World Academy of Science, Engineering and Technology
International Journal of Electrical and Information Engineering
Vol:15, No:9, 2021

Method for Tuning Level Control Loops Based on Internal Model Control and Closed Loop Step Test Data

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***Abstract*—**This paper describes a two-stage methodology derived from IMC (Internal Model Control) for tuning a PID (Proportional-Integral-Derivative) controller for levels or other integrating processes in an industrial environment. Focus is ease of use and implementation speed which are critical for an industrial application. Tuning can be done with minimum effort and without the need of time-consuming open-loop step tests on the plant. The first stage of the method applies to levels only: the vessel residence time is calculated from equipment dimensions and used to derive a set of preliminary PI (Proportional-Integral) settings with IMC. The second stage, re-tuning in closed-loop, applies to levels as well as other integrating processes: a tuning correction mechanism has been developed based on a series of closed-loop simulations with model errors. The tuning correction is done from a simple closed-loop step test and application of a generic correlation between observed overshoot and integral time correction. A spin-off of the method is that an estimate of the vessel residence time (levels) or open-loop process gain (other integrating process) is obtained from the closed-loop data.

***Keywords*—**Closed-loop model identification, IMC-PID tuning method, integrating process control, on-line PID tuning adaptation.

I. Introduction

BASE Layer Controls in general, and PID loops in particular, are critical to maintain stable, safe and profitable operating conditions of plants in the process industries. Achieving optimum performance for these loops depend on a number of factors, including instrumentation in good operating condition (sensors as well as control valves), proper control strategy and last but not least adequate tuning. As an illustration, a set of case studies can be found in [1] with typical examples of control loop issues for various process industries. Additional information about practical aspects of loop tuning in an industrial environment and the economic incentive to improve the control loops performance can be found in [3]-[5].

Industrial automation companies such as Yokogawa have developed a wide range of systems, tools and methods to help get the most of the base layer controls. This paper focuses on loop tuning and specifically on loop tuning for integrating processes such as levels.

PID controllers for integrating processes is of special importance for a number of reasons:

1) It is a fairly wide class of control loops, not just tank levels but also many pressure control loops and even a number of temperature control loops,
2) These loops have a major impact on the overall plant stability: a mistuned, oscillatory level control causes oscillations on the rest of the downstream process equipment,
3) Tuning of integrating process loops is difficult and time consuming when done according to the traditional "open-loop" method. It is then required to operate the loop in manual mode while step tests are applied to the control valve. The data are then used to characterize the process response; this model in turn is used to derive the PID parameters. The step test in open-loop is troublesome to Process Operators, as special attention is required since integrating processes are by nature unstable in open-loop.
4) How to tune integrating process loops is quite different from tuning self-regulating loops; it is counter-intuitive in some aspects and very often misunderstood. For instance, increasing the PID proportional action for a level control generally reduces the response overshoot, quite the opposite effect compared to a self-regulating process.

The paper presents a two-stage methodology for tuning level control loops. In stage 1, equipment dimension data, readily available in the process documentation, is used to characterize the open-loop response in terms of the residence time. The residence time is used to derive the PI tuning parameters by application of the standard IMC tuning rules for an integrating process. This gives a theoretical, preliminary set of tuning parameters. In stage 2, the preliminary tuning parameters are applied to the loop; a closed-loop setpoint step test is executed in order to fine-tune the loop, according to the actually observed process response. The methodology has then been extended to integrating processes other than levels.

The paper provides the details of the method so that it can be used in practice for tuning integrating process PID loops. The method has been widely applied in an industrial environment as part of actual projects. The paper is also helpful to get a good understanding of the specificities of integrating process PID control.

II. Equipment Dimension Method for Tuning a Level Controller

Level control loops can be pre-tuned based on the vessel dimensions and the instruments characteristics. The data

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requirements are:

1) Vessel dimensions, obtained from P&ID's or mechanical diagrams: vessel type (horizontal or vertical), diameter, length.
2) Level instrument span (length in mm) obtained from level data sheets,
3) Flow data: if LC to valve loop: design flow and design valve information, obtained from control valve data sheets; if LC-FC cascade loop: FC instrument range.
4) Stream density if the valve data sheet or flow meter information is on a mass flow basis.

To illustrate the concept, a simple example is given here of a vertical cylindrical vessel.

- Vessel diameter: D = 4.6 m
- Level gauge height: H = 6 m
- Flowmeter range: Fmax = 20 m^3/min

The vessel residence time is then calculated as follows:

- Useful volume for level control:

$$V = \pi H D^2 / 4 \quad (1)$$

- Residence Time:

$$RT = V / Fmax = \pi H D^2 / (4 Fmax) \quad (2)$$

For the given numerical values, the resulting Residence Time is 4.986 minutes, therefore approximately 5 minutes.

Interpretation: Assuming as starting condition a stable level with equal inlet and outlet flows, a vessel residence time of 5 minutes implies that if the inlet flow is increased by 1% of the flowmeter range, then the level will ramp up at a steady rate of 1% in 5 minutes.

The inverse of the residence time is called the ramp process open-loop gain; in this case:

$$\text{Open-Loop Gain} = 1/ 5 = 0.2 \text{ min}^{-1} \quad (3)$$

The calculations in case of a horizontal vessel follow the same principles as given above for a vertical vessel; they are somewhat more complicated because of the presence of hemispherical or ellipsoidal heads at both ends of the cylindrical vessel. It should also be noted that strictly speaking, the residence time for a horizontal vessel is not fixed and depends on the level itself, since the liquid surface varies with the level. This effect is however in general neglected and the residence time calculated at a 50% level.

After calculating the vessel residence time, the IMC method is used to derive the PID controller settings.

IMC tuning is widely documented in the literature; see for instance one of the original publications [2]. The IMC tuning formulae for a level are given further in this article in (6) and (7). Three important points should be kept in mind:

1) IMC tuning relies on specifying one single parameter, the desired closed-loop time constant, that determines the speed of the controller response. In the variant of IMC used in this study, a dimensionless Loop Tuning Factor is used instead of the closed-loop time constant.
2) It is assumed in this paper that the open-loop response is an integrating process with no or negligible time delay. IMC then results in a set of P and I parameters, with 0 derivative action. So, a PI controller as opposed to PID.
3) The PID controller structure is the "classical" one, also referred to as "standard".

III. IMC Tuning Properties for an Integrating Process

Before explaining the second part of the tuning procedure, it is useful to point out the special properties of IMC tuning for integrating processes.

Table I below summarizes the results of a series of simulations of a PI level controller for an integrating process in closed-loop, tuned with IMC.

TABLE I
IMC Tuning as a Function of Process Gain and Loop Tuning Factor

			IMC PI parameters		Setpoint step change		Load disturbance step 1%	
Process Gain	Process Residence Time	Loop Tuning Factor	Controller Gain	Ti	Overshoot	Time when PV at max	Max. PV disturbance	Time when PV disturbance is maximum
(%PV per min / %MV)	*(min)*			*(min)*	*(%)*	*(min)*	*(%)*	*(min)*
0.1	10	0.5	2.67	15	13.8	14.4	0.28	7.4
0.1	10	1	1.33	30	13.8	28.5	0.56	14.3
0.1	10	2	0.67	60	13.8	57.0	1.11	28.5
0.2	5	0.5	2.67	7.5	13.7	7.2	0.28	3.6
0.2	5	1	1.33	15	13.8	14.4	0.56	7.4
0.2	5	2	0.67	30	13.8	28.5	1.11	14.3
0.4	2.5	0.5	2.67	3.75	13.7	3.7	0.28	1.9
0.4	2.5	1	1.33	7.5	13.7	7.2	0.56	3.6
0.4	2.5	2	0.67	15	13.8	14.4	1.11	7.4

Assumptions:

1) The process is a "pure" integrator, with negligible time delay and negligible first order dynamics.
2) Variables that have been tested at different values:

- Integrator Gain i.e., inverse of the vessel residence time in case of a level; the gain is expressed in %PV per minute / % MV);
- IMC Loop Tuning Factor: 0.5, 1 and 2. The loop tuning

factor in IMC sets the desired closed-loop speed of response. A larger loop tuning factor gives a longer closed-loop response time.

3) Two scenarios are considered:
- Application of setpoint step change,
- Application of load step change

For illustration, the simulated IMC responses to a setpoint step change and load step change are shown in Figs. 1 and 2 below. This is for the case Process Gain = 0.2, Loop Tuning Factor = 1.

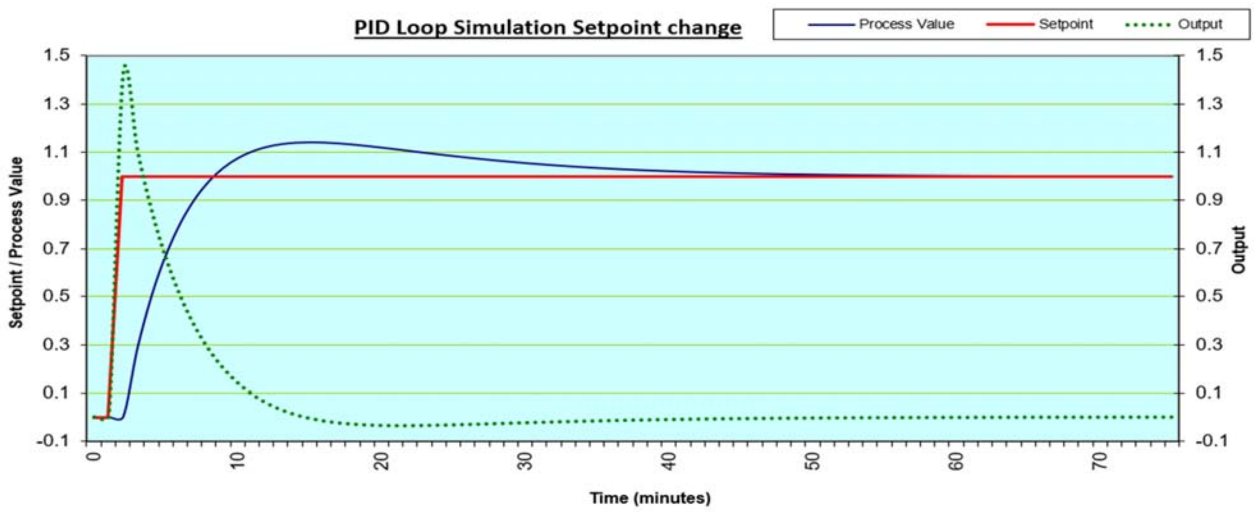

Fig. 1 Closed-loop setpoint change response with IMC tuning

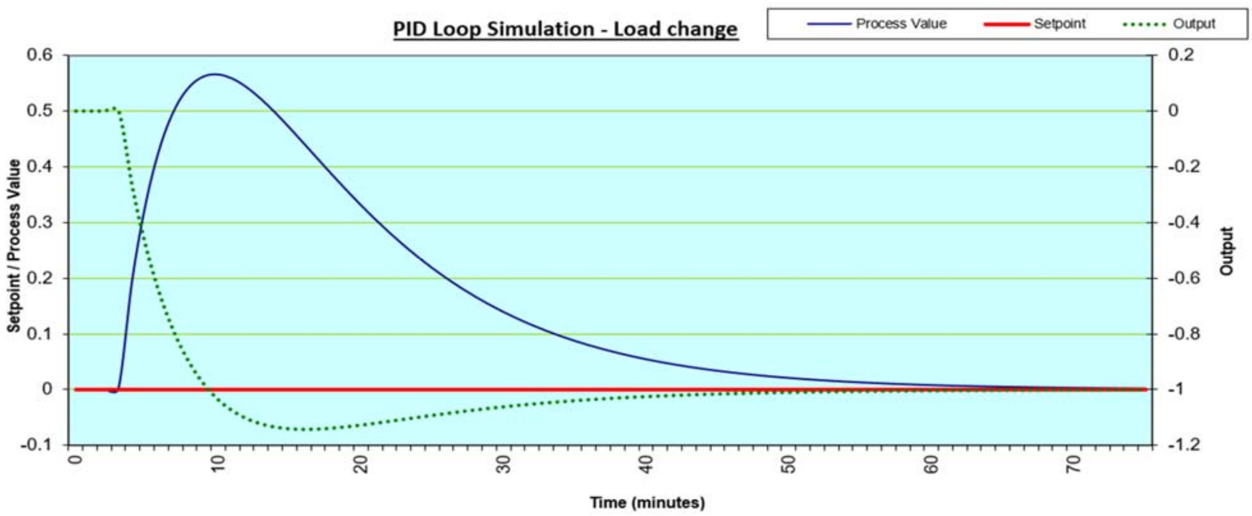

Fig. 2 Closed-loop load change response with IMC tuning

The results in Table I illustrate a number of key properties of IMC for an integrating process:

1) IMC tuning always gives an overshoot of about 14% for the PV response to a setpoint step change, independently of the process gain and of the loop tuning factor.
2) There is a one-to-one relationship between Loop Tuning Factor and controller gain, independently of the process gain. **In other words, whatever the process open-loop gain, the controller gain can be set according to the desired closed-loop speed of response**, say 0.5 for a fast response, 1 for an average speed response and 2 for a slow response.
3) The difficulty is setting the integral action Ti; this latter parameter depends on the desired speed as well as the process characteristic i.e., the open-loop process gain.
4) The Loop Tuning Factor determines the closed-loop speed of response in terms of:
   - how fast the PV reaches its maximum value in response to a setpoint change,
   - how fast a load disturbance is compensated for and how large the maximum level disturbance is.
5) In first approximation, the IMC Integral Time Ti is equal to the time when the PV reaches its maximum in response to a setpoint change.

IV. Practical Procedure for PI Tuning of a Level Controller

Pre-tuning the level controller based on the vessel dimensions and the instruments characteristics as explained in Section II will give a reasonable preliminary tuning with which the controller can be operated in automatic mode. It is however not sufficient. The residence time calculation is in general not accurate, in particular in case of a LC loop direct to the control valve because of the significant valve non-linearity. Fine-tuning the loop is therefore almost always necessary.

In this method, fine tuning is done based on executing a closed-loop step test, characterizing the observed response in terms of percent overshoot and applying a generic correction of the controller integral time parameter. In summary, the advocated tuning method for a level controller is a two-stage procedure as follows:

Stage 1: Preliminary tuning via Equipment dimension method and application of IMC tuning rules.

1) P or the Proportional Band (=100/P) only depends on the desired Loop Tuning Factor, whatever the Residence Time is.
2) Ti on the other hand depends on the Residence Time as well as the chosen Loop Tuning Factor. It is therefore necessary to have at least a rough estimate of the Residence Time to determine Ti.
3) The Residence time of the vessel can be calculated using the Equipment dimensions method described earlier; then the IMC tuning rules can be applied.

Stage 2: Re-tuning in closed-loop.

1) A closed-loop step test should be performed in order to check the performance of the preliminary IMC settings. Re-tuning/fine-tuning is done by application of a tuning correction graph described in section V,
2) Re-tuning in principle only concerns Ti; P can be kept constant since it only depends on the chosen Loop Tuning Factor.
3) Re-tuning Ti is completed when the closed-loop response to a setpoint change matches the IMC characteristics, i.e.:
   - Overshoot 14%, and
   - Ti about equal to the time of the first PV maximum.
4) A generic correlation between observed overshoot and integral time correction has been developed to make it easy to re-tune Ti based on the closed-loop step response. This is presented in the next section.

V. Integral Action Correction and Residence Time Estimation from Closed-Loop Test

A. Ti tuning correction in Closed-Loop

The Ti tuning correction mechanism has been developed based on a series of closed-loop simulations with a model error for the vessel residence time.

Principle of the simulations:

1) Reference case: Process Gain = 0.2; reference IMC tuning calculated with Loop Tuning Factor = 1. This gives Controller Gain = 1.333 and Ti = 15 minutes;
2) The Process Gain is then changed by increments from 0.015 to 1.5 and closed-loop setpoint step test simulations are run for all the cases **while keeping the controller settings the same**;
3) For each case:
   - the corresponding PV overshoot is recorded,
   - the IMC-Ti value is calculated for the Process Gain, with Loop Tuning Factor kept at 1.
4) This gives the Ti Correction Factor = IMC-Ti/ Reference IMC-Ti.

The results are given in Table II.

TABLE II
Closed-Loop Simulation Results with Process Gain Model Error

Process Gain	Process Residence Time	Setpoint step change		Ti-Corrected	Ti-Corrected / Ti
		Overshoot	Time when PV at max		
(%PV per min / %MV)	*(min)*	*(%)*	*(min)*	*(min)*	
0.015	66.7	47.6	70.0	200	13.3
0.0175	57.1	45.7	67.2	171	11.4
0.02	50.0	43.6	62.0	150	10.0
0.027	37.0	39.1	52.2	111	7.4
0.035	28.6	35.2	44.5	86	5.7
0.05	20.0	30.0	35.7	60	4.0
0.1	10.0	21.0	23.1	30	2.0
0.2	5.0	13.8	14.4	15	1.0
0.3	3.3	10.4	10.5	10	0.67
0.4	2.5	8.5	8.4	8	0.50
0.5	2.0	7.2	7.0	6	0.40
0.75	1.3	5.2	4.9	4	0.27
1	1.0	4.1	3.9	3	0.20
1.5	0.7	3.0	2.1	2	0.13

A graph that gives the Ti correction factor as a function of the observed overshoot has then been derived from Table II and is shown in Fig. 3. A logarithmic scale has been used for Ti - Corrected / Ti in order to give a proper resolution below 1.

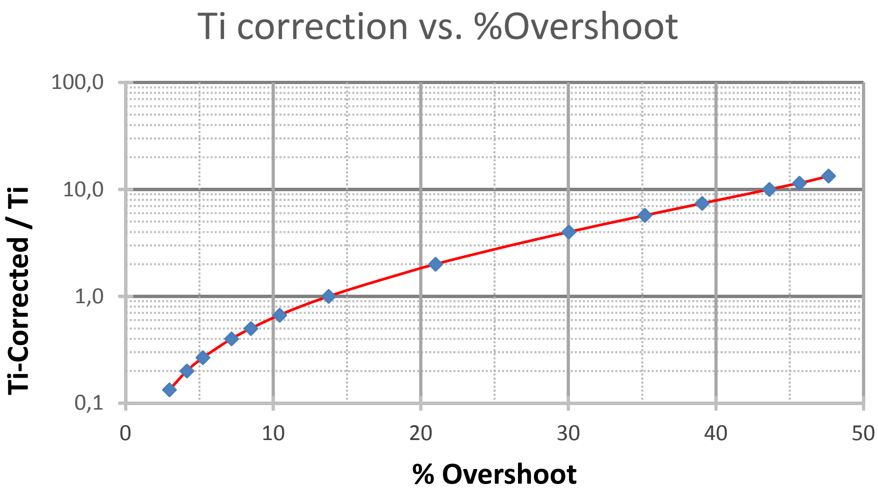

Fig. 3 IMC Ti Correction Graph

As a check that the results are generic, two other sets of simulations have been run with a different reference case; these give the same results in terms of Ti-Corrected / Ti:

- Process Gain 0.2, Loop Tuning Factor 2,
- Process Gain 0.3, Loop Tuning Factor 1.

B. Practical use of the IMC Ti Correction Graph

It is assumed that the level controller has been pre-tuned, preferably via IMC, based on a preliminary estimation of the Vessel Residence Time. The PI tuning parameters are denoted Gain, Ti.

With the controller in AUTO mode, apply a step test on the setpoint when the level is stable. Determine the observed overshoot and time of the first maximum.

If the overshoot is about 14%, no need to correct Ti; the loop response already matches an IMC response.

If overshoot is different from 14% (too large or too small), then change Ti according to:

$$\text{Corrected Ti} = \text{Ti Correction Factor} * \text{Ti} \qquad (4)$$

where the Ti Correction Factor is read from the IMC Ti Correction Graph in Fig. 3.

Repeat the ssetpoint step test and verify that the overshoot is now close to 14%. The time of the first PV maximum should also be roughly equal to the corrected Ti.

C. Vessel Residence time estimation

An additional outcome of the closed-loop step test is that it can also give an estimate of the Vessel Residence time. The IMC Ti Correction Graph can therefore also be used for the closed-loop model estimation of the integrating process characteristic, with the following formula:

Vessel Residence Time =

$$\text{Controller Gain} * \text{Ti Correction Factor} * \text{Ti} / 4 \qquad (5)$$

where:

- Vessel Residence Time (min)
- Controller Gain (%MV / %PV)
- Ti (min)

The formula is applicable whatever the original PI settings are, whether calculated via IMC or not; it is applicable to levels as well as other integrating processes.

Derivation of the formula for the Vessel Residence Time estimation:

Notations:

- RT: Residence time (min)
- G: Controller Gain (%MV / %PV)
- Ti: Controller Integral Time before correction (min)
- Corrected-Ti: Controller Integral Time after correction (min)
- LTF: IMC Loop Tuning Factor
- TCF: Ti Correction Factor

IMC tuning rules for level control, assuming no time delay between controller output and level PV:

$$G = 2 / (1.5 * \text{LTF}) \qquad (6)$$

$$\text{Corrected Ti} = 3 * \text{RT} * \text{LTF} \qquad (7)$$

Combining (6) and (7):

$$G * \text{Corrected Ti} = 4 * \text{RT} \qquad (8)$$

Ti correction based on closed-loop set point step test:

$$\text{Corrected-Ti} = \text{TCF} * \text{Ti} \qquad (9)$$

Combining (8) and (9):

$$G * \text{Corrected-Ti} = G * \text{TCF} * \text{Ti} = 4 * \text{RT} \qquad (10)$$

Therefore:

$$RT = G * TCF * Ti / 4 \quad (11)$$

VI. Application of Methodology to a Non-Level Integrating Process

Not only levels are integrating processes. Other variables such as pressure or temperature (e.g., tray temperature in special distillation columns) also can have an integrator behavior. The same method is applicable in these cases.

The difference is that strictly speaking there is no physical vessel and no "residence time" for such variables. Instead, it is more appropriate to use the Process Gain, equal to the inverse of the residence time.

Assuming that the integrating variable controller has been pre-tuned by whatever method with given values for the PI parameters, the second part of the method can then be applied as follows:

1) Conduct closed-loop setpoint step test,
2) Observe PV overshoot,
3) Use IMC Ti Correction Graph to get the Ti Correction Factor,
4) Apply Process Gain estimation formula derived from (11):

$$\text{Process Gain (\%PV per min / \% MV)} = 4 / (G * TCF * Ti) \quad (12)$$

5) Apply IMC based on the estimated Process Gain.

VII. Examples from Actual Loop Tuning Project

Two examples are given in this section of control loops from an industrial process that have been tuned by application of the presented methodology as part of a Loop Tuning and Base Layer Control improvement project. The tag names have been changed for confidentiality reasons.

A. Level Control Loop

The preliminary tuning for this loop is:

- Gain = 2
- Ti = 2.5 min

The controller behavior, including a setpoint step test is shown in Fig. 4.

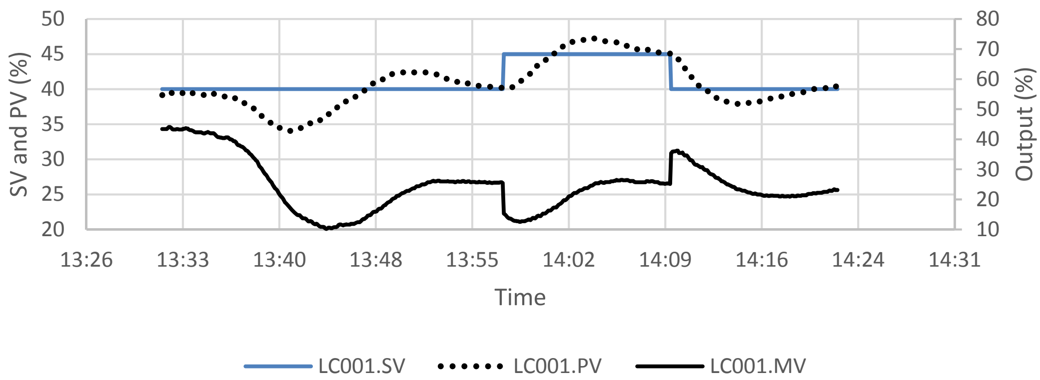

Fig. 4 Preliminary loop response; Gain = 2, Ti =2.5 min

The average PV overshoot resulting from the setpoint changes is excessive, about 43%. By application of the Ti correction graph, the Ti multiplicative factor is 9. Therefore, the corrected Ti value is 2.5 * 9 = 22.5 min.

The controller behavior with the new settings Gain = 2, Ti = 22.5 min is shown in Fig. 5.

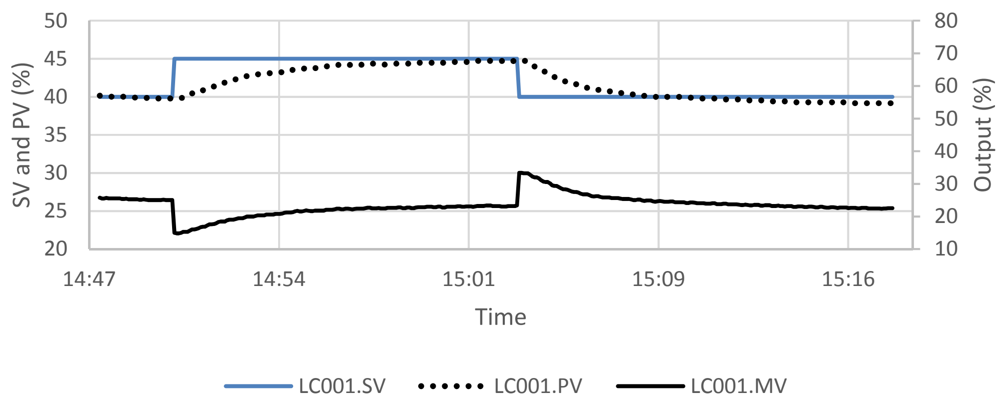

Fig. 5 Loop response after correction; Gain = 2, Ti =22.5 min

The residence time estimation gives the following result:

RT = G * TCF * Ti / 4 = 2 * 9 * 2.5 / 4 = 11.25 min.

Faster tuning has been tested, by application of IMC using the estimated residence time, and desired closed loop speed twice as fast. This gives a controller gain multiplied by 2 and Ti divided by 2, therefore: Gain = 4, Ti = 11.25 min. The corresponding controller behavior is shown in Fig. 6.

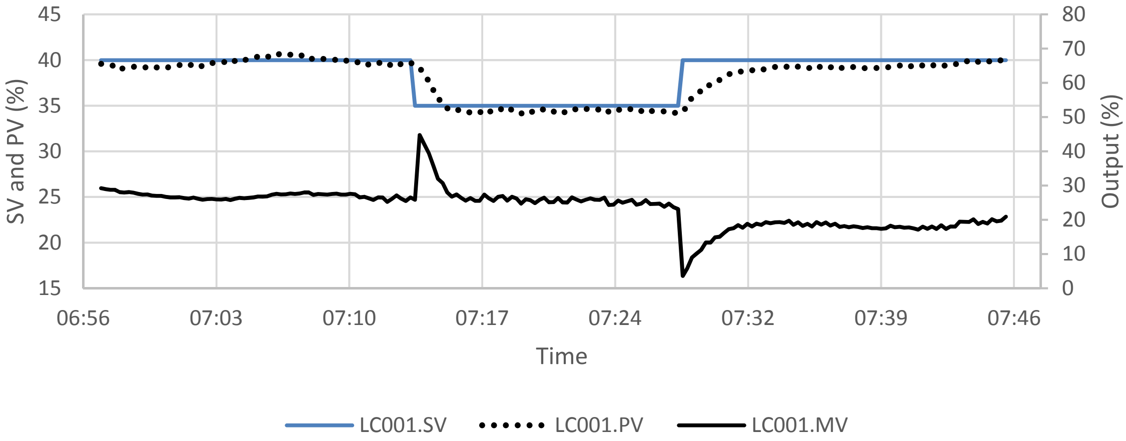

Fig. 6 Loop response with fast tuning; Gain = 4, Ti =11.25 min

B. Pressure Control Loop

In this case, a total of four setpoint steps have been applied. The first two steps with the preliminary PI settings and the last two steps with the corrected Ti.

The corresponding trends are given in Fig. 7. It should be noted that step 3 and step 4 are twice as large as step 1 and step 2. So, it can be seen that the PV response % overshoot has been reduced as expected, although on the graph the absolute values of the overshoot appear to be similar.

TABLE III
PRESSURE CONTROL STEP TESTS RESULTS

Step #	Step Size (barg)	Controller Gain	Controller Ti (min)	Overshoot (%)
1	0.1	10	10	36
2	0.1	10	10	26
3	0.2	10	42	14
4	0.2	10	42	7

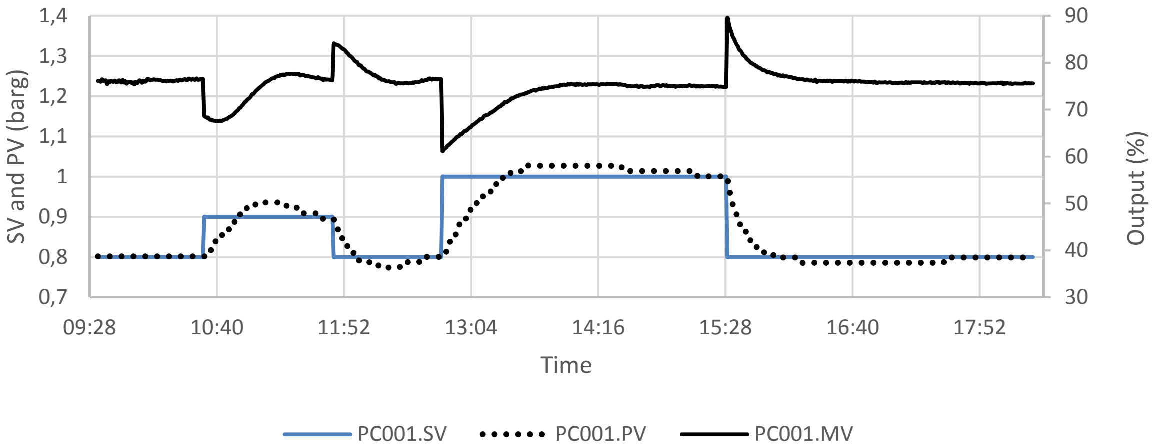

Fig. 7 Pressure controller trends before and after Ti correction

VIII. CONCLUSION

Integrating process control loops, including levels as well as many pressure loops and also a number of temperature loops, form a wide class of controllers in the process industry for which proper tuning is critical to stabilize operation and operate the plant safer and more profitably.

The method developed in this paper to tune PI loops for integrating processes is summarized as follows:

For levels: two stage procedure with the first stage of preliminary tuning based on exploiting equipment dimension data and application of the IMC tuning rules; re-tuning as a second stage via correction of the integral action from a closed-loop step test and use of graph in Fig. 3 to determine the Ti correction factor.

For non-level integrating processes: Assuming any initial PI settings, conduct a closed-loop step test; use the process gain estimation formula from (12) and apply IMC with the estimated gain via (6) and (7).

The method is easy to use and applicable with minimum effort; it avoids the time consuming and troublesome open-loop test required in a traditional tuning approach.

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