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Energy Procedia 117 (2017) 1109–1116

Energy Procedia

www.elsevier.com/locate/procedia

1st International Conference on Power Engineering, Computing and CONtrol, PECCON-2017, 2-4 March 2017, VIT University, Chennai Campus

Online Auto Selection of Tuning Methods and Auto Tuning PI Controller in FOPDT Real Time Process-pH Neutralization

Naregalkar Akshay[a,*], D. Subbulekshmi[b]

[a,b]*School of Electrical Engineering, VIT University ,Chennai-600127,India*

Abstract

This paper aims to design an algorithm to identify Transfer Function of First Order Plus Dead Time (FOPDT) process by using Process Reaction Curve(PRC) identification method, auto selection of tuning methods using Ziegler- Nichols(Z-N), Astrom-Hagglund (A-H), Tsang-Rad(T-R), Fruehauf(FF) and Internal Model Controller (IMC),ITAE-1 tuning rules ITAE -1 for set point tracking(ITAE-1 SP) and disturbance rejection (ITAE-1 DR) and updating PI Controller parameters calculated for selected tuning method to meet optimized controller parameters. The performance of different tuning methods for various case studies of FOPDT processes were simulated and analyzed first and then real time plant- pH neutralization was controlled with proposed algorithm implemented in LabVIEW software.

Keywords:
Auto tuning;Auto Selection;PI Controller ;Gain scheduling;FOPDT process;pH; neutralization; waste water; LabVIEW.

1. Introduction

The Proportional Integral(PI) controller performance mainly depends on the selection of proper controller parameters like Proportional Gain (Kp) and Integral Time (Ti) which is done by suitable Controller tuning method[4],[5] . These controller parameters has to be changed as per the process to be controlled .As the process parameters like Process Gain , Dead Time and Time constant are varying process to process ,there is a need to select a proper tuning method to retune the controller .This will help to control the process (to be controlled) effectively[6],[7],[8]. The pH measurement is very useful in different applications like agriculture, food processing,

* Corresponding author. Tel.: +91-9676954353.
E-mail address: nareg.akshayrangnath2014@vit.ac.in

10.1016/j.egypro.2017.05.235

biochemical processes and industrial applications. Among industrial applications, maintaining pH of the waste water coming out from the industries is very important as this water may contain toxic substances which may harms human being, degrade soil quality and pollute water resources, thereby causing great impact on society. The automatic control systems with PID Controllers are used in industries to neutralize waste water effectively [1], [2], [3]. The effective controller performance depends of suitable tuning method selection and adjusting or scheduling PID Controller parameters as per the variation in plant parameters and disturbances affecting the waste water treatment plant operation [13].

2. **Experimental Set Up**

The experimental set up under study is a pH neutralization process plant as shown in Fig.1(a) and its Instrumentation & control is shown in Fig.1(b).

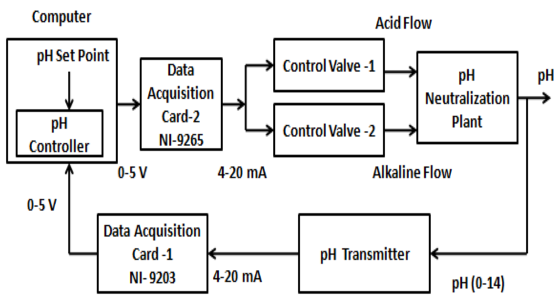

Fig.1 (a) Experimental Set Up under Study; (b) Instrumentation and Control for Experimental Set Up

The real time control algorithm is implemented such that if waste water is acidic in nature then the flow rate of alkaline solution is increased and acid flow rate is decreased vice versa by controlling flow rates to neutralize the waste water. Further it maintains the pH of waste water to neutral region in reactor tank in presence of disturbances such as temperature [19],[20]. The experimental set up is a First Order Plus Dead Time (FOPDT) which is described by equation (1) in which three parameters viz. K-process gain that describes how much a process variable can be changed and in which direction , T –time constant that tells how fast process variable can responds and Ɵ- dead time associated with process.

$$G(s) = \frac{k}{Ts+1} * e^{-\theta s} = \frac{7.0921}{8.54s+1} * e^{-1.71s} \quad (1)$$

These three process parameters are identified using Process Reaction Curve (PRC) Method standard procedure [9],[10],[11],[12],[14],[21].

3. Analysis of Tuning Methods Used In Proposed Design Implementation

In this paper, seven different tuning methods are used to analyze and select controller tuning parameters under different process parameters and constraints like process gain, time constant, dead time, disturbances and dynamics of process. These tuning methods are Z-N, A-H, T-R, FF, IMC, ITAE-1(set point tracking) and ITAE-1(disturbance rejection). The table 1 gives the formulae provided in each methods[4],[5],[6],[9],[10],[11], [13],[14],[15],[16] ,[17].

4. Proposed Method

Flow chart shown in Fig.2 describes the design flow of proposed method used for Online Auto switching of Tuning Methods and Gain Scheduling of Controller. The implantation done in such a way that the plant model will be identified first and then the identified plant parameters K, T, Ɵ and constraints like disturbance will decide suitable tuning method. After that the tuning parameters for the selected tuning method will be calculated based on formulae implemented. And these calculated tuning parameters Kp and Ti will update or retune PI controller. This retuned and updated PID Controller will be used to control the process/plant under study. As the PI controller parameters are selected based on constraints and plant parameters, the plant can be controlled effectively.

Table 1. PI Controller Parameter Calculation Formulae

	Z-N	A-H	T-R	FF	IMC	ITAE1(SP)	ITAE1(DR)
Kp	0.45*Ku	$\frac{0.94}{ku}$	$\frac{0.809*T}{\theta*K}$	$\frac{5}{9}*K$	$\frac{(2T+\theta)}{2\lambda K}$	$0.586\left(\frac{\theta}{T}\right)^{-0.916}*\frac{1}{K}$	$0.859\left(\frac{\theta}{T}\right)^{-0.977}*\frac{1}{K}$
Ti	Tu/1.2	$2*Tu$	T	$5*\theta$	$T+\frac{\theta}{2}$	$\frac{T}{1.030-0.165\left(\frac{\theta}{T}\right)}$	$\frac{T}{0.674\left(\frac{\theta}{T}\right)^{-0.680}}$

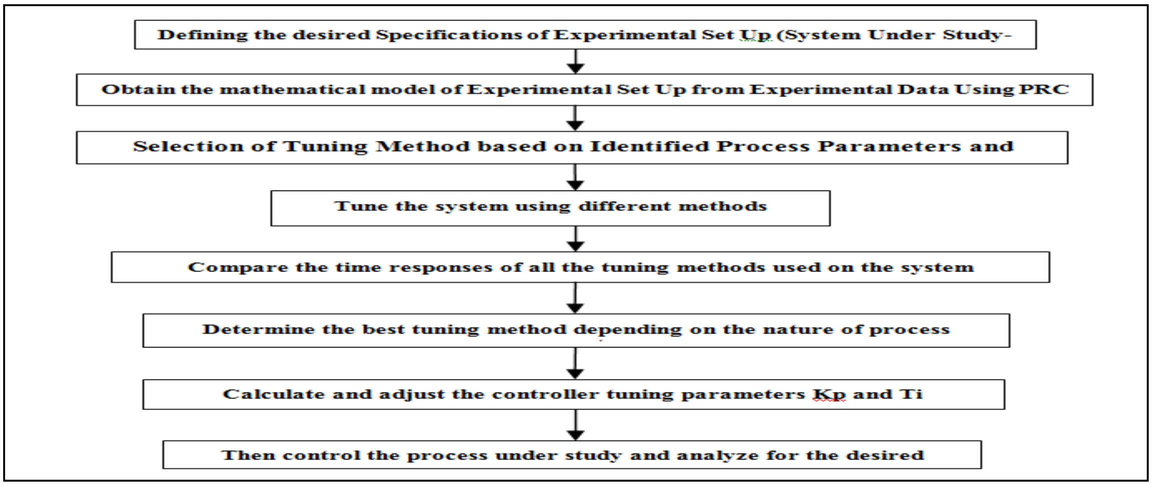

Fig.2 Flow chart for Proposed Design Implementation

5. Simulated Results using Proposed Algorithm for Auto switching and Selection of Suitable Tuning Method and Controller Parameter Updating (Re-tuning)

Different ten cases are used in this study to represent different plants and for them tuning parameters selected are automatically by selecting switched tuning method with controller performance. The different constraints used to select and switch to a suitable tuning method automatically are dynamics of process i.e. slow or fast, process gain low, medium or high, dead time small, medium or large and effect of disturbance like temperature. The Controller performance is evaluated using time response parameters Rise Time (Tr), Settling Time (Ts) and % Peak overshoot (%Mp) under different plant operating conditions and plant parameters. The rise time curve in seconds is indicated with blue color line and the settling time curve in seconds is indicated with orange color line from Fig.3 to Fig. 5.

5.1. Case Study 1

In this case study 1, a FOPDT process with smaller process gain, Time Constant and Dead time is considered given by equation (2).

$$G(s) = \frac{2}{s+1} * e^{-0.2S} \tag{2}$$

Table 2(a) and Fig.3 (a) shows the performance of PI Controller with different tuning methods and indicates that Z-N tuning method can give required performance, but gives overshoot. The T-R tuning method gives best response as the settling time required for output response at set point is the smallest among all the tuning methods. In case of disturbance rejection, ITAE-1(DR) tuned controller can reject it quickly and forces output to steady state again.

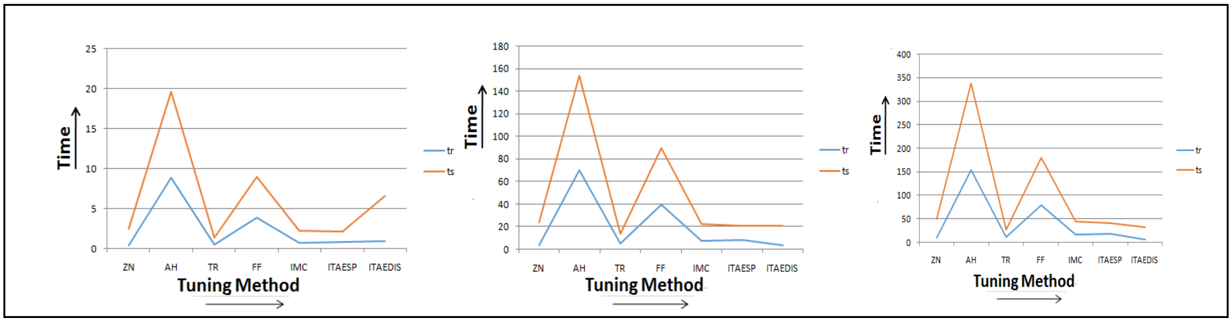

Fig.3 Comparison of PI Controller with Different Tuning Methods for (a) Process-1; (b) Process-2; (c) Process-3

Table 2. Tuning Method wise PI Controller parameters Settings and its time response for (a) Case Study 1; (b) Case Study 2

(a) Case Study 1						(b) Case Study 2					
Tuning Method	Kp	Ti (sec)	Tr (sec)	Ts (sec)	Mp (%)	Tuning Method	Kp	Ti (sec)	Tr (sec)	Ts (sec)	Mp (%)
Z-N	1.932	0.66	0.432	2.52	3.72	Z-N	1.93	5.41	4.11	23.84	6.21
A-H	0.22	1.6	8.91	19.6	0.01	A-H	0.22	13	69.98	153.95	0.01
T-R	2.02	1	0.543	1.38	0.01	T-R	2.02	10	5.43	13.84	0.01
FF	0.277	1	3.96	9.0	0.01	FF	0.28	10	39.6	90.0	0.01
IMC PID	1.62	1.1	0.773	2.26	0.01	IMC PID	1.62	11	7.73	22.61	0.01
ITAE1(SP)	1.28	1	0.857	2.10	0.01	ITAE1(SP)	1.28	10.03	8.57	21.05	0.01
ITAE1(DR)	2.07	2.14	0.93	6.63	0.01	ITAE1(DR)	2.07	4.46	3.89	21.01	8.56

5.2. Case Study 2

In this case study 2, a FOPDT process with smaller process gain, medium Time Constant and smaller Dead time is considered given by equation (3).

$$G(s) = \frac{2}{10s+1} * e^{-2S} \quad (3)$$

Table 2(b) and Fig. 3(b) shows the performance of PI Controller with different tuning methods and indicates that Z-N tuning method can give required performance (with faster rise time) with quickly responding to change in process dynamics, but gives overshoot. The T-R tuning method gives best response as the settling time required for output response at set point is the smallest among all the tuning methods. In case of disturbance rejection, ITAE-1(DR) tuned controller can reject it quickly and forces output to steady state again.

5.3. Case Study 3

In this case study 3, a FOPDT process with smaller process gain, large Time Constant and medium Dead time is considered given by equation (4).

$$G(s) = \frac{2}{20s+1} * e^{-4S} \quad (4)$$

Table 3(a) and Fig 3(c) shows the performance of PI Controller with different tuning methods and indicates that the T-R tuning method gives best response as the settling time required for output response at set point is the smallest among all the tuning methods. In case of disturbance rejection, ITAE-1(DR) tuned controller can reject it quickly and forces output to steady state again. As the dead time is increasing, the Z-N tuned PI controller response is showing more overshoot.

5.4. Case Study 4

In this case study 4, a FOPDT process with medium process gain, small Time Constant and smaller Dead time is considered given by equation (5).

$$G(s) = \frac{10}{1s+1} * e^{-0.2s} \tag{5}$$

Table 3(b) and Fig.4 (a) shows the performance of PI Controller with different tuning methods and indicates that in case of disturbance rejection, ITAE-1(DR) tuned controller can reject it quickly and forces output to steady state again, Z-N tuning method can give required performance (with faster rise time) with quickly responding to change in process dynamics, but little overshoot which can be tolerated. The T-R tuning method gives best response as the settling time required for output response at set point is the smallest among all the tuning methods.

Table 3: Tuning Method wise PI Controller parameters settings and its time response for (a) Case Study 3; (b) Case Study 4

(a) Case Study 3						(b) Case Study 4					
Tuning Method	Kp	Ti (sec)	Tr (sec)	Ts (sec)	Mp (%)	Tuning Method	Kp	Ti (sec)	Tr (sec)	Ts (sec)	Mp (%)
Z-N	1.93	11.6	8.22	49.32	5.31	Z-N	0.39	0.75	0.48	2.41	2.44
A-H	0.22	28	153.76	338.2	0.01	A-H	1.09	1.80	0.24	2.94	0.01
T-R	2.02	20	10.87	27.68	0.01	T-R	0.40	1	0.54	1.38	0.01
FF	0.28	20	79.20	180.0	0.01	FF	0.06	1	3.95	8.99	0.01
IMC PID	1.62	22	15.47	45.23	0.01	IMC PID	0.32	1.1	0.77	2.26	0.01
ITAE1(SP)	1.28	20.0	17.15	42.11	0.01	ITAE1(SP)	0.26	1	0.85	2.1	0.01
ITAE1(DR)	2.07	5.57	5.57	32.02	15.25	ITAE1(DR)	0.41	2.14	0.93	6.63	0.01

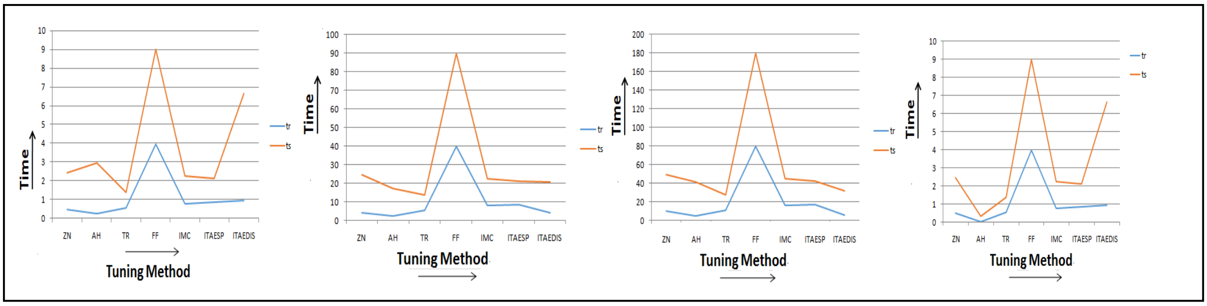

Fig.4 Comparison of PI Controller with Different Tuning Methods for (a) Process-4; (b) Process-5; (c) Process-6; (d) Process-7

5.5. Case Study 5

In this case study 5, a FOPDT process with medium process gain, medium Time Constant and smaller Dead time is considered given by equation (6).

$$G(s) = \frac{10}{10s+1} * e^{-2s} \tag{6}$$

Table 4(a) and Fig.4(b) shows the performance of PI Controller with different tuning methods and indicates that the T-R tuning method gives best response as the settling time required for output response at set point is the smallest among all the tuning methods.

5.6. Case Study 6

In this case study 6, a FOPDT process with medium process gain, large Time Constant and medium Dead time is considered given by equation (7).

$$G(s) = \frac{10}{20s+1} * e^{-4S} \quad (7)$$

Table 4(b) and Fig.4(c) shows the performance of PI Controller with different tuning methods and indicates that the T-R tuning method gives best response as the settling time required for output response at set point is the smallest among all the tuning methods.

Table 4: Tuning Method wise PI Controller parameters settings and its time response For (a) Case Study 5; (b) Case Study 6

(a) Case Study 5						(b) Case Study 6					
Tuning Method	Kp	Ti (sec)	Tr (sec)	Ts (sec)	Mp (%)	Tuning Method	Kp	Ti (sec)	Tr (sec)	Ts (sec)	Mp (%)
Z-N	0.39	5.83	4.10	24.64	5.31	Z-N	0.39	12.4	9.85	49.28	4.46
A-H	1.09	14	2.31	17.44	0.01	A-H	1.09	30	4.60	41.47	0.01
T-R	0.40	10	5.43	13.84	0.01	T-R	0.40	20	10.87	27.68	0.01
FF	0.06	10	39.59	89.99	0.01	FF	0.06	20	79.19	179.9	0.01
IMC PID	0.32	11	7.73	22.61	0.01	IMC PID	0.32	22	15.47	45.23	0.01
ITAE1(SP)	0.26	10.0	8.57	21.05	0.01	ITAE1(SP)	0.26	20.0	17.15	42.11	0.01
ITAE1(DR)	0.41	4.46	3.89	21.016	8.56	ITAE1(DR)	0.41	5.57	5.57	32.02	15.2

5.7. Case Study 7

In this case study 7, a FOPDT process with large process gain, small Time Constant and smaller Dead time is considered given by equation (8).

$$G(s) = \frac{20}{1s+1} * e^{-0.2S} \quad (8)$$

Table 5: Tuning Method wise PI Controller parameters settings and its time response For (a) Case Study 7;(b) Case Study 8

(a) Case Study 7						(b) Case Study 8					
Tuning Method	Kp	Ti (sec)	Tr (sec)	Ts (sec)	Mp (%)	Tuning Method	Kp	Ti (sec)	Tr (sec)	Ts (sec)	Mp (%)
Z-N	0.19	0.62	0.49	2.46	4.46	Z-N	0.19	6.24	4.93	24.65	4.46
A-H	2.187	1.5	0.04	0.33	0.01	A-H	2.18	15	0.49	3.35	0.01
T-R	0.20	1	0.54	1.38	0.01	T-R	0.20	10	5.43	13.84	0.01
FF	0.03	1	3.96	9.002	0.01	FF	0.02	10	39.60	90.02	0.01
IMC PID	0.16	1.1	0.77	2.26	0.01	IMC PID	0.16	11	7.73	22.62	0.01
ITAE1(SP)	0.13	1	0.85	2.1	0.01	ITAE1(SP)	0.12	10	8.57	21.05	0.01
ITAE1(DR)	0.21	2.14	0.93	6.63	0.01	ITAE1(DR)	0.20	4.46	3.89	21.01	8.56

Table 5(a) and Fig.4 (d) shows the performance of PI Controller with different tuning methods and indicates that the Z-N tuning method can give required performance (with faster rise time) with quickly responding to change in process dynamics, but gives overshoot. The T-R tuning method gives best response as the settling time required for output response at set point is the smallest among all the tuning methods. Also ITAE-1(SP) tuning method gives good response.

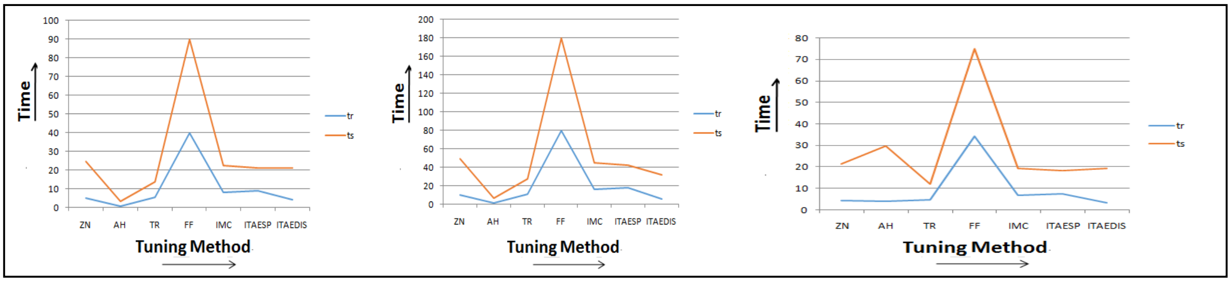

Fig.5 Comparison of PI Controller with Different Tuning Methods for (a) Process-8; (b) Process-9; (c) Process-10

5.8 .Case Study 8

In this case study 8, a FOPDT process with large process gain, small Time Constant and smaller Dead time is considered given by equation (9).

$$G(s) = \frac{20}{10s+1} * e^{-2S} \tag{9}$$

Table 5(b) and Fig.5 (a) shows the performance of PI Controller with different tuning methods and indicates that the T-R tuning method gives best response as the settling time required for output response at set point is the smallest among all the tuning methods. In case of disturbance rejection, ITAE-1(DR) tuned controller can reject it quickly and forces output to steady state again but it introduces overshoot in output response.

5.9. Case Study 9

In this case study 9, a FOPDT process with large process gain, Time Constant and medium Dead time is considered given by eq. (10).

$$G(s) = \frac{20}{20s+1} * e^{-4S} \tag{10}$$

Table 6(a) and Fig.5 (b) shows the performance of PI Controller with different tuning methods and indicates that Z-N tuning method gives overshoot and the A-H tuning method gives best response as the settling time required for output response at set point is the smallest among all the tuning methods. In case of disturbance rejection, ITAE-1(DR) tuned controller can reject it quickly and forces output to steady state again but it introduces overshoot in output response.

Table 6: Tuning Method wise PI Controller parameters settings and its time response For Case Study 8 (a) Case Study 9; (b) Case Study 10

(a) Case Study 9						(b) Case Study 10					
Tuning Method	Kp	Ti (sec)	Tr (sec)	Ts (sec)	Mp (%)	Tuning Method	Kp	Ti (sec)	Tr (sec)	Ts (sec)	Mp (%)
Z-N	0.193	12.07	9.86	49.3	4.88	Z-N	0.53	5.41	4.24	21.24	4.3
A-H	2.18	29	0.99	6.71	0.01	A-H	0.78	13	4.01	29.56	0.01
T-R	0.20	20	10.8	27.68	0.01	T-R	0.56	8.53	4.65	11.83	0.01
FF	0.027	20	79.2	180.04	0.01	FF	0.07	8.55	34.1	75.04	0.01
IMC PID	0.16	22	15.4	45.24	0.01	IMC PID	0.45	9.39	6.61	19.33	0.01
ITAE1(SP)	0.12	20.06	17.1	42.1	0.01	ITAE1(SP)	0.36	8.56	7.33	18.00	0.01
ITAE1(DR)	0.020	5.57	5.57	32.02	15.25	ITAE1(DR)	0.58	4.24	3.32	19.29	7.2

5.10. Case Study 10- Actual Plant under Study - pH neutralization plant

In this case study 10, a FOPDT process i.e. Actual Plant under Study - pH neutralization plant is considered. This process is having medium process gain, medium Time Constant and smaller Dead time is considered given by equation (11).

$$G(s) = \frac{7.0921}{8.54s+1} * e^{-1.71S} \tag{11}$$

Table 6(b) and Fig.5(c) shows the performance of PI Controller with different tuning methods and indicates that the Z-N tuning method can give required performance (with faster rise time) with quickly responding to change in process dynamics, but gives overshoot. The T-R tuning method gives best response as the settling time required for output response at set point is the smallest among all the tuning methods and IMC tuning method also gives better response. In case of disturbance rejection, ITAE-1(DR) tuned controller can reject it quickly and forces output to steady state again but it introduces overshoot in output response.

6. Results and Discussion

As observed from the analysis and comparison results, it is evident that in most of the cases from low to moderate gain Z-N and T-R methods gave satisfactory response. Z-N method gives smaller rise time while TR method gave better settling time. Hence between Z-N and T-R method there is a trade off between rise time and settling time. The decision whether to choose Z-N method or T-R method is made on the basis of temperature and its effect on rate of reaction which in turn changes the rise time. Usually at lower temperatures the rate of reaction is less hence we choose Z-N method which gives better rise time so the pH reaches to 90% for the final value as fast as possible. At higher temperatures the rate of reaction increases hence the rise time automatically decreases hence here we try to minimize the settling time by choosing TR method. As for when the gain is high A-H method gives better response in terms of both rise and settling times hence it is chosen irrespective of the changes in temperature. Thus the algorithm is implemented such that based on constraints and plant parameters like gain, dead time and time constant, a suitable tuning method will be selected and Kp and Ti values are calculated to update or retune the PI Controller. Any sudden changes in set point can be tracked by ITAE1 (SP) method and sudden disturbances can be rejected with ITAE1 (DR) method.

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