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# USING CONTROLLER TUNING FORMULAE TO IMPROVE PERFORMANCE

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## ABSTRACT

The proportional integral derivative (PID) controller is the most dominant form of automatic controller in industrial use today. With this device, it is necessary to adjust the controller parameters according to the nature of the process. Thus, for effective control of a HVDC system, for example, specific values need to be chosen for the P, I and D parameters, which will be different for the values required to control, for example, an induction motor drive. This tailoring of controller to process is known as *controller tuning*. Controller tuning is easily and effectively performed using *tuning rules* (i.e. formulae for controller tuning, based on process information). Such tuning rules allow the easy set up of controllers to achieve optimum performance at commissioning. Importantly, they allow ease of re-commissioning if the characteristics of the process change. The paper communicates the results of recent work in the collation of industry-relevant PI and PID controller tuning rules, which may be applied to a variety of applications in power electronics, machines and drives.

**Keywords :** Control, PI, PID, tuning rules.

## 1 INTRODUCTION

PI and PID controllers have been at the heart of control engineering practice for seven decades. Historically, the first tuning rule for setting up controller parameters was defined in 1934 for the design of a proportional-derivative (PD) controller for a process modelled by an integrator plus delay (IPD) model [1]. Subsequently, tuning rules were defined for PI and PID controllers, assuming the process was modelled by a first order lag plus delay (FOLPD) model [2] or a pure delay model [2], [3].

In the wide area covered by power systems, power electronics, machines and drives, PI or PID controllers have been considered for the control of DC-DC converters (e.g. [4]), flexible AC transmission systems (e.g. [5]), synchronous machines (e.g. [6]), HVDC systems (e.g. [7]), electric vehicle speed (e.g. [8]) and induction motor servodrives (e.g. [9]). In general, at commissioning, the PID controller is installed and tuned. However, surveys indicating the state of industrial practice report sobering results. For example, in the testing of thousands of control loops, it has been found that 65% of loops operating in automatic mode produce less variance in manual than in automatic (i.e. the automatic controllers are poorly tuned) [10]. Process performance deteriorates when the controller is poorly tuned; this deterioration may be reflected, for example, in a reduction in energy efficiency and increased environmental emissions. The net effect will be an increase in operating costs and a reduction in overall competitiveness. However, good controller tuning, for example, can allow the recovery of up to 6% of energy costs, in a variety of industries [11].

Thus, there is strong evidence that PI and PID controllers remain poorly understood and, in particular,

poorly tuned in many applications. This is surprising, as very many tuning rules exist to allow the specification of the controller parameters. Tuning rules have the advantage of ease of calculation of the controller parameters (when compared to more analytical controller design methods), on the one hand; on the other hand, the use of tuning rules is a good alternative to trial and error tuning. It is clear that the many controller tuning rules proposed in the literature are not having an impact on industrial practice. One reason is that the tuning rules are not very accessible, being scattered throughout the control literature; in addition, the notation used is not unified.

It is timely, therefore, to communicate the results of recent work done in the collation of tuning rules, using a unified notation, for continuous-time PI and PID control of single-input, single-output (SISO) processes, extending the work reported in [12]. Such rules may be specified for processes either without or with a time-delay (dead-time) term; such terms arise in voltage source inverters, for example, where a dead-time is required to prevent a shorting condition during switching [13]. Generally, a dead-time term is common; sources of dead-time range from the finite time required for information transmission to application-specific issues, such as the dead time in a motor drive due to imperfect mechanical coupling [9].

Firstly, a brief summary of the range of PI and PID controller structures proposed in the literature, together with the process models used to define the controller tuning rules, is provided. Then, controller architecture and process modeling issues are outlined, followed by the outline of tuning rules for setting up PI and PID controllers, with an emphasis on rules that extend the work reported in [12]. Finally, conclusions to the paper are drawn. Due to space restrictions, a case study of the

application of tuning rules to design a controller for a pilot-scale plant is detailed in the poster presentation accompanying this paper.

## 2 CONTROLLER ARCHITECTURE AND PROCESS MODELLING

A practical difficulty with PID control technology is a lack of industrial standards, which has resulted in a wide variety of PID controller architectures. Seven different structures for the PI controller and forty-six different structures for the PID controller have been identified. Controller manufacturers vary in their choice of architecture; controller tuning that works well on one architecture may work poorly on another. Full details are given in [12]; considering the PID controller, the most common architecture is the ‘ideal’ PID controller, whose Laplace transfer function is given by

$$G_c(s) = K_c \left( 1 + \frac{1}{T_i s} + T_d s \right) \quad (1),$$

with  $K_c$  = proportional gain,  $T_i$  = integral time constant and  $T_d$  = derivative time constant. The most dominant PI controller architecture is the ‘ideal’ PI controller:

$$G_c(s) = K_c \left( 1 + \frac{1}{T_i s} \right) \quad (2)$$

The wide variety of controller architectures is mirrored by the wide variety of (linear) process model transfer functions used. The most common model is the stable FOLPD model, whose transfer function is given by

$$G_m(s) = \frac{K_m e^{-s\tau_m}}{1 + sT_m} \quad (3)$$

Some 82% of the PI controller tuning rules identified have been defined for the ideal PI controller structure, with 42% of tuning rules based on a FOLPD process model. The range of PID controller variations has led to a less homogenous situation than for the PI controller; 40% of tuning rules identified have been defined for the ideal PID controller structure, with 37% of PID tuning rules based on a FOLPD process model [12]. Of course, the modeling strategy used to obtain a particular process model transfer function influences the value of the model parameters, which, in turn, affect the controller values determined from the tuning rules. Forty-one modeling strategies have been detailed to determine the parameters of the FOLPD process model, for example. Space does not permit a full discussion of this issue; further details are provided in [12].

## 3 TUNING RULES FOR PI AND PID CONTROLLERS

Before considering tuning rules for PI and PID controllers in more detail, it is timely to review the action of the PID controller. Consider the ideal PID controller, for example, given by equation (1). If

$T_i = \infty$  and  $T_d = 0$  (that is, P control), then the closed loop measured value is always less than the desired value for processes without an integrator term, as a positive error is necessary to keep the measured value constant, and less than the desired value. The introduction of integral action facilitates the achievement of equality between the measured value and the desired value, as a constant error produces an increasing controller output. The introduction of derivative action means that changes in the desired value may be anticipated, and thus an appropriate correction may be added prior to the actual change. Thus, in simplified terms, the PID controller allows contributions from present, past and future controller inputs.

PI and PID controller tuning rules may be broadly classified as follows:

- Tuning rules based on a measured step response
- Tuning rules based on minimising an appropriate performance criterion
- Tuning rules that give a specified closed loop response
- Robust tuning rules, with an explicit robust stability and robust performance criterion built in to the design process
- Tuning rules based on recording appropriate parameters at the ultimate frequency.

Tuning rules in the first four subdivisions are typically based on process model parameters; the development of a process model is typically not required for using tuning rules in the final subdivision above. 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. An outline of tuning rules in these subdivisions is now provided. An extensive collection of the tuning rules is available [12].

Tuning rules based on a measured step response are also called *process reaction* curve methods. The first (and most well-known) tuning rule of this type was suggested in 1942 [14]; in this method, the process is modeled by a FOLPD process model with the model parameters estimated using a tangent and point method. Simple formulae are used to define tuning parameters for PI and PID controllers. The PI controller settings are given by

$$K_c = \frac{0.9T_m}{K_m \tau_m}, \quad T_i = 3.33\tau_m \quad (4)$$

The (ideal) PID controller settings are given by

$$K_c \in \left[ \frac{1.2T_m}{K_m \tau_m}, \frac{2T_m}{K_m \tau_m} \right], \quad T_i = 2\tau_m, \quad T_d = 0.5\tau_m \quad (5)$$

In addition to the rules reported in [12], further such process reaction curve tuning rules are available, based on a variety of process models [1], [15], [16]. The advantage of process reaction curve tuning strategies is that only a single experimental test is necessary. However, the disadvantages of the strategy are primarily based on the difficulty, in practice, of obtaining an

accurate process model; for example, load changes may occur during the test which may distort the test results and a large step input may be necessary to achieve a good signal to noise ratio. Similar disadvantages arise in any tuning method dependent on prior model development.

Tuning rules based on minimising an appropriate performance criterion may be defined either for optimum regulator or optimum servo action. Performance criteria, such as the minimisation of the integral of absolute error (IAE) in a closed loop environment, may be used to determine a unique set of controller parameter values. Tuning rules have been described, sometimes in graphical form, to optimise the regulator response, servo response or other characteristics of a compensated delayed process, represented by a variety of models [12]; in addition, further such tuning rules are available, based on a variety of process models, to optimise the regulator response [17]-[29], servo response [18], [20], [22]-[25], [30]-[37] and other characteristics [38]-[44].

Tuning rules that give a specified closed loop response (*direct synthesis* tuning rules) may be defined by specifying a time domain related metric, such as the desired poles of the closed loop response. The definition may be expanded to cover techniques that allow the achievement of a frequency domain metric, such as a specified gain margin and/or phase margin. Tuning rules of this type have been specified to compensate a delayed process, represented by a variety of models [12]; in addition, further such tuning rules are available, based on a variety of process models, to achieve time domain metrics [15], [17], [26], [29], [45]-[82] and frequency domain metrics [59], [71], [80], [83]-[101].

Robust tuning rules have an explicit robust stability and/or robust performance criterion built in to the design process. Tuning rules of this type have also been specified to compensate a delayed process, represented by a variety of models [12]; in addition, further such tuning rules are available, based on a variety of process models [62], [71], [74], [80], [99], [102]-[130].

Ultimate cycle tuning rules are based on recording appropriate parameters at the ultimate frequency (that is, the frequency at which marginal stability of the closed loop control system occurs). The first such tuning rule was defined in 1942 [14] for the tuning of P, PI and PID controller parameters of a process that may or may not include a delay. Briefly, the experimental technique is as follows:

- a) Place the controller in proportional mode only
- b) Increase  $K_c$  until the closed loop system output goes marginally stable; record  $K_c$  (calling it  $K_u$ , the *ultimate gain*), and the *ultimate period*,  $T_u$ . Simple formulae are used to define tuning parameters for PI and PID controllers. The PID controller settings are given by

$$K_c = 0.45K_u, T_i = 0.83T_u \quad (6)$$

with the (ideal) PID controller settings given by

$$K_c = 0.6K_u, T_i = 0.5T_u, T_d = 0.125T_u \quad (7)$$

The tuning rules implicitly build an adequate frequency domain stability margin into the compensated system [131]. However, there are a number of disadvantages to the ultimate cycle tuning approach:

- the system must generally be destabilised under proportional control
- the empirical nature of the method means that uniform performance is not achieved in general [132]
- several trials must typically be made to determine the ultimate gain
- the resulting process upsets may be detrimental to product quality
- there is a danger of misinterpreting a limit cycle as representing the stability limit [133] and
- the amplitude of the process variable signal may be so great that the experiment may not be carried out for cost or safety considerations.

Some of these disadvantages are addressed by defining modifications of the rules in which, for example, the proportional gain in the experiment is set up to give a closed loop transient response decay ratio of 0.25, or a phase lag of  $135^\circ$ . Ultimate cycle tuning rules, and their modifications, have been specified to compensate general, possibly delayed processes, represented by a variety of models [12]; in addition, further such tuning rules are available, based on a variety of process models [16], [46], [59], [68], [71], [114], [119], [134]-[150].

## 4 CONCLUSIONS

Control academics and practitioners remain interested in the use of PI and PID controllers. PID controller tuning rules can be directly implemented in a variety of applications i.e. the hardware already exists, but it needs to be optimised. The outcome is directly measurable in, for example, energy savings and waste reduction (including greenhouse gas emission reduction). This paper summarises work carried out in tuning rule development. The most startling statistic to emerge from the work is the quantity of tuning rules identified to date; 665 PI tuning rules and 998 PID tuning rules, a total of 1663 separate rules. Recent years have seen an acceleration in the accumulation of tuning rules. In general, there is a lack of comparative analysis regarding the performance and robustness of closed loop systems compensated with controllers whose parameters are chosen using the tuning rules; associated with this is the lack of benchmark processes, at least until recently [151]. In addition, much work remains to be done in the evaluation of controllers designed using tuning rules in a wide variety of practical applications, including applications in power electronics, machines and drives. The main priority for future research in the area should be a critical analysis of available tuning rules, rather than the proposal of further tuning rules.

## 5 REFERENCES

- [1] Callendar, A. (1934). Preliminary notes on automatic control, *I.C.I. Alkali Ltd., Northwich, U.K., Central File No. R.525/15/3*.
- [2] Callendar, A., Hartree, D.R. and Porter, A. (1935/6). *Phil. Trans. Royal Society of London Series A*, 235, 415-444.
- [3] Hartree, D.R., Porter, A., Callendar, A. and Stevenson, A.B. (1937). *Proc. Royal Society of London*, 161(A), 460-476.
- [4] Alvarez-Ramirez, J., Cervantes, I., Espinosa-Perez, G., Maya, P. and Morales, A. (2000). *IEEE Trans. Circuits and Systems – I: Fundamental Theory and Applications*, 46, 103-106.
- [5] Morris, S., Dash, P.K. and Basu, K.P. (2002). *Proc. IEEE Transmission Distribution Conf. Exhib.*, 1, 330-335.
- [6] De Azevedo, H.R. and Wong, K.P. (1993). *Proc. IEEE Power Conversion Conf.*, 672-677.
- [7] Padiyar, K.R. and Prabhu, N. (2004). *Proc. Int. Conf. on Power Systems Technology*, 774-779.
- [8] Matsumura, S., Omatu, S. and Higasa, H. (1994). *Proc. IEEE World Congress on Computational Intelligence*, 4, 2649-2654.
- [9] Lin, F.J., Liaw, C.M., Shieh, Y.S., Guey, R.J. and Hwang, M.S. (1995). *IEE Proc. - Electr. Power Appl.*, 142, 79-86.
- [10] Ender, D.B. (1993). *Control Engineering*, Sept., 180-190.
- [11] Case histories accompanying Good Practice Guide 346 (Improving the effectiveness of basic closed loop control systems), The Carbon Trust ([www.thecarbontrust.co.uk](http://www.thecarbontrust.co.uk)).
- [12] O'Dwyer, A. (2006). *Handbook of PI and PID controller tuning rules (Edition 2)*. London, U.K.: Imperial College Press.
- [13] Jung, J. and Nam, K. (1998). *IEEE Trans. Ind. App.*, 34, 452-457.
- [14] Ziegler, J.G. and Nichols N.B. (1942). *Trans. ASME*, 64, 759-768.
- [15] Chidambaram, M. (2002). *Computer control of processes*, Alpha Science International Ltd., UK.
- [16] Alfaro Ruiz, V.M. (2005). *Ingeniería*, 15, 1-2, 39-52.
- [17] Lopez, A.M. (1968). *Ph.D. dissertation*, Louisiana State University, USA.
- [18] Murata, H. and Sagara, S. (1977). *Systems and Control (Japan)*, 21, 9, 517-524.
- [19] Kosinsani, S. (1985). *Ph.D. thesis*, Oklahoma State University, USA.
- [20] Harriott, P. (1988). *Ind. Eng. Chem. Res.*, 27, 11, 2060-2063.
- [21] Hill, A.G. and Venable, S.W. (1989). *Proc. ISA/89 Int. Conf. and Exhib.*, 44, 1, 51-64.
- [22] Park, H.L., Sung, S.W., Lee, I.-B. and Lee, J. (1997). *Chem. Eng. Comm.*, 161, 163-184.
- [23] Arrieta Orozco, O. and Alfaro Ruiz, V.M. (2003). *Ingeniería*, 13, 1-2, 31-39.
- [24] Arrieta Orozco, O. (2003). *Proyecto Eléctrico*, Universidad de Costa Rica.
- [25] Alfaro Ruiz, V.M. (2005). *Ingeniería*, 15, 1, 79-90.
- [26] Kotaki, M., Yamakawa, Y., Yamazaki, T., Kamimura, K. and Kurosu, S. (2005). *ASHRAE Trans.*, 111, 2, 13-22.
- [27] Kotaki, M., Yamkazi, T., Matuba, T., Kamimura, K. and Kurosu, S. (2005). *Trans. Soc. Inst. Control Eng. (Japan)*, 41, 2, 177-179.
- [28] PMA (Prozeß-und Maschinen-Automation) GmbH (2006). *Industrieregler KS40-1, KS41-1, KS42-1 Manuelle Optimierung*.
- [29] Slätteke, O. (2006). *Ph.D. thesis*, Lund University, Sweden.
- [30] Fukura, S. and Tanura, H. (1983). *Trans. Soc. Inst. Control Eng. (Japan)*, 19, 6, 514-515.
- [31] Zhuang, M. (1992). *Ph.D. thesis*, University of Sussex, U.K.
- [32] Argelaguet, R., Pons, M., Martin Aguilar, J. and Quevedo, J. (1997). *Proc. European Control Conf.*
- [33] Xing, J., Wang, P. and Wang, L. (2001). *Proc. IFAC New Technologies for Computer Control Conf.*, 479-484.
- [34] Majhi, S. (2005). *J. Process Control*, 15, 859-867.
- [35] Paz Ramos, M.A., Morales, L.E.M., Juan, L.B.M. and Bazán, G.R. (2005). *Proc. 15<sup>th</sup> Int. Conf. on Elect., Comm. Computers*.
- [36] Barberà, E. (2006). [http://www.angel.qui.ub.es/abstracts/T10\\_004.pdf](http://www.angel.qui.ub.es/abstracts/T10_004.pdf) [accessed 9 May 2006].
- [37] Tavakoli, S., Griffin, I. and Fleming, P.J. (2006). *Control Eng. Practice*, 14, 1069-1080.
- [38] Araki, M. (1985). *Systems and Control (Japan)*, 29, 649-656.
- [39] Taguchi, H., Doi, M. and Araki, M. (1987). *Trans. Soc. Inst. Control Eng. (Japan)*, 23, 9, 889-895.
- [40] Pecharroman, R. (2000). *Ph.D. thesis*, Universidad Pontificia Comillas, Madrid, Spain.
- [41] Taguchi, H. and Araki, M. (2002). *Trans. Soc. Inst. Control Eng. (Japan)*, 38, 5, 441-446.
- [42] Taguchi, H., Kokawa, M. and Araki, M. (2002). *Proc. 4<sup>th</sup> Asian Control Conf.*, 268-273.
- [43] Alenany, A., Abdelrahman, O. and Ziedan, I. (2005). *Proc. Int. Conf. Global Science and Technology*.
- [44] Tavakoli, S., Griffin, I. and Fleming, P.J. (2005). *Proc. IEEE Conf. Control Applications*, 1015-1020.
- [45] Ream, N. (1954). *Trans. Soc. Instrument Technology*, 6, 1, 19-28.
- [46] Kuwata, R. (1987). *Trans. Soc. Inst. Control Eng. (Japan)*, 23, 3, 232-239.
- [47] Nomura, M., Saito, T. and Kitamori, T. (1993). *Trans. Inst. Elect. Eng. Japan*, 113-C, 1, 59-68.
- [48] Gonzalez, A.M. (1994). *Ph.D. dissertation*, UNED, Madrid, Spain.
- [49] Jacob, E.F. and Chidambaram, M. (1996). *Comp. Chem. Eng.*, 20, 579-584.
- [50] Atherton, D.P. and Boz, A.F. (1998). *Proc. Control '98*, 1066-1071.
- [51] Atherton, D.P. and Majhi, S. (1998). *Proc. 3<sup>d</sup> Portuguese Conf. on Automatic Control*.
- [52] Majhi, S. and Atherton, D.P. (1999). *IEE Proc. – Control Theory Applications*, 146, 5, 415-425.
- [53] Klán, P. (2000). *Automa*, 9, 54-57.
- [54] Prokop, R., Husták, P. and Prokopová, Z. (2000). *Preprints Proc. PID '00: IFAC Workshop on Digital Control*, 320-325.
- [55] Chien, I.-L. (2003). *Ind. Eng. Chem. Res.*, 42, 4461-4477.
- [56] Huang, H.P., Luo, K.-Y. and Jeng, J.-C. (2003). *Proc. IFAC Advanced Control Chemical Processes Conf.*, 625-630.
- [57] Huba, M. (2005). *Automatisierungstechnik*, 53, 6, 273-284.
- [58] Lee, C.-H. and Teng, C.-C. (2003). *ISA Trans.*, 42, 391-400.
- [59] Hägglund, T. and Åström, K.J. (2004). *Asian J. Control*, 6, 4, 469-482.
- [60] Skoczowski, S. (2004). *Proc. 6<sup>th</sup> Portuguese Conf. on Automatic Control*.
- [61] Skogestad, S. (2004). <http://www.nt.ntnu.no/users/skoge/publications/2003/tuningPID/more/extensions/oscillating.txt> [Accessed 9 March 2005].
- [62] Anil, C. and Sree, R.P. (2005). *Indian Chemical Engineer, Section A*, 47, 4, 235-242.
- [63] Foley, M.W., Ramharack, N.R. and Copeland, B.R. (2005). *Ind. Eng. Chem. Res.*, 44, 17, 6741-6750.
- [64] Huang, H.-P. Lin, F.-Y. and Jeng, J.-C. (2005). *J. Chem. Eng. Japan*, 38, 9, 742-756.
- [65] Klán, P. and Gorez, R. (2005). *Proc. IFAC World Congress*.
- [66] Klán, P. and Gorez, R. (2005). *Automa*, 2, 50-52.
- [67] Manum, H. (2005). <http://www.nt.ntnu.no/users/skoge/diplom/prosjekt05/manum/rapport.pdf> [accessed 9 May 2006].
- [68] McMillan, G.K. (2005). *Good tuning: a pocket guide*, ISA.
- [69] Trybus, L. (2005). *Archives of Control Sciences*, 15(LI), 1, 5-17.
- [70] Xu, Y., Deng, H., Zhang, P. and Yang, J. (2005). *Proc. Int. Conf. Communications, Circuits and Systems*, 1, 630-634.
- [71] Åström, K.J. and Hägglund, T. (2006). *Advanced PID control*, ISA.
- [72] Cuesta, A., Grau, L. and López, I. (2006). *Proc. IEEE Conf. Computer Aided Control System Design*, 3036-3041.
- [73] Kukul, J. (2006). *Automatizace*, 49, 1, 16-20.
- [74] Larionescu, S. (2006). available at <http://www.geocities.com/larionescu/Internalmodel.pdf> (accessed 13 April 2006).
- [75] Mesa, F., Lozano, J.L. and Marin, L. (2006). *Proc. IEEE MELECON Conf.*, 421-424.
- [76] Rao, A.S. and Chidambaram, M. (2006). *Ind. Eng. Chem. Res.*, 45, 3604-3614.
- [77] Rao, A.S. and Chidambaram, M. (2006). *Asia-Pacific J. Chem. Eng.*, 1, 63-69.
- [78] Skogestad, S. (2006). [http://www.nt.ntnu.no/users/skoge/publications/2006/skogestad\\_iecr\\_smooth\\_pid/smooth06.pdf](http://www.nt.ntnu.no/users/skoge/publications/2006/skogestad_iecr_smooth_pid/smooth06.pdf) [accessed 9 May 2006].
- [79] Skogestad, S. (2006). *Ind. Eng. Chem. Res.*, 45, 7817-7822.

- [80] Sree, R.P. and Chidambaram, M. (2006). *Control of unstable systems*, Alpha Science Int. Ltd., Oxford, U.K.
- [81] Visioli, A. (2006). *Practical PID control*, Springer.
- [82] Vítěcková, M. (2006). *Trans. VŠB – Technical University of Ostrava, Mechanical Series*, 2, LII, 225-230.
- [83] Buckley, P., Shunta, J. and Luyben, W. (1985). *Design of distillation column control systems* Butterworth-Heinemann Ltd.
- [84] Latzel, W. (1988). *Automatisierungstechnik*, 36, 170-178.
- [85] Chidambaram, M. (1998). *Applied Process Control*, Allied Publishers PVT Ltd., India.
- [86] Schlegel, M. (1998). *Automatizace*, 41, 2, 70-78.
- [87] Wang, Y.-G. and Shao, H.-H. (1999). *Proc. IEEE 38<sup>th</sup> Conf. Decision and Control*, 3802-3803.
- [88] Arvanitis, K.G., Sigrimis, N.A., Pasgianos, G.D. and Kalogeropoulos, G. (2000). *Proc. IFAC Conf. Modelling Control Agriculture, Horticulture Post-Harvest Processing*, 191-196.
- [89] Wang, X.-S. (2000). *Optics and Precision Engineering (China)*, 8, 4, 381-384.
- [90] Jyothi, S.N., Arvind, S. and Chidambaram, M. (2001). *Indian Chemical Engineer, Section A*, 43, 4, 288-293.
- [91] Klán, P. (2001). *Automa*, 1, 52-54.
- [92] Kristiansson, B. and Lennartson, B. (2002). *Proc. IFAC World Congress*.
- [93] Kristiansson, B. and Lennartson, B. (2003). *Proc. Nordic Process Control Workshop XI*, available at <http://www.itk.ntnu.no/groups/npcw11/> (accessed 21 March 2005).
- [94] Xu, J. and Shao, H. (2004). *Chinese Journal of Scientific Instrument*, 25, 6, 714-716, 720.
- [95] Huang, H.-P. and Jeng, J.-C. (2005). in M.A. Johnson and M.H. Moradi (Eds.). *PID control: new identification and design methods*, Springer-Verlag London Ltd.
- [96] Clarke, D.W. (2006). *IEE Proc. Control Theory Applications*, 153, 6, 671-683.
- [97] King, R. (2006). Private communication, 6 March.
- [98] Kristiansson, B. and Lennartson, B. (2006). *IEEE Control Systems Magazine*, February, 55-69.
- [99] Lee, Y., Park, S. and Lee, M. (2006). *Hydrocarbon Processing*, January, 87-91.
- [100] Padhy, P.K. and Majhi, S. (2006). *Comp. Chem. Eng.*, 30, 790-796.
- [101] Paraskevopoulos, P.N., Pasgianos, G.D. and Arvanitis, K.G. (2006). *IEEE Trans. Control Systems Technology*, 14, 5, 926-936.
- [102] Gong, X.F., Gao, J. and Zhou, C. (1998). *Control and Decision (China)*, 13, 4, 337-341.
- [103] Gong, X.F. (2000). *J. of Zhejiang University (China)*, 43, 1, 43-48.
- [104] Zhang, W., Xu, X. and Zhang, W. (2000). *J. of Shanghai Jiaotong University*, 34, 5, 589-592.
- [105] Marchetti, G., Scali, C. and Lewin, D.R. (2001). *Automatica*, 37, 2049-2055.
- [106] Zhang, J.-G., Liu, Z.-Y. and Pei, R. (2002). *Control and Decision (China)*, 17, 6, 886-889.
- [107] Zhang, Z. (2002). *Chinese Journal of Scientific Instrument*, 23, 1, 28-30, 48.
- [108] Wang, J.-Y. (2003). *Masters thesis*, Feng Chia University, Taiwan. Available at <http://ethesys.lib.fcu.edu.tw> [Accessed 25 October 2006].
- [109] Ou, L., Gu, D., Zhang, W. and Cai, Y. (2005). *Proc IEEE Int. Conf. Industrial Technology*, 655-659.
- [110] Ou, L., Tang, Y., Gu, D. and Zhang, W. (2005). *Proc. American Control Conf.*, 4247-4252.
- [111] Ou, L., Zhang, W. and Gu, D. (2005). *Proc. IFAC World Congress*.
- [112] Visioli, A. (2005). *Proc. IFAC World Congress*.
- [113] Wang, J.-G., Zhang, J.-G. and Zhao, Z.-C. (2005). *Electric Machines and Control (China)*, 9, 2, 133-135.
- [114] Chen, P., Zhang, W. and Zhu, L. (2006). *Proc. American Control Conf.*, 274-279.
- [115] Cooper, D.J. (2006). <http://www.controlguru.com/wp/p86.html> [accessed 14 February 2007].
- [116] Cooper, D.J. (2006). <http://www.controlguru.com/wp/p78.html> [accessed 14 February 2007].
- [117] Jones, R.W. and Tham, M.T. (2006). *Proc. SICE-ICASE Int. Joint Conf.*, 4618-4623.
- [118] Lavanya, K., Umamaheswari, B. and Panda, R.C. (2006). *Indian Chemical Engineer, Section A*, 48, 3, 94-102.
- [119] Leva, A., Bascetta, L. and Schiavo, F. (2006). *Ind. Eng. Chem. Res.*, 45, 12, 4052-4062.
- [120] Nascu, I., De Keyser, R., Folea, S. and Buzdugan, T. (2006). *Proc. IEEE-TTTC Int. Conf. Automation, Quality, Testing and Robotics*.
- [121] Panda, R.C., Hung, S.-B. and Yu, C.-C. (2006). *Ind. Eng. Chem. Res.*, 45, 1397-1407.
- [122] Pohjola, M. (2006). *M.Sc thesis*, Helsinki University of Technology, Finland.
- [123] Rice, B. (2006), <http://www.controlguru.com/wp/p79.html> [accessed 14 February 2007].
- [124] Shamsuzzoha, M. and Lee, M. (2006). *Proc. SICE-ICASE Int. Joint Conf.*, 2485-2490.
- [125] Shamsuzzoha, M. and Lee, M. (2006). *Proc. SICE-ICASE Int. Joint Conf.*, 3324-3329.
- [126] Urrea, R., Castellanos-Sahagun, E., Alvarez, J. and Alvarez-Ramirez, J. (2006). *Ind. Eng. Chem. Res.*, 45, 6828-6841.
- [127] Vilanova, R. (2006). *Proc. American Control Conf.*, 256-261.
- [128] Vilanova, R. and Balaguer, P. (2006). *Proc. IEEE Int. Conf. Control Applications*, 2956-2961.
- [129] Zhang, J., Wang, J. and Zhao, Z. (2006). *Proc. 6<sup>th</sup> World Congress Intelligent Control and Automation*, 6388-6391.
- [130] Zhang, W. (2006). *Ind. Eng. Chem. Res.*, 45, 1408-1419.
- [131] De Paor, A.M. (1993). *Int. J. Elect. Eng. Education*, 30, 303-316.
- [132] Hwang, S.-H. and Tseng, T.-S. (1994). *Chem. Eng. Sci.*, 49, 1973-1983.
- [133] Pessen, D.W. (1994). *Trans. ASME. J. Dyn. Sys., Meas. Control*, 116, 553-557.
- [134] Idzerda, H.H., Ensing, L., Janssen, J.M.L. and Offereins, R.P. (1955). *Trans. Soc. Instrument Technology*, September, 105-122.
- [135] Johnson, E.F. (1956). *Chem. Eng. Progress*, 52, 2, 64-68.
- [136] Atkinson, P. (1968). *Feedback control theory for engineers*, Heinemann Educational Books Ltd., London.
- [137] Hill, A.G. and Adams, C.B. (1988). *Proc. ISA/88 Int. Conf. Exhib.*, 43, 3, 967-983.
- [138] Tyreus, B.D. and Luyben, W.L. (1992). *J. Process Control*, 3, 4, 241-251.
- [139] Luyben, W.L. (1993). *Ind. Eng. Chem. Res.*, 32, 466-475.
- [140] Zhang, G., Shao, C. and Chai, T. (1996). *Proc. 35<sup>th</sup> Conf. Decision and Control*, 2527-2532.
- [141] Majhi, S. (1999). *Ph.D. thesis*, University of Sussex, UK.
- [142] Klán, P. and Gorez, R. (2000). *Automa*, 4, 49-53.
- [143] Pagola, F.L. and Pecharrormán, R.R. (2002). *Proc. 15th IFAC World Congress Automatic Control*.
- [144] Gu, D., Liu, T. and Zhang, W. (2003). *Proc. 42<sup>nd</sup> IEEE Conf. Decision and Control*, 4082-4083.
- [145] Thyagarajan, T. and Yu, C.-C. (2003). *Ind. Eng. Chem. Res.*, 42, 4425-4440.
- [146] Zhang, W., Gu, D. and Xu, X. (2003). *Proc. 42<sup>nd</sup> IEEE Conf. Decision and Control*, 4080-4081.
- [147] Keane, M.A., Koza, J.R. and Streeter, M.J. (2005). *US Patent No. 6,847,851 B1*.
- [148] Lee, J., Park, H.C. and Sung, S.W. (2005). *Canadian J. Chem. Eng.*, 83, 990-995.
- [149] Prokop, R., Korbel, J. and Matuš, R. (2005). *Proc. IFAC World Congress*.
- [150] Prokop, R. and Korbel, J. (2006). *Automatizace*, 48, 3, 190-195.
- [151] Åström, K.J. and T. Hägglund, T. (2000). *Preprints Proc. PID '00: IFAC Workshop*, 181-182.

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