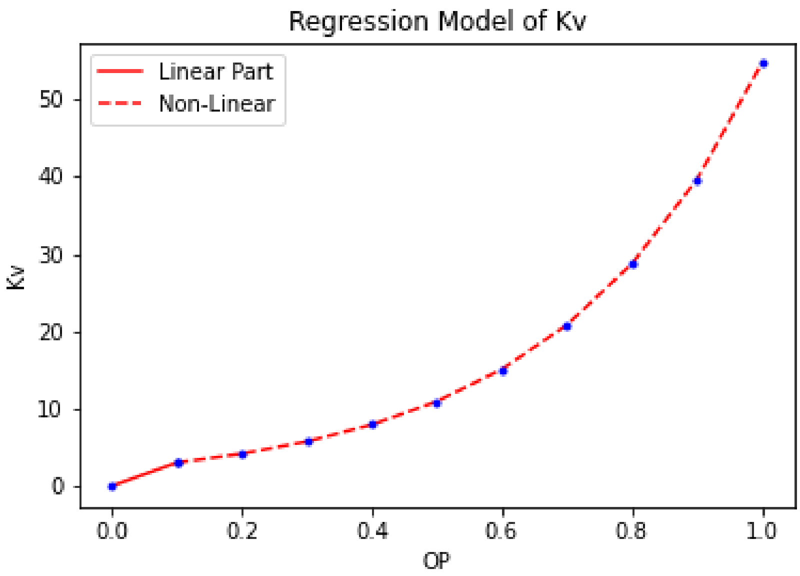

Figure 11: Regression Model of Kv

5.3 Implementation of Mass Flow Equation

The Normalized Mass Flow Equation is implemented in Simulink as follows:

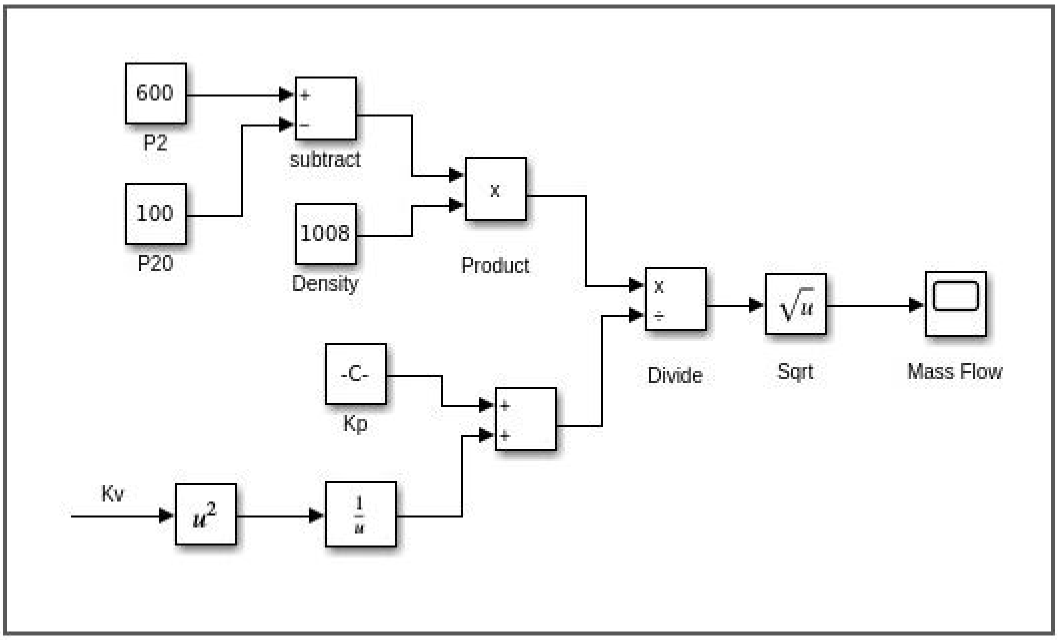

Figure 12: Mass Flow implementation

5.4 Implementation of Kv in Simulink

Kv is implemented in Simulink corresponding to their OP ranges. For OP range from 0% to 10% the linear part or 1st order polynomial is implemented and for the OP range from 10% to 100% the non linear part or 3rd order polynomial is implemented. A condition is applied to check the OP valve to select the corresponding Kv value as shown in Figure 13.

5.5 Implementation of Dynamic Behaviour

The Dynamic behaviour equation because of the actuator in UniSim is implemented using a First order Lag function in Simulink as shown in Figure 13.

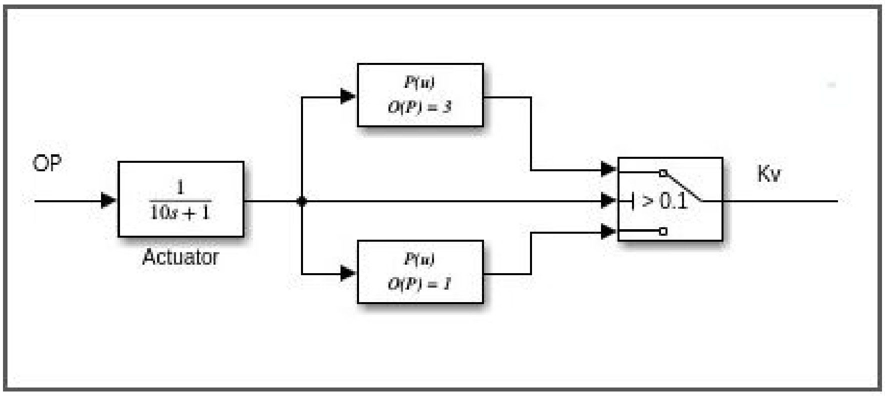

Figure 13: Implementation in Simulink

5.6 Implementation of PI Controller

The PI controller is implemented in the Simulink as follows:

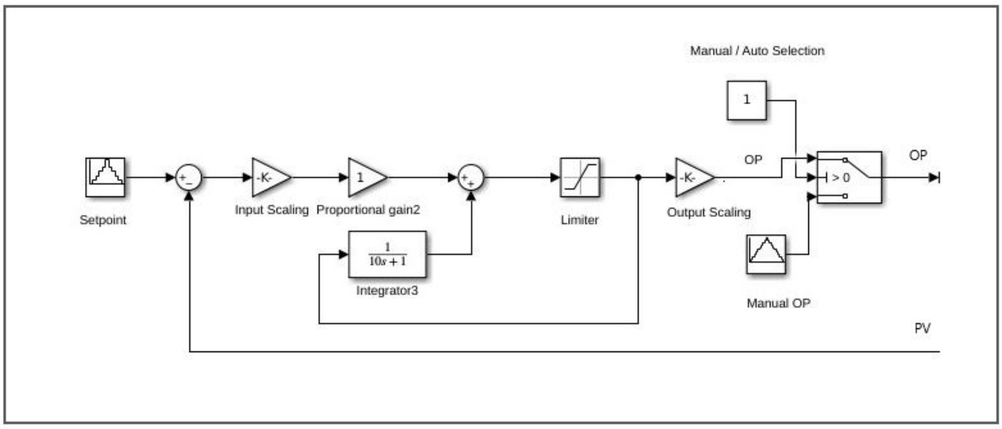

Figure 14: Controller Implementation in Simulink

The PI controller with Anti-Windup scheme is implemented in the Simulink in the Override configuration. The integral is in feedback as a first-order lag with the saturation block to limit OP value.

The Proportional gain is set to 1, the integral time constant Ti to 10 sec and the upper and lower limit in saturation block to 0 and 100 in Simulink corresponding value of 0kg/hr to 24580kg/hr in UniSim with scaling as shown in the following figure.

There are two scaling blocks with the controller. One is Input Scaling with a gain of 0.00407 to compensate for the Plant gain and the second scaling is Output scaling with a gain of 0.1 to change the OP from a range of 0-100 to 0-1.

The manual and Auto mode of the controller in UniSim is also implemented in Simulink using a condition when Manual/Auto Selection is greater than 0 the nodel is in Auto Mode and take OP value from the controller and when it is 0 the model is in Manual Mode and take OP value manually.

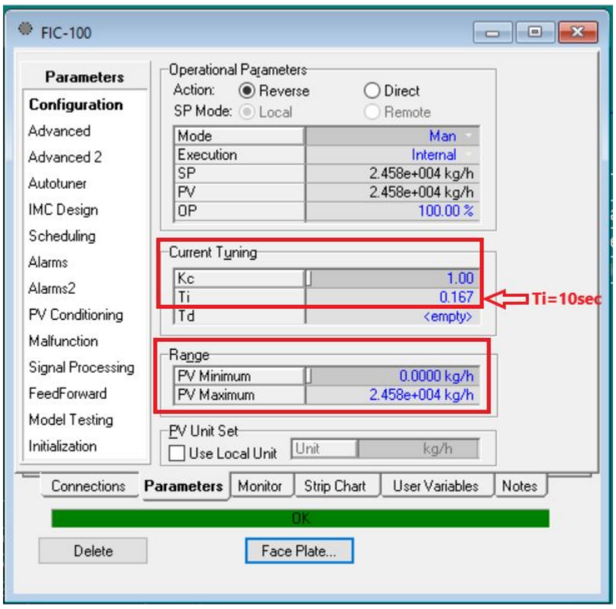

Figure 15: Controller setting in UniSim

6 Analysis and Results

6.1 Open Loop System

The following model represents the Open Loop system implementation in Simulink.

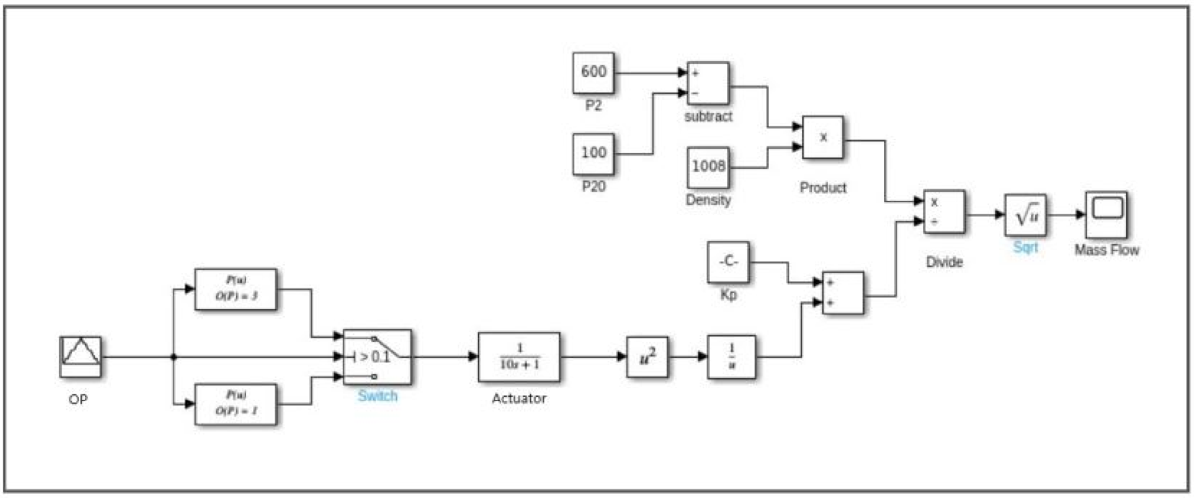

Figure 16: Open Loop System in Simulink

The open loop system implemented in Simulink is tested by giving manual OP values input to the model from 0% to 100% with the increment and decrement of 10% and flow readings are noted. The result is shown in the following figure.

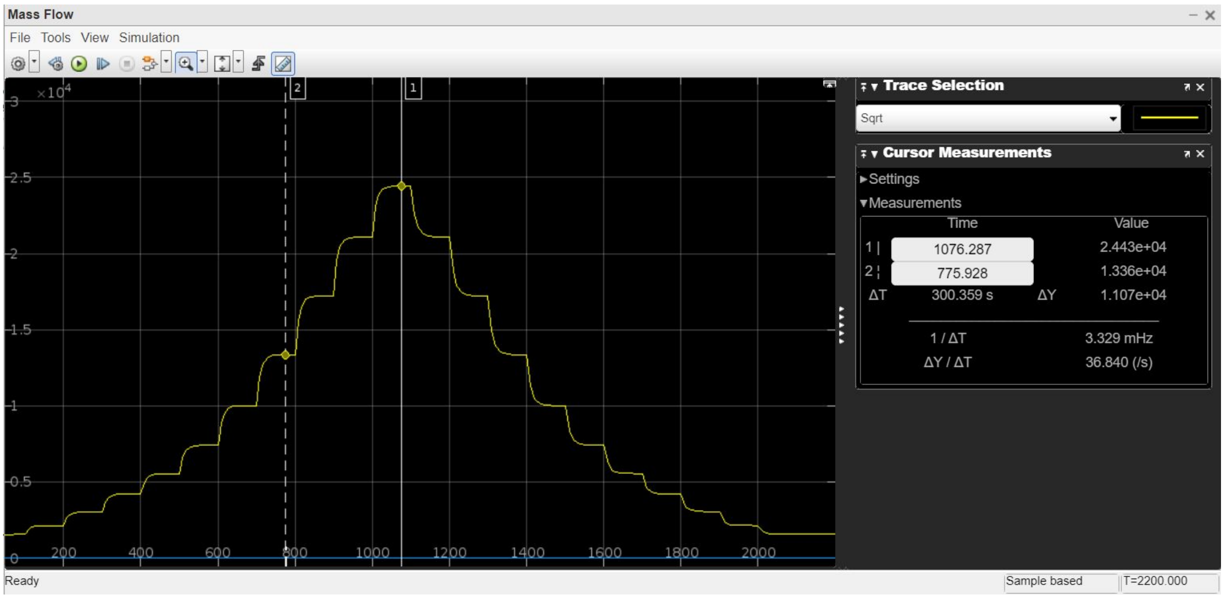

Figure 17: Response in Simulink

Manual OP step and step down test is done from 0% to 100% with the increment and decrement of 10% and flow readings are noted in UniSim. The result is shown in the following figure.

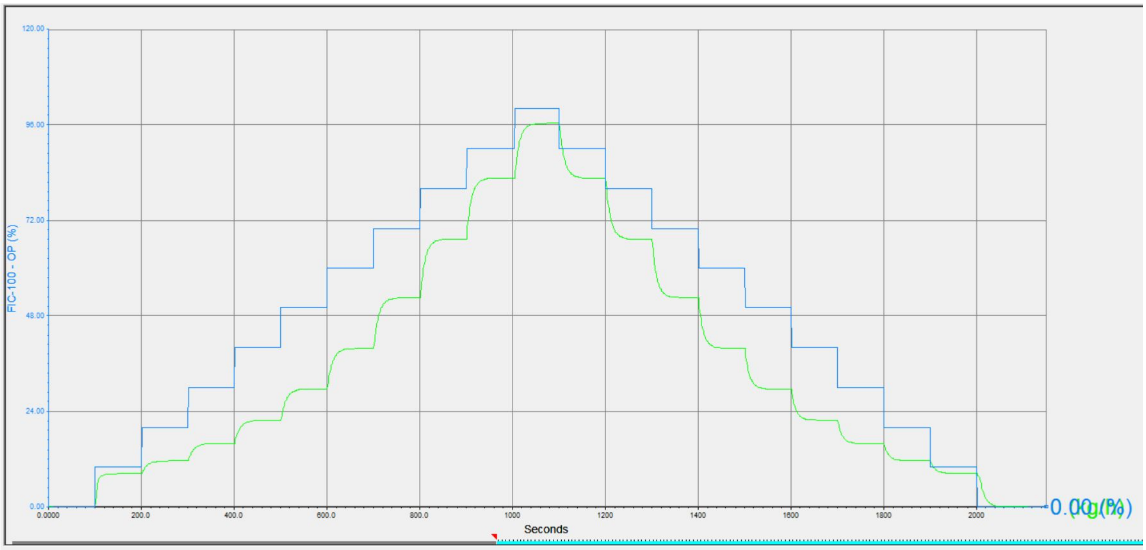

Figure 18: UniSim Result

The results of UniSim model and Simulink model are compared in the following Table.

OP value	Flow from UniSim (kg/h)	Flow from Simulink (kg/h)
0%	0	0
10%	2137	2134
20%	2942	3052
30%	4044	4194
40%	5539	5550
50%	7539	7418
60%	10147	10010
70%	13396	13360
80%	17153	17240
90%	21053	21110
100%	24579	24430

Figure 19: Output Comparision

Comparing the flows of UniSim and Simulink models on different OP values, it can be deduced that the results are quite similar with a little bit of difference, which can be due to the approximate Kv regression model in Simulink.

6.2 Close Loop System

The following model represents the Close Loop system implementation in Simulink.

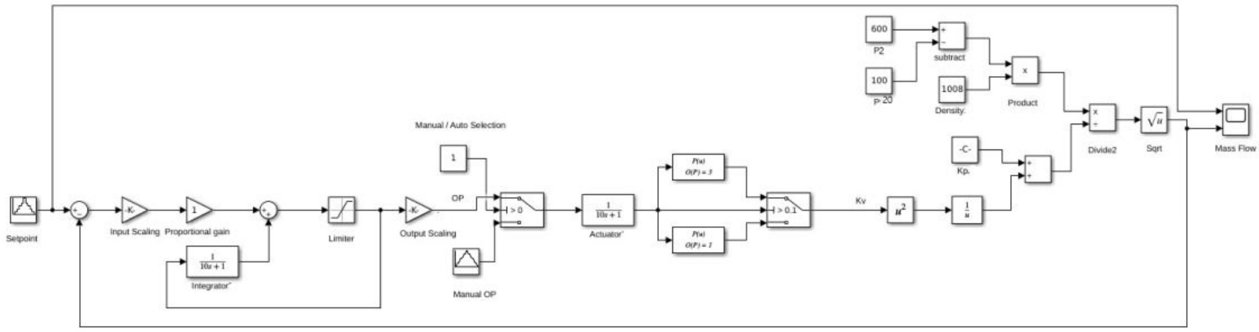

Figure 20: Close Loop System in Simulink

The close loop system is tested in Auto mode by providing a set-point of 5000 kg/hr and next with a increment of 5000 till the max value of 24580 kg/hr. Similarly, step-down steps were performed and results in Simulink were recorded and compared with UniSim results.

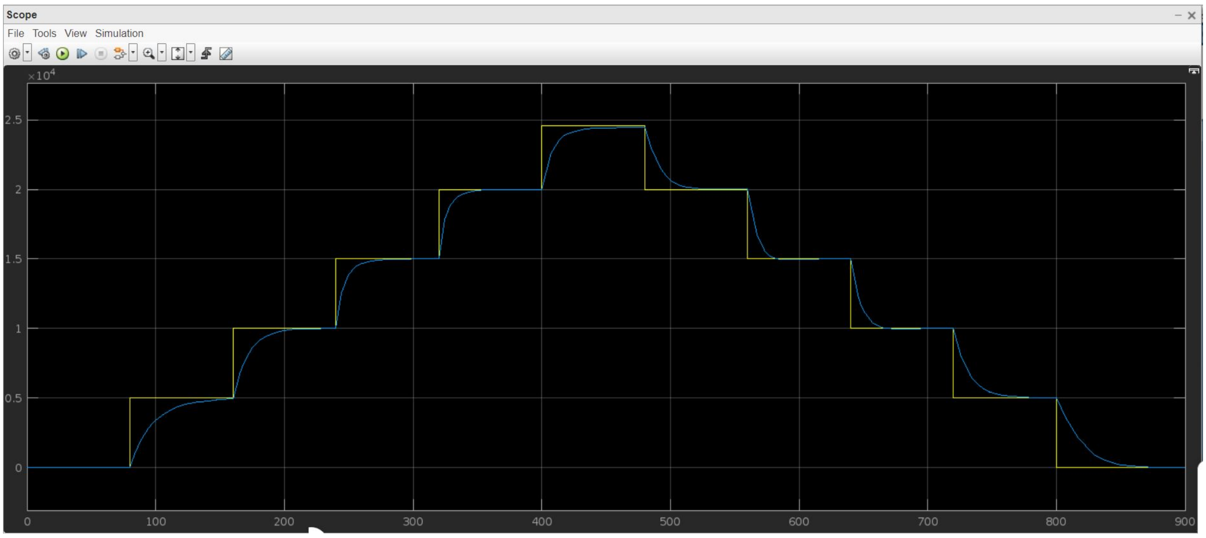

Figure 21: Response in Simulink

The PI controller with an Anti-Windup override control mechanism model also behaves in a similar way as in UniSim, in finding the optimum OP value to keep the Mass flow value according to the given set point and this model has the ability to keep the OP value in a specified range and thus resist the Mass flow to go beyond a certain limit(max PV).

6.3 Anti Windup scheme with Override configuration Results

In the following graph, The results of two different configurations of the controller are compared.

The red line in the graph is the output of the implementation of the simple PI controller in the model and the yellow line in the graph is the PI controller in override configuration. Whereas the blue line is the Set point input to the model. Keeping in mind that the output limit here is 24580kg/hr set according to our UniSim model, the difference between the outputs of both configurations can be seen. The first configuration of a simple PI controller after limiting the output to maximum when the input crosses the maximum limit is unable to follow the input when it comes back in working range and takes time to follow the input. On the other hand, the second configuration of the Override configuration is following the input even after the maximum limit is reached and input comes back in the working range thus taking care of Integrator windup phenomenon.

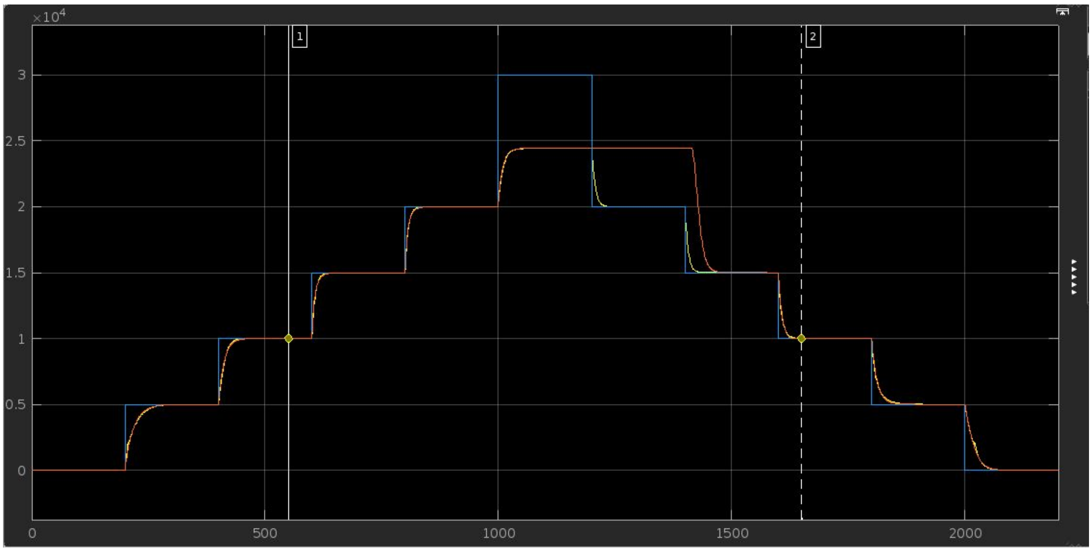

Figure 22: Response in Simulink

6.4 Anti Windup scheme with Back calculation

Another anti-windup technique is modeled in Simulink using Karl Astroms's back calculation method [1].

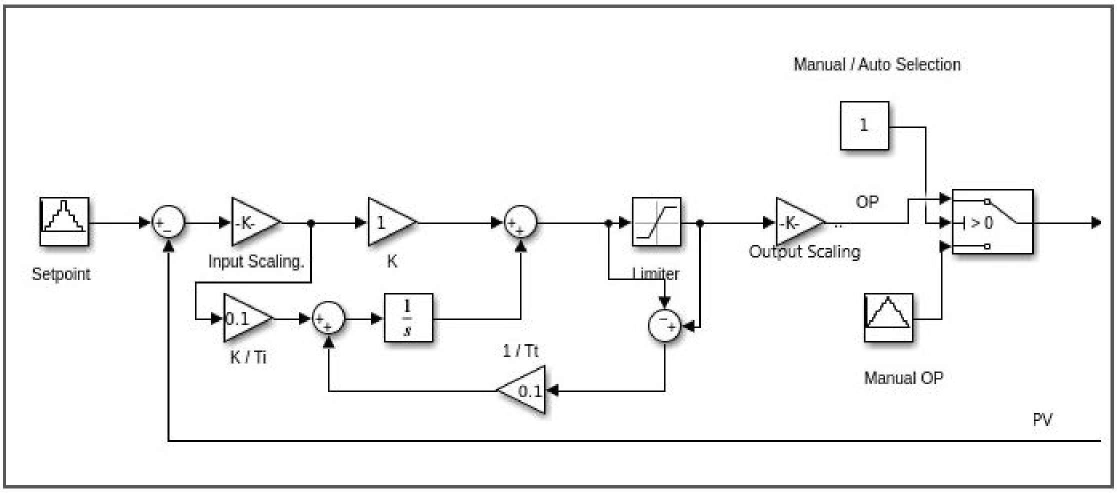

Figure 23: Back calculation Simulink model

This implementation also gives the same results as the PI-controller in the override configuration implementation earlier. It solves the integrator windup problem with affecting the overall response.

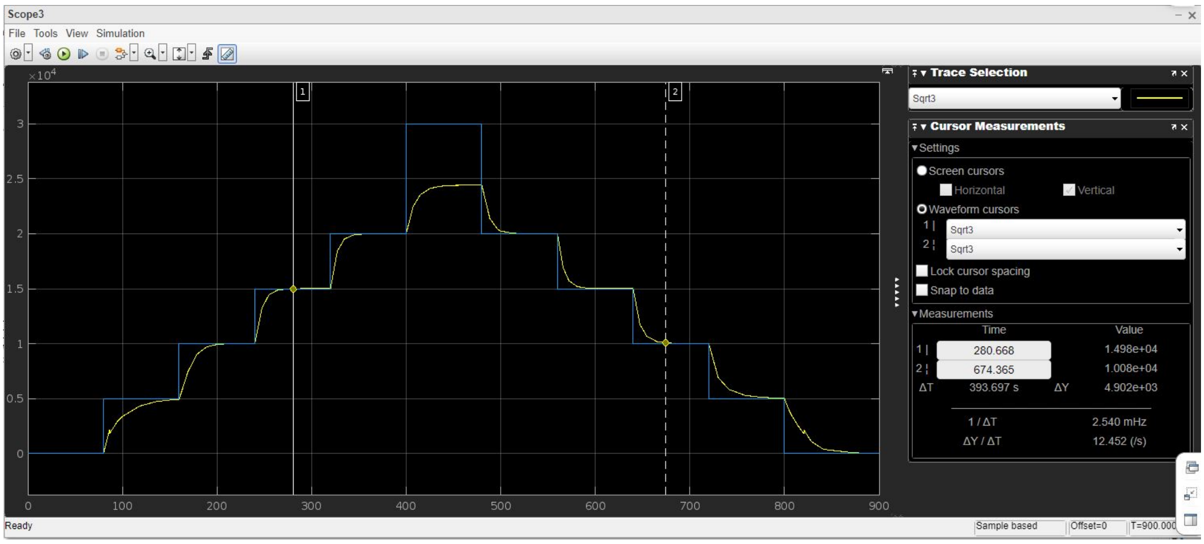

Figure 24: Back calculation Simulink response K=1, Ti=10, Tt=10

While implementing this schematic, an important parameter is the time constant Tt which determines how quickly the integrator of the PI controller is reset. Changing the Tt from 10 to 2, the following graph shows the change in response of the model. The blue line represents the response when Tt is 10 and the yellow line shows the model response when Tt is 2.

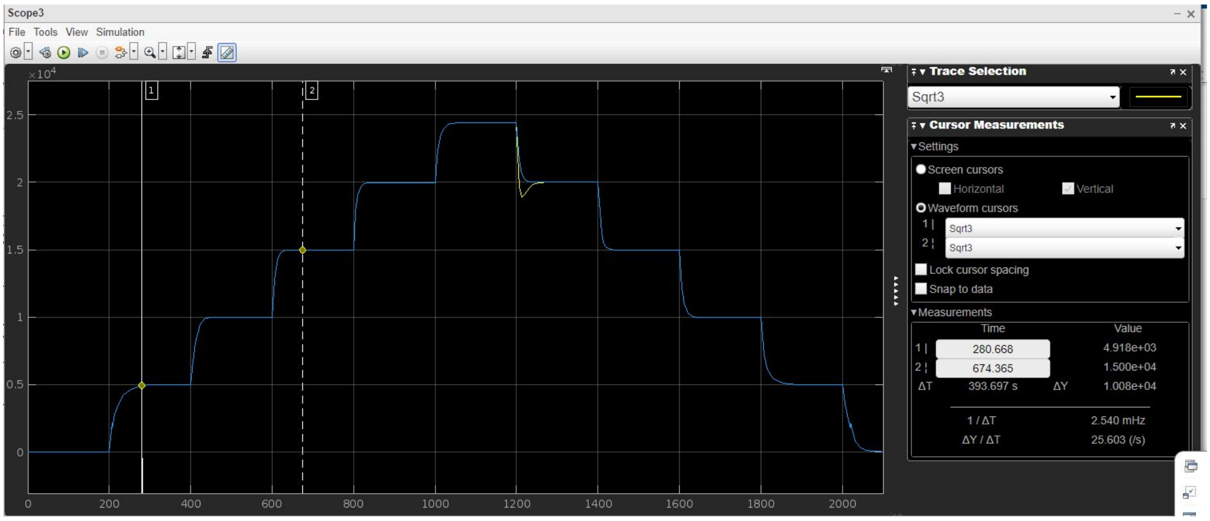

Figure 25: Back calculation Simulink response K=1, Ti=10, Tt=2

7 Linear Characteristic Valve

7.1 Kv Calculation

Kv calculation is done for the Valve of the Linear Characteristic curve for implementation in Simulink. Kvmax is calculated as previously and Kv is calculated by the following formula [3].

$$K_v = K_{vmax} * x \tag{39}$$

where x is the OP value between 0 to 1.

To implement the relation between OP and Kv in Simulink, the approximation of this linear behaviour of Kv is done.

$$Kv = 54.65OP - 7.8159700933611020e - 014 \tag{40}$$

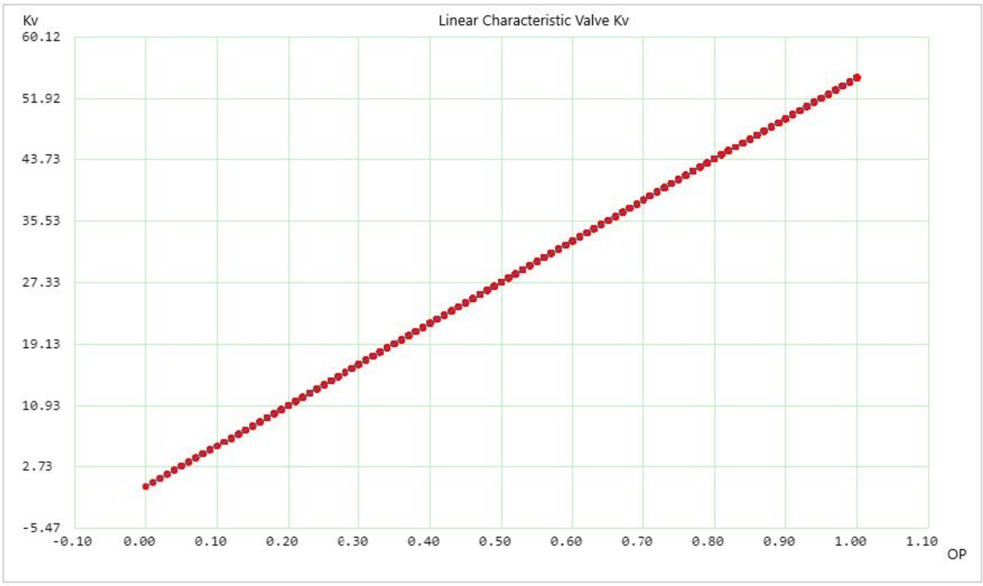

Figure 26: Kv calculation

7.2 Simulink Model

Linear valve model is implemented by updating the Kv in the implemented model in Simulink.

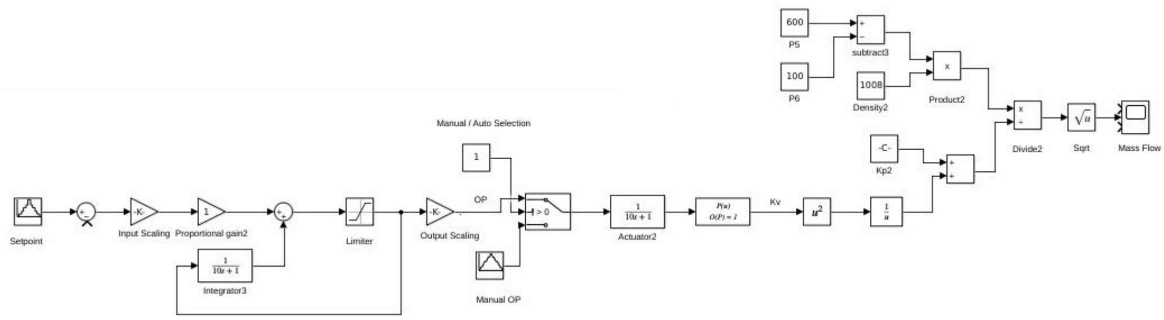

Figure 27: Linear valve Simulink Model

7.3 Simulink Model analysis

The Step-up sequence of OP valves is given of the Open loop system. The comparison of Mass flow rate of Unisim and Simulink model is made corresponding to OP values. The output of Simulink model is following the same trend as Unisim model and the values are close enough to each other.

OP value	Flow from UniSim (kg/h)	Flow from Simulink (kg/h)
0%	0	0
10%	3852	3850
20%	7539	7530
30%	10931	10930
40%	13946	13940
50%	16558	16554
60%	18778	18780
70%	20644	20626
80%	22201	22182
90%	23498	23470
100%	24579	24555

Figure 28: Flow comparision of UniSim and Simulink Model

7.4 Linear and Equal Percentage Valve comparision

The following graph shows the comparison of results of the open loop system model in Simulink of Linear Valve and Non-linear(Equal Percentage) valve.

The blue line in the graph shows the Mass flow of the Linear valve in OP ranging from 0% to 100% with a step of 10%. The yellow line in the graph shows the Mass flow of the Non-Linear(Equal Percentage) valve in OP range from 0% to 100% with a step of 10%.

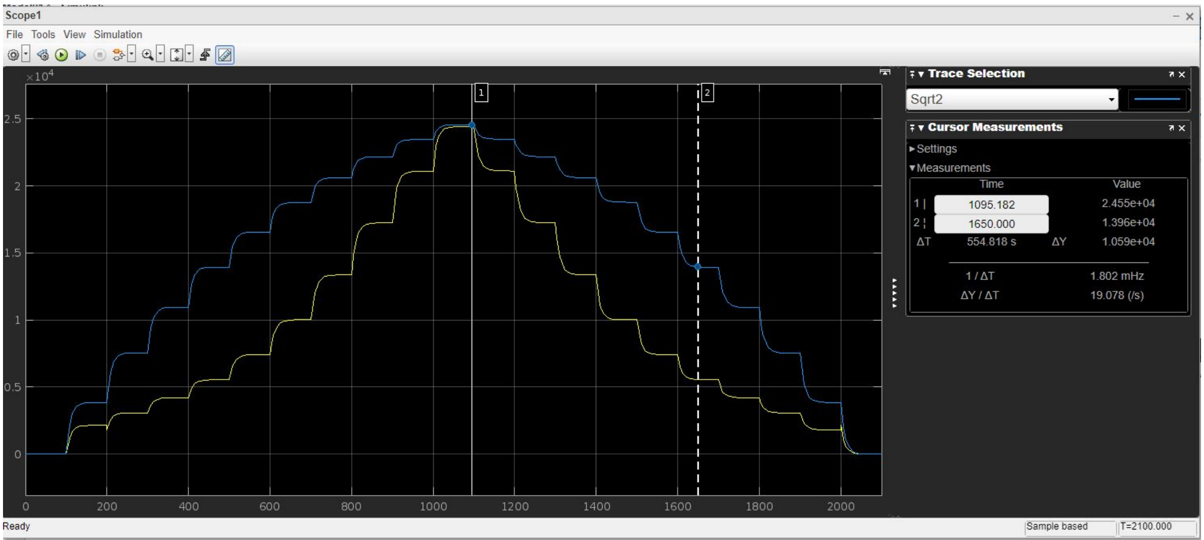

Figure 29: Open Loop Response

Similarly, the following graph shows the comparison of results of the close loop system model in Simulink of Linear Valve and Non-linear(Equal Percentage) valve. The blue line in the graph shows the Mass flow of the Linear valve and the yellow line in the graph shows the Mass flow of the Non-Linear(Equal Percentage) valve with a Setpoint ranging from 0 kg/hr to 24580 kg/hr with the step change of 5000 kg/hr.

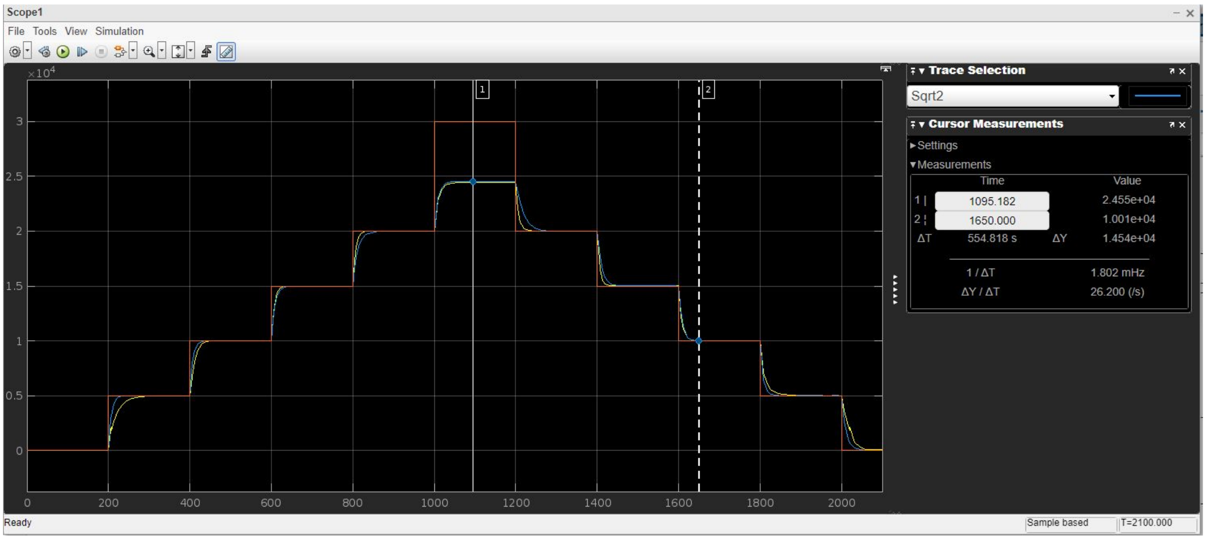

Figure 30: Close Loop Response

Since both curves follow their respective characteristic behaviour, it implies that our modelling in Simulink is the same as reality(UniSim).

References

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