# A SUMMARY OF PI AND PID CONTROLLER TUNING RULES FOR PROCESSES WITH TIME DELAY. PART 1: PI CONTROLLER TUNING RULES.

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Abstract: The ability of proportional integral (PI) and proportional integral derivative (PID) controllers to compensate many practical industrial processes has led to their wide acceptance in industrial applications. The requirement to choose either two or three controller parameters is perhaps most easily done using tuning rules. A summary of tuning rules for the PI control of single input, single output (SISO) processes with time delay is provided in this paper. *Copyright ©2000 IFAC*

Keywords: PI controllers, rules, time delay.

## 1. INTRODUCTION

The ability of PI and PID controllers to compensate most practical industrial processes has led to their wide acceptance in industrial applications. It has been suggested, for example, that just 5 to 10% of control loops cannot be controlled by SISO PI or PID controllers (Koivo and Tanttu, 1991); in particular, these controllers perform well for processes with benign dynamics and modest performance requirements (Astrom and Hagglund, 1995). It has been stated that 98% of control loops in the pulp and paper industries are controlled by SISO PI controllers (Bialkowski, 1996) and that, in process control applications, more than 95% of the controllers are of PID type (Astrom and Hagglund, 1995). The PI or PID controller implementation has been recommended for the control of processes of low to medium order, with small time delays, when parameter setting must be done using tuning rules and when controller synthesis is performed either once or more often (Isermann, 1989).

However, in the testing of thousands of control loops in hundreds of plants, Ender (1993) has found that more than 30% of installed controllers are operating in manual mode and 65% of loops operating in automatic mode produce less variance in manual than in automatic (i.e. the automatic controllers are poorly tuned); this is rather sobering, considering the wealth of information available in the literature for determining controller parameters automatically. It is true that this information is scattered throughout papers and books; the author is not aware of a comprehensive summary, in the published literature, of PI and PID controller tuning rules for processes with time delays. Such a summary has recently been prepared by the author (O'Dwyer, 2000a); selected data from this summary is provided in Table 1.

Table 1: PI and PID tuning rules – some data

| Process Model | Number of rules |
|---|---|
| $K_m e^{-s\tau_m} / 1 + sT_m$ | PI – 81; PID - 117 |
| $K_m e^{-s\tau_m} / 1 - sT_m$ | PI – 6; PID - 6 |
| $K_m e^{-s\tau_m} / s$ | PI – 22; PID - 15 |
| $K_m e^{-s\tau_m} / s(1 + sT_m)$ | PI – 6; PID - 15 |
| $K_m e^{-s\tau_m} / (1 + 2\xi_m T_m s + T_m{}^2 s^2)$ | PI – 15; PID - 48 |
| $K_m e^{-s\tau_m} / (1 - sT_{m1})(1 + sT_{m2})$ | PI – 2; PID - 6 |
| Other delayed models | PI – 1; PID - 12 |
| Delayed or undelayed model | PI – 21; PID - 39 |
| **Total** | **PI - 154; PID - 258** |

For space considerations, this paper and a companion paper (O'Dwyer, 2000b) will summarise some of the most directly applicable tuning rules for PI and PID controllers, respectively, that have been developed to compensate SISO processes with time delay, modeled in either first order lag plus delay (FOLPD) form or integral plus delay (IPD) form; such models are popular in process control because of their simple structure. A major criterion for choosing the tuning rules summarised is their appropriateness for the analytical calculation of robustness criteria in previous work done by the author (O'Dwyer, 1998). Some such results will be presented in Section 4.

The tuning rules will be organised in tabular form; within each table, the tuning rules are classified further. The main subdivisions made are as follows:

(i) Tuning rules based on a measured step response (also called process reaction curve methods).
(ii) Tuning rules based on minimising an appropriate performance criterion, either for optimum regulator or optimum servo action.
(iii) Tuning rules that gives a specified closed loop response (direct synthesis tuning rules).
(iv) Robust tuning rules, with an explicit robust stability and robust performance criterion built in to the design process.
(v) Tuning rules based on recording appropriate parameters at the ultimate frequency (also called ultimate cycle methods).

Some tuning rules could be considered to belong to more than one subdivision, so the subdivisions cannot be considered to be mutually exclusive; nevertheless, they provide a convenient way to classify the rules. Tuning rules for the variations that have been proposed in the 'ideal' PI and PID structure are included in the appropriate table. Considerable variations in the ideal PID controller structure, in particular, are encountered; these variations are explored in more detail by O'Dwyer (2000b). One column in the tables summarise the conditions under which the tuning rules are designed to operate, if appropriate. A list of symbols and abbreviations used in the papers is provided (Appendix 1).

## 2. TUNING RULES - $\frac{K_m e^{-s\tau_m}}{1+sT_m}$ MODEL

| Rule | $K_c$ | $T_i$ | Comment |
|---|---|---|---|
| Controller | $G_c(s) = K_c\left(1+\frac{1}{T_i s}\right)$ | | |
| **Process reaction** | | | |
| Ziegler and Nichols (1942) | $\frac{0.9T_m}{K_m\tau_m}$ | $3.33\tau_m$ | $\frac{\tau_m}{T_m} \le 1$ |
| Astrom and Hagglund (1995) | $\frac{0.63T_m}{K_m\tau_m}$ | $3.2\tau_m$ | |
| Chien, *et al.* (1952) - regulator | $\frac{0.6T_m}{K_m\tau_m}$ | $4\tau_m$ | $0.11 < \frac{\tau_m}{T_m} < 1.0$ 0% o.s. |
| Astrom and Hagglund (1995) – regulator | $\frac{0.7T_m}{K_m\tau_m}$ | $2.3\tau_m$ | 20% o.s. |
| Chien, *et al.* (1952) – servo | $\frac{0.35T_m}{K_m\tau_m}$ | $1.17T_m$ | $0.11 < \frac{\tau_m}{T_m} < 1.0$ 0% o.s. |
| Chien *et al.* (1952) – servo | $\frac{0.6T_m}{K_m\tau_m}$ | $T_m$ | $0.11 < \frac{\tau_m}{T_m} < 1.0$ 20% o.s. |
| Murrill (1967) – 2 constraints criterion | $\frac{0.928}{K_m}\left(\frac{T_m}{\tau_m}\right)^{0.946}$ | $\frac{T_m}{1.078}\left(\frac{\tau_m}{T_m}\right)^{0.583}$ | $0.1 \le \frac{\tau_m}{T_m} \le 1.0$ |
| St. Clair (1997) | $\frac{0.333T_m}{K_m\tau_m}$ | $T_m$ | $\frac{T_m}{\tau_m} \le 3.0$ |
| **Regulator tuning** | | | |
| Murrill (1967) – min. IAE | $\frac{0.984}{K_m}\left(\frac{T_m}{\tau_m}\right)^{0.986}$ | $\frac{T_m}{0.608}\left(\frac{\tau_m}{T_m}\right)^{0.707}$ | $0.1 \le \frac{\tau_m}{T_m} \le 1.0$ |
| Shinskey (1988) – min. IAE | $1.00T_m/K_m\tau_m$<br>$1.04T_m/K_m\tau_m$<br>$1.11T_m/K_m\tau_m$<br>$1.39T_m/K_m\tau_m$ | $3.0\tau_m$<br>$2.25\tau_m$<br>$1.45\tau_m$<br>$\tau_m$ | $\tau_m/T_m = 0.2$<br>$\tau_m/T_m = 0.5$<br>$\tau_m/T_m = 1$<br>$\tau_m/T_m = 2$ |
| Murrill (1967) – min. ISE | $\frac{1.305}{K_m}\left(\frac{T_m}{\tau_m}\right)^{0.959}$ | $\frac{T_m}{0.492}\left(\frac{\tau_m}{T_m}\right)^{0.739}$ | $0.1 \le \frac{\tau_m}{T_m} \le 1.0$ |
| Zhuang and Atherton (1993) – min. ISE | $\frac{1.279}{K_m}\left(\frac{T_m}{\tau_m}\right)^{0.945}$ | $\frac{T_m}{0.535}\left(\frac{\tau_m}{T_m}\right)^{0.586}$ | $0.1 \le \frac{\tau_m}{T_m} \le 1.0$ |
| | $\frac{1.346}{K_m}\left(\frac{T_m}{\tau_m}\right)^{0.675}$ | $\frac{T_m}{0.552}\left(\frac{\tau_m}{T_m}\right)^{0.438}$ | $1.1 \le \frac{\tau_m}{T_m} \le 2.0$ |
| Murrill (1967) – min. ITAE | $\frac{0.859}{K_m}\left(\frac{T_m}{\tau_m}\right)^{0.977}$ | $\frac{T_m}{0.674}\left(\frac{\tau_m}{T_m}\right)^{0.680}$ | $0.1 \le \frac{\tau_m}{T_m} \le 1.0$ |
| Zhuang and Atherton (1993) – min. ISTSE | $\frac{1.015}{K_m}\left(\frac{T_m}{\tau_m}\right)^{0.957}$ | $\frac{T_m}{0.667}\left(\frac{\tau_m}{T_m}\right)^{0.552}$ | $0.1 \le \frac{\tau_m}{T_m} \le 1.0$ |
| | $\frac{1.065}{K_m}\left(\frac{T_m}{\tau_m}\right)^{0.673}$ | $\frac{T_m}{0.687}\left(\frac{\tau_m}{T_m}\right)^{0.427}$ | $1.1 \le \frac{\tau_m}{T_m} \le 2.0$ |
| Zhuang and Atherton (1993) - min. ISTES | $\frac{1.021}{K_m}\left(\frac{T_m}{\tau_m}\right)^{0.953}$ | $\frac{T_m}{0.629}\left(\frac{\tau_m}{T_m}\right)^{0.546}$ | $0.1 \le \frac{\tau_m}{T_m} \le 1.0$ |
| | $\frac{1.076}{K_m}\left(\frac{T_m}{\tau_m}\right)^{0.648}$ | $\frac{T_m}{0.650}\left(\frac{\tau_m}{T_m}\right)^{0.442}$ | $1.1 \le \frac{\tau_m}{T_m} \le 2.0$ |

| Rule | $K_c$ | $T_i$ | Comment |
|---|---|---|---|
| **Servo tuning** | | | |
| Rovira, *et al.* (1969) - min. IAE | $\frac{0.758}{K_m}\left(\frac{T_m}{\tau_m}\right)^{0.861}$ | $\frac{T_m}{1.020 - 0.323\frac{\tau_m}{T_m}}$ | $0.1 \le \frac{\tau_m}{T_m} \le 1.0$ |
| Zhuang and Atherton (1993) – min. ISE | $\frac{0.980}{K_m}\left(\frac{T_m}{\tau_m}\right)^{0.892}$ | $\frac{T_m}{0.690 - 0.155\frac{\tau_m}{T_m}}$ | $0.1 \le \frac{\tau_m}{T_m} \le 1.0$ |
| | $\frac{1.072}{K_m}\left(\frac{T_m}{\tau_m}\right)^{0.560}$ | $\frac{T_m}{0.648 - 0.114\frac{\tau_m}{T_m}}$ | $1.1 \le \frac{\tau_m}{T_m} \le 2.0$ |
| Rovira, *et al.* (1969) – min. ITAE | $\frac{0.586}{K_m}\left(\frac{T_m}{\tau_m}\right)^{0.916}$ | $\frac{T_m}{1.030 - 0.165\frac{\tau_m}{T_m}}$ | $0.1 \le \frac{\tau_m}{T_m} \le 1.0$ |
| Zhuang and Atherton (1993) – min. ISTSE | $\frac{0.712}{K_m}\left(\frac{T_m}{\tau_m}\right)^{0.921}$ | $\frac{T_m}{0.968 - 0.247\frac{\tau_m}{T_m}}$ | $0.1 \le \frac{\tau_m}{T_m} \le 1.0$ |
| | $\frac{0.786}{K_m}\left(\frac{T_m}{\tau_m}\right)^{0.559}$ | $\frac{T_m}{0.883 - 0.158\frac{\tau_m}{T_m}}$ | $1.1 \le \frac{\tau_m}{T_m} \le 2.0$ |
| Zhuang and Atherton (1993) – min. ISTES | $\frac{0.569}{K_m}\left(\frac{T_m}{\tau_m}\right)^{0.951}$ | $\frac{T_m}{1.023 - 0.179\frac{\tau_m}{T_m}}$ | $0.1 \le \frac{\tau_m}{T_m} \le 1.0$ |
| | $\frac{0.628}{K_m}\left(\frac{T_m}{\tau_m}\right)^{0.583}$ | $\frac{T_m}{1.007 - 0.167\frac{\tau_m}{T_m}}$ | $1.1 \le \frac{\tau_m}{T_m} \le 2.0$ |
| **Direct synthesis** | | | |
| Haalman (1965) | $\frac{2T_m}{3K_m\tau_m}$ | $T_m$ | Closed loop sensitivity = 1.9 |
| Pemberton (1972) –min. IAE – regulator | $\frac{T_m}{K_m\tau_m}$ | $T_m$ | $0.1 \le \frac{\tau_m}{T_m} \le 0.5$ |
| Smith and Corripio (1985) – min. IAE – servo | $\frac{3T_m}{5K_m\tau_m}$ | $T_m$ | $0.1 \le \frac{\tau_m}{T_m} \le 0.5$ |
| Smith and Corripio (1985) – 5% o.s. – servo | $\frac{T_m}{2K_m\tau_m}$ | $T_m$ | |
| Schneider (1988) | $0.368\frac{T_m}{K_m\tau_m}$ | $T_m$ | CL response $\xi = 1$ |
| | $0.403\frac{T_m}{K_m\tau_m}$ | $T_m$ | CL response $\xi = 0.6$ |
| Hang, *et al.* (1993a, b) | $\frac{0.7854T_m}{K_m\tau_m}$ | $T_m$ | $A_m = 2$, $\phi_m = 45^0$ |
| | $\frac{0.524T_m}{K_m\tau_m}$ | $T_m$ | $A_m = 3$, $\phi_m = 60^0$ |
| Hang, *et al.* (1993a, b) - continued | $\frac{0.393T_m}{K_m\tau_m}$ | $T_m$ | $A_m = 4$, $\phi_m = 67.5^0$ |
| | $\frac{0.314T_m}{K_m\tau_m}$ | $T_m$ | $A_m = 5$, $\phi_m = 72^0$ |
| Voda and Landau (1995) | $\frac{T_m}{2K_m\tau_m}$ | $T_m$ | $\phi_m = 60^0$; $0.25 \le \frac{\tau_m}{T_m} \le 1$ |
| Bi, *et al.* (1999) | $\frac{0.5064T_m}{K_m\tau_m}$ | $T_m$ | |
| **Robust** | | | |
| Rivera, *et al.* (1986) | $\frac{T_m}{\lambda K_m}$ | $T_m$ | $\lambda \ge 1.7\tau_m$, $\lambda > 0.1T_m$. |
| | $\frac{2T_m + \tau_m}{2\lambda K_m}$ | $T_m + 0.5\tau_m$ | $\lambda \ge 1.7\tau_m$, $\lambda > 0.1T_m$. |
| Chien (1988) | $\frac{T_m}{K_m(\tau_m + \lambda)}$ | $T_m$ | $\lambda = T_m$ |
| Fruehauf, *et al.* (1993) | $\frac{5T_m}{9\tau_m K_m}$ | $5\tau_m$ | $\frac{\tau_m}{T_m} < 0.33$ |
| | $\frac{T_m}{2\tau_m K_m}$ | $T_m$ | $\frac{\tau_m}{T_m} \ge 0.33$ |
| Lee, *et al.* (1998) | $\frac{T_i}{K_m(\lambda + \tau_m)}$ | $T_m + \frac{\tau_m^{\ 2}}{2(\lambda + \tau_m)}$ | $\lambda = 0.333\tau_m$ |
| **Ultimate cycle** | | | |
| Shinskey (1988) – min. IAE | $0.5848K_u$ | $0.81T_u$ | $\tau_m/T_m = 0.2$ |
| | $0.5405K_u$ | $0.66T_u$ | $\tau_m/T_m = 0.5$ |
| | $0.4762K_u$ | $0.47T_u$ | $\tau_m/T_m = 1$ |
| | $0.4608K_u$ | $0.37T_u$ | $\tau_m/T_m = 2$ |
| **Alternative PI controller structure** | | | |
| Controller | $G_c(s) = K_c\left(b + \frac{1}{T_i s}\right)$ | | |
| Astrom and Hagglund (1995) | $\frac{0.4T_m}{K_m\tau_m}$ | $0.7T_m$ | $b = 0.5$; $0.1 \le \frac{\tau_m}{T_m} \le 2$ |

## 3. PI TUNING RULES – $\frac{K_m e^{-s\tau_m}}{s}$ MODEL

| Rule | $K_c$ | $T_i$ | Comment |
|---|---|---|---|
| **Process reaction** | | | |
| Ziegler and Nichols (1942) | $\frac{0.9}{K_m\tau_m}$ | $3.33\tau_m$ | Quarter decay ratio |
| Tyreus and Luyben (1992) | $\frac{0.487}{K_m\tau_m}$ | $8.75\tau_m$ | Max. CL loop log mod. = 2dB |

| Rule | $K_c$ | $T_i$ | Comment |
|---|---|---|---|
| Astrom and Hagglund (1995) | $\frac{0.63}{K_m \tau_m}$ | $3.2\tau_m$ | |
| **Regulator** | | | |
| Shinskey (1994) – min. IAE regulator | $\frac{0.9259}{K_m \tau_m}$ | $4\tau_m$ | |
| **Robust** | | | |
| Fruehauf, *et al.* (1993) | $\frac{0.5}{K_m \tau_m}$ | $5\tau_m$ | |
| **Direct synthesis** | | | |
| Cluett and Wang (1997) - designed closed loop time constant in 'comment' column | $\frac{0.9588}{K_m \tau_m}$ | $3.0425\tau_m$ | $\tau_m$ |
| | $\frac{0.6232}{K_m \tau_m}$ | $5.2586\tau_m$ | $2\tau_m$ |
| | $\frac{0.4668}{K_m \tau_m}$ | $7.2291\tau_m$ | $3\tau_m$ |
| | $\frac{0.3752}{K_m \tau_m}$ | $9.1925\tau_m$ | $4\tau_m$ |
| | $\frac{0.3144}{K_m \tau_m}$ | $11.1637\tau_m$ | $5\tau_m$ |
| | $\frac{0.2709}{K_m \tau_m}$ | $13.1416\tau_m$ | $6\tau_m$ |
| Rotach (1995) | $\frac{0.75}{K_m \tau_m}$ | $2.41\tau_m$ | $\xi = 0.75$. |
| **Other** | | | |
| Penner (1988) | $\frac{0.58}{K_m \tau_m}$ | $10\tau_m$ | Max. CL gain = 1.26 |
| | $\frac{0.8}{K_m \tau_m}$ | $5.9\tau_m$ | Max. CL gain = 2.0 |
| Srividya and Chidambaram (1997) | $\frac{0.67075}{K_m \tau_m}$ | $3.6547\tau_m$ | |

## 4. SIMULATION RESULTS

Space considerations dictate that only representative simulation results may be provided. In these results, approximate gain margin and phase margin are analytically calculated, using the method outlined by Ho, *et al.* (1995), for processes compensated using an appropriately tuned PI controller. The MATLAB package has been used in the simulations. In these results, Z-N refers to the process reaction curve method of Ziegler and Nichols (1942); IAE reg, ISE reg and ITAE reg refer to the tuning rules for regulator applications that minimise the IAE, ISE and ITAE criterion, respectively, as defined by Murrill (1967); IAE ser, ITAE ser and ISE ser refer to the tuning rules for servo applications that minimise the IAE, ITAE and ISE criterion, respectively, as defined by Rovira, *et al.* (1969) and Zhuang and Atherton (1993); $A_m = 2, \phi_m = 45^\circ$, $A_m = 3$, $\phi_m = 60^\circ$ and $A_m = 4$, $\phi_m = 67.5^\circ$ refer to the direct synthesis tuning rules of Hang, *et al.* (1993a, b).

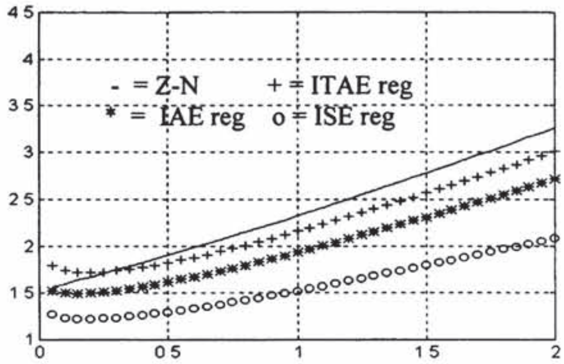


Figure 1: Gain margin

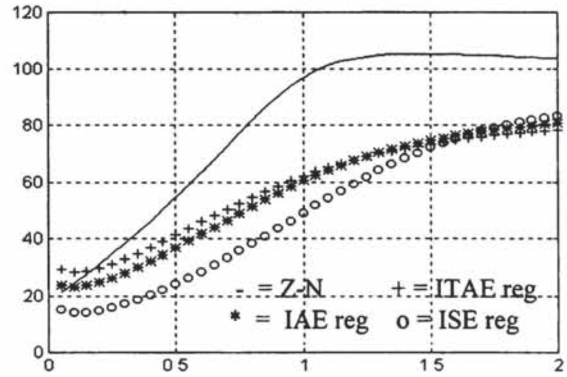


Figure 2: Phase margin

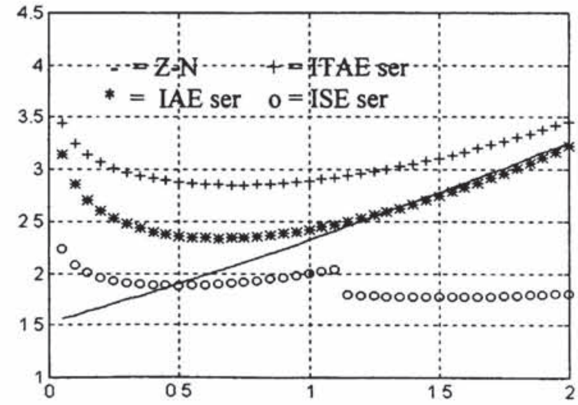


Figure 3: Gain margin

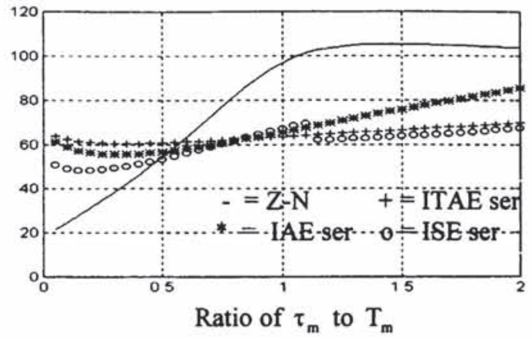


Figure 4: Phase margin

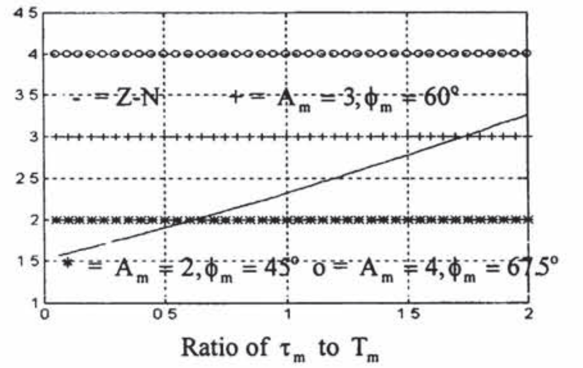


Figure 5: Gain margin

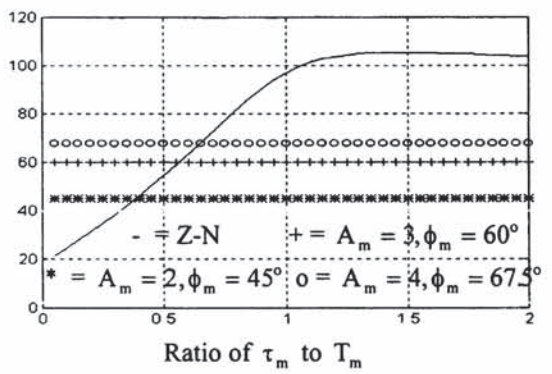


Figure 6: Phase margin

It is interesting that, over a wide range of time delay to time constant ratios, the ISE based tuning rules have the smallest gain margin and have also a small phase margin, suggesting that this is a less robust tuning strategy. This is compatible with application experience. The direct synthesis tuning rules simulated provide a constant gain and phase margin at all ratios of time delay to time constant; it may be shown analytically that, for a FOLPD process, a gain margin of $1.57/a$ and a phase margin of $(1.57 - a)$ radians is achieved with the use of a PI controller with $K_c = aT_m / K_m \tau_m$ and $T_i = T_m$.

## 5. CONCLUSIONS

A large number of PI controller tuning rules have been defined in the literature to compensate SISO processes with time delays. The paper has presented a flavour of the variety of tuning rules defined. Some results associated with the analytical calculation of the gain margin and phase margin of compensated delayed systems, as the ratio of time delay to time constant varies, have also been presented. Future work will concentrate on further analytical evaluation of the robustness of delayed processes compensated using tuning rule based PI controllers.

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## APPENDIX: LIST OF SYMBOLS AND ABBREVIATIONS USED

$A_m$ = gain margin

CL = closed loop

FOLPD = first order lag plus delay

$G_c(s)$ = PI controller transfer function

IAE = integral of absolute error

IPD = integral plus delay

ISE = integral of squared error

ISTES = integral of squared time multiplied by error, all to be squared

ISTSE = integral of squared time multiplied by squared error

ITAE = integral of time multiplied by absolute error

$K_c$ = Proportional gain of the controller

$K_m$ = Gain of the process models

$K_u$ = Ultimate gain

max. = maximum

min. = minimum

o.s. = overshoot

PI = proportional integral

PID = proportional integral derivative

SISO = single-input, single-output

$T_i$ = Integral time of the controller

$T_m, T_{m1}, T_{m2}$ = Time constants of the process models

$T_u$ = Ultimate period

$\xi$, $\xi_m$ = damping factor

$\lambda$ = Parameter that determines robustness of compensated system.

$\phi_m$ = phase margin

$\tau_m$ = time delay of the process models.