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Performance Analysis Of Various Anti-Reset Windup Algorithms For A Flow Process Station

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Abstract
The study was aimed to develop the various aspects of Anti reset windup or Integral windup and also the different algorithms available to eliminate the phenomenon of windup. Different open loop responses were obtained from a Flow process Station using MATLAB and SIMULINK and VI Microsystems process control software. The open loop responses were evaluated and different system models were generated using the two point method. The system models were found to follow a decreasing order of Gain values and an increasing order of T_d and T values. A SIMULINK model was obtained to implement Back calculation combined with Conditional Integration. The models for the system obtained were simulated using the SIMULINK model and a PID controller and the closed loop responses were generated. The closed loop responses using a PID controller with Back calculation and Conditional integration were found to follow the set point as expected.
Keywords—Anti reset windup, Integral windup, back-calculation, conditional integration, flow process, tracking time constant, PID controller, SIMULINK.

I. INTRODUCTION

In practice all control loops and processes contain nonlinearities. Examples are saturation in actuators, gain or parameter variations due to changes in operating point of the process, and backlashes in valves and gears. The influence of nonlinearities is often eliminated by keeping the process close to a desired operating point. A linearized model is then often valid and can be used for the design of the controller.

A control system which operates over a wide range of operating conditions, windup phenomena may happen as the manipulated variable reaches the actuator limits. When windup happens the feedback loop is assumed as broken and the system runs in open loop because the actuator will lock in saturation as its limit independent of the error dynamics. The controller output then becomes very large. The control signal then remains saturated even the error changes its direction and it may take a long time before the integrator and the controller output comes inside the saturation range. The consequence is that there are large transients.

Generally when a large set point change is given and the PID controller produces a control signal (as the integral of the larger error) which the maximal effort is taken by the controller for regulation of the process variable. Then the control signal lets the actuator immediately go to its saturation limits, thus the process variable overshoots and continues to increase as this error being accumulated by the controller itself. This is known as Integral Windup in control systems. The project aims at eliminating windup problem using various techniques available in literature.

II. ANTI RESET WINDUP

Bohn. C, and D.P. Atherton [3], represented additional actuator dynamics rather than the saturation in the first position of system to be controlled. A lower limit for the actuator output leads to higher integrator output and higher settling time. The effect of integrator windup can be explained by the fact that when the control signal saturates the actuator, a further increase of the control signal will not lead to a faster response of the system. If integration of error continues in this case it becomes very large compared to the linear system it winds up, without having any effect on the plant output. The control error then has to be of the opposite sign for a long time to bring the integrator back to its steady state value. This results in a large overshoot and a high settling time.

In order to effectively employ a PID controller in practical cases, implementation of some additional functionalities are needed. The derivative action is often applied directly to the process variable instead of to the error in order to avoid the so-called derivative kick when a step signal is applied to the set-point. Suitable techniques should be implemented properly in order to avoid the windup effect of the integral action which has a detrimental effect when large set-point changes are applied.

III. ANTI WINDUP ALGORITHMS FOR A PID CONTROLLER

A PID controller is typically employed in a unity feedback control system which can be described by the following transfer function,

$$u(s) = K_c\left(1+\frac{1}{T_i s}+\frac{T_d s}{1+\frac{T_d s}{N}}\right)e(s) \qquad (1)$$

A. Back-calculation:

This method back calculates the integral value when the control signal reaches the saturation region which depends on the difference between saturated and unsaturated control signal. While the controller output saturated, the integral value is adjusted to stop an integrator output to the saturation level. The error signal (e_i) that produced from the difference between the actuator input and output is fed back to the controller through an integrator having the tracking time constant (T_t). The time constant is a tuning parameter to achieve the performance of the controller. The equation for integral error (e_i) is as follows,

$$e_i = \frac{K_P}{T_i}e + \frac{1}{T_t}(u_s - u) \qquad (2)$$

Where u is the controller output, u_s is the saturated controller output. The tracking time constant can be either: $T_t = \sqrt{T_i T_d}$ or $T_t = T_i$, depends whether PID or PI controller respectively. Fig 2 shows the anti-windup technique for PID controller with back-calculation.

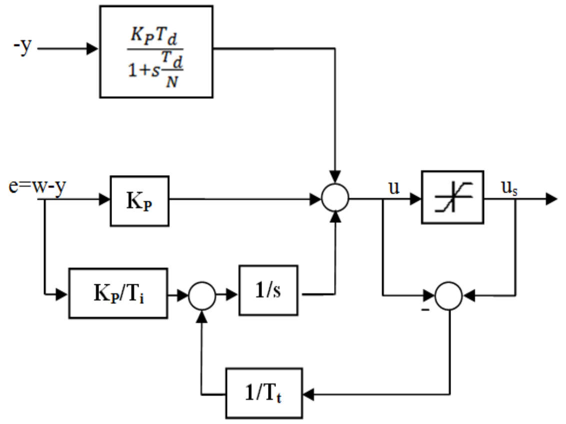

Fig1. PID controller with anti-windup scheme (Back-calculation)

B. Conditional integrator:

Conditional integrator (or integrator clamping), is one of the basic method for anti-windup. The main concept of this method is to switch the integral on or off (increase the integral term or make it constant) based on a four condition suggested by Visioli [10]:

- The integral term is limited to a predefine value;
- The integration is stopped when the error is greater than a predefine threshold;
- The integration is stopped when the control variable saturates, i.e., when u ≠ u';
- The integration is stopped when the control variable saturates and the control error and the control variable have the same sign.

$$u * e > 0, \qquad (3)$$

$$u \neq u_s \qquad (4)$$

$$|e| > \bar{e}. \qquad (5)$$

IV. PROCESS EXPERIMENTAL SETUP AND IDENTIFICATION

The actual experimental setup is a flow process station (VFPA-201CE) as shown below:

Fig2. Experimental Setup of Flow Process Trainer.

The schematic of the experimental setup is as shown below:

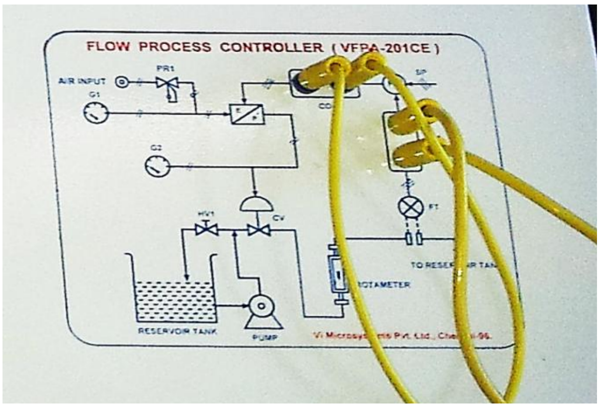

Fig3. Schematic of experimental setup of Flow Process Trainer.

As we can see from the *Fig 3.*,it consists of a reservoir tank filled with liquid and a facility to pump the water to the system. Flow through system is controlled by a pneumatic linear control valve (air to open). The flow can be measure visibly by the Rota meter. The Orifice plate is mounted along the pipeline to measure the flow rate. The two pressure inputs across the orifice is taken and given as sensor signal to a Differential Pressure Transmitter (DPT) which produces 4-20mA analog signal to Data Acquisition Card. Then it's connected to PC using RS232.

To identify the process, a step change in the manipulated variable was given and the change in process variable noted. From the process reaction curve the two-point method was applied to get a first order process with dead time model. Instead of a value in psi units, the same value in lph units was chosen as percentage of psi, to give change in manipulated variable in terms of value.

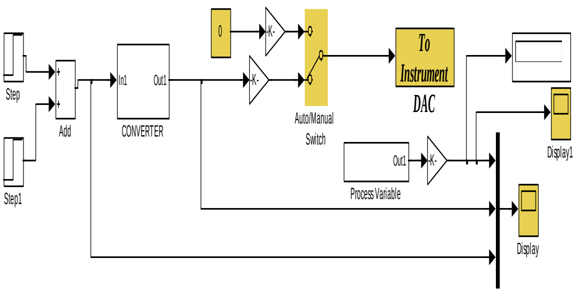

Fig 4. Simulink Model of the Flow Process Station used for open loop responses.

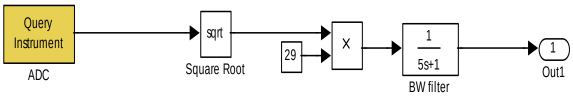

Fig.5. Process Variable block of the Simulink Model shown in *Fig 4.*

The subsystem illustrated above consists of the Query Instrument or the output from the ADC (Analog to Digital Converter) which gives the pressure differential of the control valve with the help of the Differential Pressure Transmitter.

Now we know that,

For a control valve, Flow rate:

$$Q = Cv \times \sqrt{\frac{DP}{Gf}} \qquad (6)$$

Here, in the above equation,

Q= Volumetric Flow Rate (lph).

Cv = Control Valve flow coefficient, dimensionless.

DP= Pressure differential, psi.

Gf= Liquid specific gravity, dimensionless.

The Pressure Differential is obtained from the DPT (Differential Pressure Transmitter) and is transmitted to the system through the ADC. In order to obtain the Valve Flow rate the square root of the ratio of DP and Gf is multiplied by the Valve coefficient to obtain the volumetric flow rate. A Butterworth filter is also provided to attenuate any disturbances in the output. This is the main function of the Process Variable block in the above SIMULINK.

V. RESULTS

The open loop responses for the flow process system shown above were obtained and recorded using a DAQ card and VI Instruments integrated software. The Flow Process Station was taken for identification. It is a fast process and the Process Reaction Curves for different CP values were generated by taking the open loop responses of the Flow Process Station. The system was set to manual mode and the set point was set to 500.The open loop responses were then generated by real time simulation.

Different percentage opening values were given as input and that in turn controls the opening of the control valve. Different open loop responses were noted from 20% opening to 100% opening of the valve. These responses are documented below.

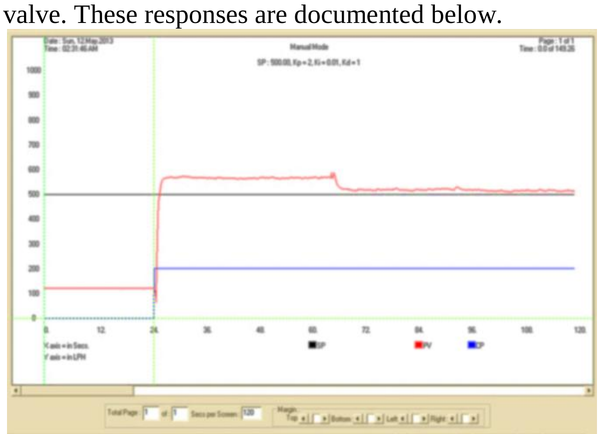

Fig 6. Process Reaction Curve for CP=20%

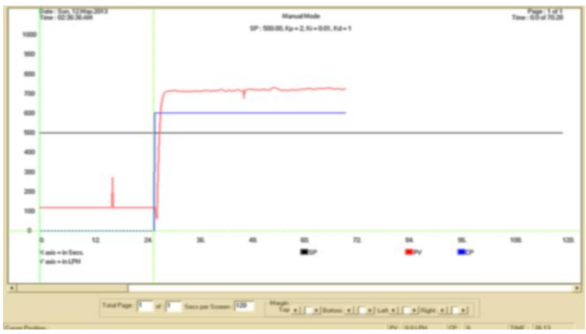

Fig 7. Process Reaction Curve for CP=60%

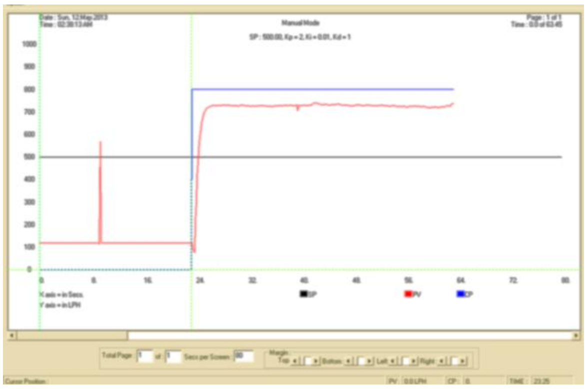

Fig 8. Process Reaction Curve for CP=80%

The VI Instruments process control software used for the real time open loop responses generated the PV values on a scale of 0-1000. However, the Rota meter device present on the system can give output values only from 0-500.

Hence, the PV values were converted from 1000 scale to 500 scale and a comparison of the actual 1000 scale PV values and the visible 500 scale rota meter flow values have been tabulated below for better understanding.

Table I. Comparison of actual 1000scale (PV) and visible 500 scale (Rota mater) outflow rate data.

S. No.	CP (%)	MV (psi)	PV (lph)	Rota meter (lph)
1	20	5	588.52	270
2	40	7	689.62	320
3	60	10	740.5	340
4	80	12	758.03	350
5	100	15	783.36	360

After the data was obtained the system modelling was done using the 'two point method' for FOPDT systems the following wing known transfer function for FOPDT systems:

$$\frac{Kp}{(T_s + 1)} \times e^{-T_d s} \qquad (7)$$

Here, K_p= process Gain,
T_s= process time constant,
Td= process dead time

T1 and T2 were calculated by taking change in PV value and taking the Time corresponding to the 28.3% and 63.2% of the difference in the starting point of change in PV and the point at which the PV settles.

The two point method was applied for two points on the response curve T1 and T2 according to the formulas:

$$T = 1.5 \times (T_2 - T_1) \qquad (8)$$

$$T_d = T_2 - T \qquad (9)$$

$$Gain = \frac{Change\ in\ output}{Change\ in\ input} \qquad (10)$$

The models of the FOPDT processes obtained by the two point method are tabulated below:

Table II. Process model identification (2 pt. method).

R. no	CP (%)	T1 (s)	T2 (s)	Td (s)	T (s)	Gain	Model
1	20	0.62	1.14	0.36	0.78	3.489	$\frac{3.4}{0.78s + 1} e$
2	40	0.72	1.24	0.46	0.78	2.105	$\frac{2.105}{0.78s + 1} e$
3	60	0.78	1.43	0.46	0.975	1.525	$\frac{1.525}{0.975s + 1}$
4	80	0.87	1.57	0.52	1.05	1.175	$\frac{1.175}{1.05s + 1} e$

It can be observed that the dead time and time constant are increasing with increase in valve opening (and hence, PV) while the Gain values are decreasing steadily for the models obtained.

VI. CLOSED LOOP SIMULATION STUDY AND REAL TIME IMPLEMENTATION OF ANTI WINDUP STRATEGIES.

Back Calculation combined with Conditional Integration:

The SIMULINK diagram shown below consists of a PID controller with anti windup strategies of Back calculation combined with Conditional Integrator. It can be operated both in Back calculation mode and the combined Back calculation and Conditional Integration mode due to the presence of a switch.

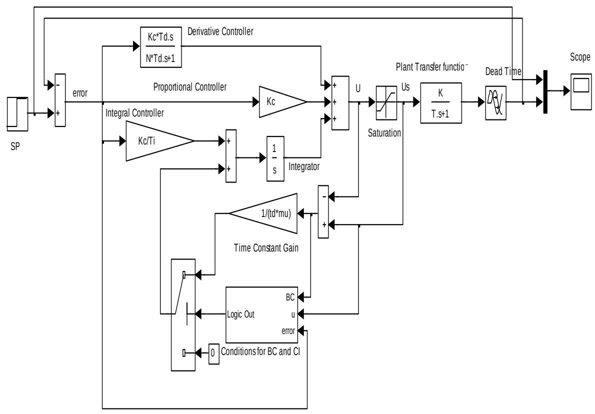

Fig 9. Simulink Model of Back Calculation method combined with conditional integration.

The closed loop responses were simulated using SIMULINK and the responses were obtained according to the following controller settings by Ziegler Nichols tuning:

$$Kc = 1.2 * T/(K * td) \qquad (11)$$

$$Ti = 2 * td \qquad (12)$$

$$Td = 0.5 * td \qquad (13)$$

$$ts = 0.1 \qquad (14)$$

N=10,mu=50,Actmin=0,Actmax=100,Emin= 0.001. Here N represents the filter coefficient for derivative action, mu represents the online tuning parameter for the Tracking time constant in Back calculation method, e_{min} represents the minimum error as defined by the conditional integration method and Act_{max} and Act_{min} represent the maximum and minimum saturation range.

The responses obtained for the above specifications are shown below.

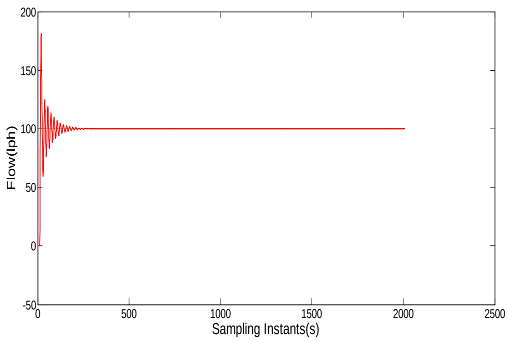

Fig 10. Closed loop response for K=3.4, T=0.78, td= 0.36, SP=100.

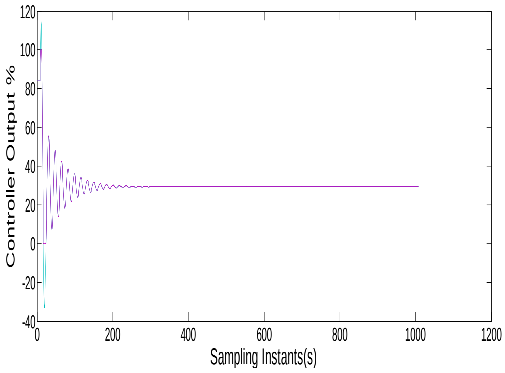

Fig 11. Controller Action of saturated and unsaturated control signal for K=3.4, T=0.78, td= 0.36, SP=100.

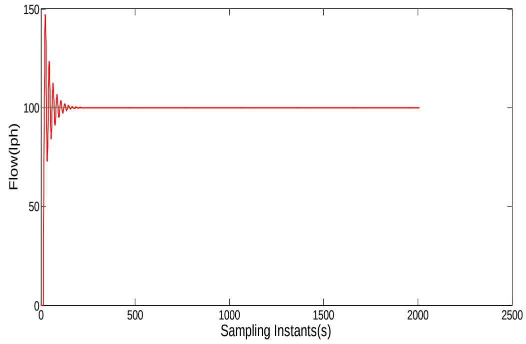

Fig 12. Closed loop response for K=2.105, T=0.78, td= 0.46, SP=100.

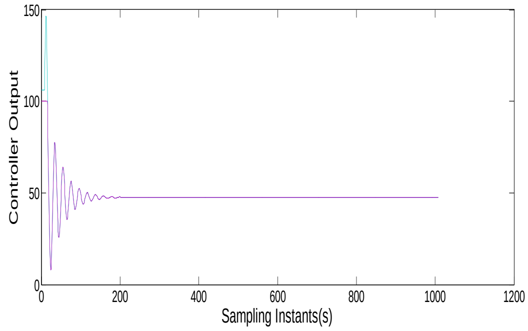

Fig 13. Controller Action of saturated and unsaturated control signal for K=2.105, T=0.78, td= 0.46, SP=100.

A. Real Time Implementation of Closed Loop System:

The closed loop responses of the flow station were taken using VI instruments process control software and Industrial tuning method was used for tuning the PID controller values.

The closed loop response for SP=250, Kp=1.8, Ki=0.02, Kd=1 is shown below:

Fig 14. Closed loop response of PID controller for SP=250, K_p=1.8, K_i=0.02, K_d=1.

VII. CONCLUSION

It can be concluded from the above open loop responses that the models obtained are validated as the gain values in Table II can be seen decreasing gradually with increase in valve opening and the dead time and the time constants are increasing gradually. The closed loop responses were simulated for the models and they were found to be satisfactorily tracking the set point. Hence it can be concluded that the back calculation and conditional algorithm is found to be effective and it manages to eliminate the windup phenomenon which is one of the most pertinent problems among the various control system nonlinearities.

VIII. FUTURE WORK

Currently the online implementation of the Back calculation and Conditional algorithm is underway and it is being tested on the Flow station for various PID structures. Itcan further be tested with various PID algorithms to find various methods of eliminating Integral windup and doing this would ensure great advancements in the field of Control systems due to the removal of nonlinearities in control valves.

IX. ACKNOWLEDGMENT

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