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SIMULATION OF TUNING GAINS DECOUPLING EFFECT FOR PI RELATED CONTROL

Choon Lih Hoo[1], Sallehuddin Mohamed Haris[2]
and Edwin Chin Yau Chung[1]

[1]School of Engineering
Taylor's University Lakeside Campus
Subang Jaya 47500, Malaysia
ChoonLih.Hoo@taylors.edu.my

[2]Department of Mechanical and Material Engineering
Universiti Kebangsaan Malaysia
Bangi 43600, Malaysia

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Abstract. *PI control gains the interest of many in research and industrial application due to its simple implementation despite the introduction of many new control techniques. However, PI control system shows tuning difficulty with limited and restricted tuning range. The coupled k_p and k_i tuning gains in PI control do not allow the coexistence of short settling time and no overshoot. A short settling time will easily induce overshooting performance. A new PI controller, SIPIC that possesses decoupling tuning gains was introduced in the year 2015. The analysis and simulation result using MATLAB/Simulink show that SIPIC can have shorter settling time while maintaining no overshoot performance. The change of tuning gains in SIPIC has insignificant effect on the damping ratio of SIPIC. Conversely, conventional PI controller suffers great effect on damping state from changing tuning gains, which results in overshoot when introducing shorter settling time. SIPIC can have greater flexibility in tuning range for desired performance.*

Keywords: PI control, Tuning gains, Decoupling, Steady-state integral proportional integral control, Simulation

1. **Introduction.** Following the evolution of the control system and with the advanced technology and digitalisation, modern intelligent approaches have been integrated into the control field [1]. However, the classical PID (Proportional-Integral-Derivative) or PI (Proportional-Integral) related controller remains the method of choice for many researchers and applications due to its simplicity in operation and ease of implementation. Many have worked on optimisation and hybrid control system involving the use of PID [2].

Unfortunately, as each gain parameter in this method contributes to different functionality, it is not easy to attain the coexistence of fast settling time and non-overshooting conditions. This is due to the dependency of damping ratio with the change in proportional gain, k_p and integral gain, k_i. If allowed, this may be classified as the coupling of the tuning gains. Many different tuning methods have been introduced for robust and quick fine tune. [3] did a comparison between a few tuning methods such as the Skogestad's Model-based method, Ziegler-Nichols, Hägglund and Åstrøm's Robust tuning method, Tyreus-Luyben's method and Relay method on tuning a temperature controller for a real air heater. In the same year, [4] derived an alternative PI controller tuning rules for integrator plus time delay systems by using different approximations to the time delay in the time lag dominant processes. The introduction of a few parameters allows better robustness measure and the method can be used to obtain new modified Ziegler-Nichols parameters with increased robustness margins. Knowing that any PI related control system will be subjected to the tuning complication due to the coupling of k_p and k_i, this encourages further study and development for a new PI controller that could resolve the coupling effect.

In the year 2015, [5-7] have introduced a novel anti-windup SIPIC (Steady-state Integral Proportional Integral Controller) that can reduce the tuning gain coupling effect. SIPIC shows improved performance with little to no overshoot at short settling time as compared to the existing PI and anti-windup techniques. However, the decoupling effect was only studied analytically in [5-8]. This paper intends to give a better insight of the decoupling effect through simulation approach.

This paper will continue with Section 2 that further explains the tuning gains decoupling effect and SIPIC. Section 3 will discuss the derivation of characteristic equations. Simulation setup and results will be discussed in Sections 4 and 5 respectively. This paper ends with a summary of the overall work.

2. **Tuning Gains Decoupling Effect.** Referring to [8], for a generic motor speed control block diagram given in Figure 1 with a general system plant (1) and controlled by a PID controller (2), the general error dynamic equation in its Laplace domain is given as (3).

$$P(s) = p(s)/d(s) = \sum_{i=0}^{i=m} g_i s^i \Bigg/ \sum_{j=0}^{j=n} h_j s^j \tag{1}$$

$$V(s) = k_p E(s) + k_i Q(s) + k_d s \left(E(s) - e(0)\right) \tag{2}$$

$$E(s) = \frac{\sum\limits_{k=0}^{k=n-1} \left\{ \frac{e^{(k)}(0)}{s^{k+1}} \left[\frac{d(s) - \sum\limits_{j=0}^{j=k} h_j s^j}{p(s)} \right] \right\} + k_d k_T e(0) + k_i k_T \left[\frac{q_{ss}}{s} - Q(s) \right]}{\frac{d(s)}{p(s)} + k_d k_T s + \frac{g_0}{h_0} + k_p k_T} \tag{3}$$

$E(s)$, $V(s)$, $T_L(s)$, $P(s)$, $Y(s)$, Y_r, $Q(s)$, $p(s)$ and $d(s)$ are the Laplace form for error, controller output, external torque, system plant, system output, input reference, integral component, numerator and denominator of the system plant respectively. g_i and h_j are the coefficients, i, j, k, m and $n \in \mathbb{N}^+$, $m < n$ while e, k_T, k_p, k_i, k_d and q_{ss} are the error, torque constant, proportional gain, integral gain, derivative gain and steady state integral respectively.

According to [8], if the tuning gain terms, k_p, k_i and k_d appear in the same pole located in the denominator of Equation (3), the tuning gains of the control system are coupled. Decoupling effect will only happen when the tuning gains stay in separate pole which are deemed to have more distinct contribution to the system response and have less effect on each other. Knowing this, in the year 2015, [5-7] introduced a new controller, SIPIC as described by Equation (4). Equation (5) gives the Laplace form of (4).

$$k_i \left(q_{ss} - q\right) = \dot{q} \tag{4}$$

$$q_{ss}/s - Q(s) = \left(sQ(s) - q(0)\right)/k_i \tag{5}$$

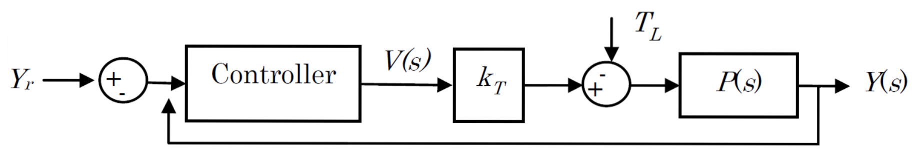

FIGURE 1. Block diagram for closed loop control system

SIPIC was designed in order to achieve the desired tuning gain decoupling effect. Focusing only on proportional and integral controls for simplicity and referring to [7], for a general closed loop system plant of (6), the error dynamic equation for a PI and SIPIC controlled system can be represented as (7) and (8) respectively. a, b, c and f are all constants (parameters of a plant) to denote the generality of the mathematical expressions.

$$P(s) = Y(s)/R(s) = f/(bs + a) \tag{6}$$

$$E(s) = \left[e(0)bs/f + k_i k_T (q_{ss} - q(0))\right] \Big/ \left[bs^2/f + (a/f + k_p k_T)s + k_i k_T\right] \tag{7}$$

$$E(s) = (e(0)b/f) \big/ (bs/f + a/f + k_p k_T) + (k_i k_T (q_{ss} - q(0))) \big/ \big[(s + k_i)(bs/f + a/f + k_p k_T)\big] \tag{8}$$

The denominator of Equation (8) shows that the tuning gains k_p and k_i are located in the separate pole. The possibility of decoupling depends on the separability of the tuning parameters into distinct poles in the performance curve. In a PI control system, k_p and k_i will always be dependent as shown by Equation (7), where both tuning parameters are linked in the denominator and coexist in the same pole. It was learnt from [8] that decoupling can happen when the parameter k_i appears in the denominator of $Q(s)$ function, which eventually leads both tuning parameters to be separated into distinct poles. Decoupling allows the two parameters to be more independent and reduce their effects on each other, which gives better flexibility in manipulating settling time without affecting much on the damping state.

3. **Characteristic Equation.** The characteristic of the control system can be studied by using the generic characteristic equation for second order gain (9). Apply (9) into (7) and (8) to obtain their respective natural frequency, ω_0 and damping ratio, ζ. The natural frequency of PI and SIPIC is given as (10) and (11) respectively, and Equations (12) and (13) denote the damping ratio of PI and SIPIC respectively. From the expressions (12) and (13), SIPIC and PI have different numerator parameters that affect the damping ratio in operation. These expressions will be used later to discuss the simulation result.

$$s^2 + 2\zeta\omega_0 s + \omega_0^2 \tag{9}$$

$$\omega_0 = \sqrt{f k_i k_T / b} \tag{10}$$

$$\omega_0 = \sqrt{a k_i + f k_p k_T k_i} / \sqrt{b} \tag{11}$$

$$\zeta = (a + f k_p k_T) \Big/ \left(2b\sqrt{f k_i k_T / b}\right) \tag{12}$$

$$\zeta = (b k_i + a + f k_p k_T) \Big/ \left(2\sqrt{b}\sqrt{a k_i + f k_p k_T k_i}\right) \tag{13}$$

4. **Simulation for Decoupling Effect.** MATLAB R2011a/Simulink software was used to demonstrate the tuning parameters decoupling effect of SIPIC in comparison to a conventional PI controller for a simple generic second order error dynamic system. Simulations were structured as given in Figure 1 to investigate the effect of k_p and k_i on the system response. The controllers were simulated at $k_i = 1, 5, 10, 15$ and 20 for every k_p value of 1, 5, 10, 15 and 20 in order to show a significant difference between the two controllers. Other parameters are set to unity for simplicity on a system plant taken as $P(s) = 1/(s + 1)$ with load, $L = 200$ in loading condition and 1000 rpm input. The simulation is later repeated for 1500 rpm. The whole process is then implemented on SIPIC with the structure as shown in Figure 2. With these simulation parameters, (7) and (8) can be simplified into (14) and (15) respectively.

$$E(s) = (e(0)s + k_i[q_{ss} - q(0)]) \big/ \left(s^2 + (1 + k_p k_T)s + k_i\right) \tag{14}$$

$$E(s) = e(0)/(s + 1 + k_p) + k_i[q_{ss} - q(0)] / \left\lfloor (s + k_i)(s + 1 + k_p) \right\rfloor \tag{15}$$

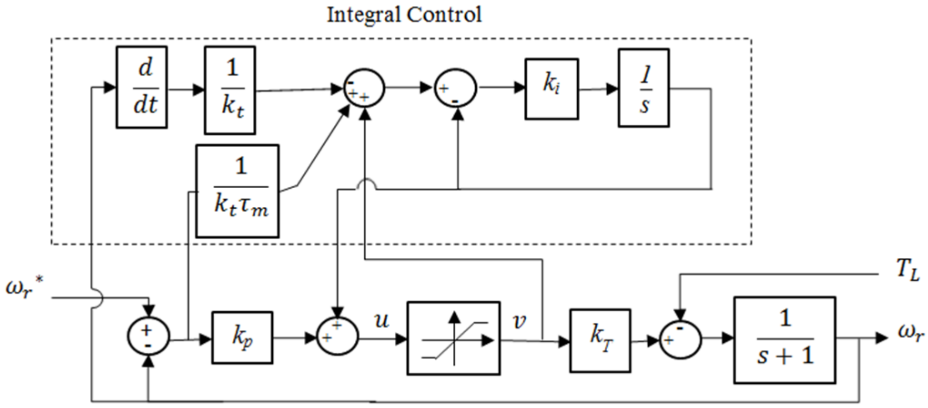

FIGURE 2. Block diagram for SIPIC

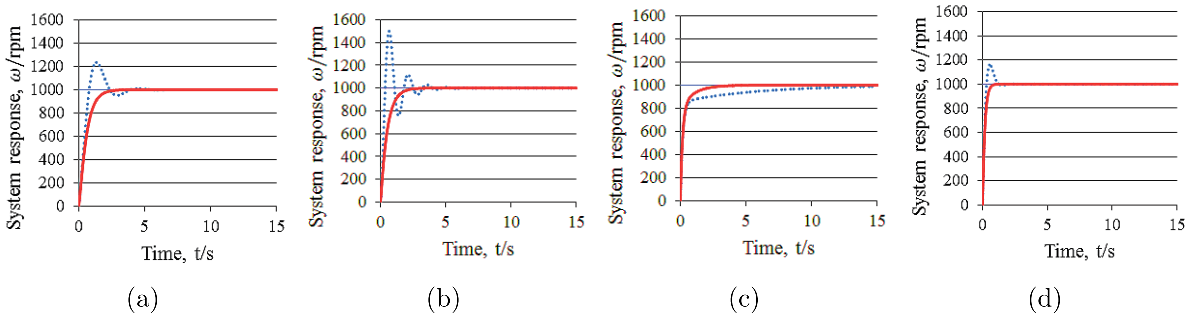

FIGURE 3. No load condition: (a) $k_p = 1$ and $k_i = 5$, (b) $k_p = 1$ and $k_i = 20$, (c) $k_p = 5$ and $k_i = 1$, (d) $k_p = 5$ and $k_i = 20$ (dash: PI, solid: SIPIC)

5. **Result of Decoupling Effect Simulation.** Figure 3 depicts a few results for the MATLAB simulation in investigating the decoupling mode for SIPIC under no load condition for 1000 rpm. The responses for other settings are not shown but will be discussed as listed in Table 1.

To explain the results, their damping ratios are first determined using the obtained expressions (12) and (13) for PI and SIPIC respectively and listed in Table 1 together with the respective tuning parameters for 1000 rpm and 1500 rpm.

5.1. **No load condition.** The results shown in Figure 3 illustrate that increasing the k_p or k_i will shorten the rise and settling time while only has little effect on the damping ratio for SIPIC as indicated in Table 1. Similarly, the conventional PI controller will also reduce the rise and settling times when increasing the k_p or k_i; however, they greatly affect the damping ratio that invites the overshoot phenomenon. This limits the range of choice of tuning parameters available for the non-overshoot requirement in control applications. The result holds for no load condition regardless of the reference speed. This phenomenon can be explained by referring to Equations (12) and (13). Increasing the k_p and k_i gains will have contrasting effects on the damping ratio of conventional PI but they behave differently in SIPIC. In other words, k_p will increase with damping ratio while k_i has an inverse relation with the damping ratio in conventional PI. Meanwhile, the tuning parameters, k_p and k_i, in SIPIC increase or decrease together with the damping ratio due to their existence in both denominator and numerator.

Table 1. Summary of decoupling simulation

k_p	k_i	1000 rpm								1500 rpm							
		No Load				Loading				No Load				Loading			
		Damping ratio		Settling time (s)		Damping ratio		Settling time (s)		Damping ratio		Settling time (s)		Damping ratio		Settling time (s)	
		PI	SIPIC	PI	SIPIC	PI	SIPIC	PI	SIPIC	PI	SIPIC	PI	SIPIC	PI	SIPIC	PI	SIPIC
1	1	1.00	1.06	3.00	3.00	1.00	1.06	3.53	3.17	1.00	1.06	3.00	3.00	1.00	1.06	3.37	3.12
1	5	0.45	1.11	2.14	1.64	0.45	1.11	2.18	1.67	0.45	1.11	2.14	1.64	0.45	1.11	2.17	1.66
1	10	0.32	1.34	2.42	1.56	0.32	1.34	2.44	1.57	0.32	1.34	2.42	1.56	0.32	1.34	2.43	1.57
1	15	0.26	1.55	2.71	1.54	0.26	1.55	2.72	1.54	0.26	1.55	2.71	1.54	0.26	1.55	2.72	1.54
1	20	0.22	1.74	2.95	1.53	0.22	1.74	2.96	1.53	0.22	1.74	2.95	1.53	0.22	1.74	2.96	1.53
5	1	3.00	1.43	6.26	1.39	3.00	1.43	7.52	1.57	3.00	1.43	6.26	1.39	3.00	1.43	7.13	1.52
5	5	1.34	1.00	0.60	0.60	1.34	1.00	0.72	0.62	1.34	1.00	0.60	0.60	1.34	1.00	0.68	0.61
5	10	0.95	1.03	1.09	0.53	0.95	1.03	0.97	0.54	0.95	1.03	1.09	0.53	0.95	1.03	1.02	0.54
5	15	0.78	1.11	1.08	0.52	0.78	1.11	1.07	0.52	0.78	1.11	1.08	0.52	0.78	1.11	1.07	0.52
5	20	0.67	1.19	0.98	0.51	0.67	1.19	0.98	0.51	0.67	1.19	0.98	0.51	0.67	1.19	0.98	0.51
10	1	5.50	1.81	5.66	0.71	5.50	1.81	7.83	0.88	5.50	1.81	5.66	0.71	5.50	1.81	7.15	0.82
10	5	2.46	1.08	0.46	0.34	2.46	1.08	0.78	0.36	2.46	1.08	0.46	0.34	2.46	1.08	0.63	0.35
10	10	1.74	1.00	0.30	0.30	1.74	1.00	0.34	0.31	1.74	1.00	0.30	0.30	1.74	1.00	0.32	0.31
10	15	1.42	1.01	0.25	0.29	1.42	1.01	0.27	0.29	1.42	1.01	0.25	0.29	1.42	1.01	0.26	0.29
10	20	1.23	1.05	0.23	0.28	1.23	1.05	0.24	0.28	1.23	1.05	0.23	0.28	1.23	1.05	0.23	0.28
15	1	8.00	2.13	2.65	0.36	8.00	2.13	5.73	0.48	8.00	2.13	2.65	0.36	8.00	2.13	4.77	0.44
15	5	3.58	1.17	0.29	0.24	3.58	1.17	0.47	0.25	3.58	1.17	0.29	0.24	3.58	1.17	0.37	0.24
15	10	2.53	1.03	0.23	0.21	2.53	1.03	0.26	0.22	2.53	1.03	0.23	0.21	2.53	1.03	0.25	0.21
15	15	2.07	1.00	0.20	0.20	2.07	1.00	0.22	0.20	2.07	1.00	0.20	0.20	2.07	1.00	0.21	0.20
15	20	1.79	1.01	0.18	0.20	1.79	1.01	0.19	0.20	1.79	1.01	0.18	0.20	1.79	1.01	0.19	0.20
20	1	10.50	2.40	0.25	0.22	10.50	2.40	2.04	0.26	10.50	2.40	0.25	0.22	10.50	2.40	0.80	0.25
20	5	4.70	1.27	0.20	0.18	4.70	1.27	0.25	0.19	4.70	1.27	0.20	0.18	4.70	1.27	0.23	0.18
20	10	3.32	1.07	0.18	0.16	3.32	1.07	0.20	0.17	3.32	1.07	0.18	0.16	3.32	1.07	0.19	0.16
20	15	2.71	1.01	0.16	0.16	2.71	1.01	0.17	0.16	2.71	1.01	0.16	0.16	2.71	1.01	0.17	0.16
20	20	2.35	1.00	0.15	0.15	2.35	1.00	0.16	0.15	2.35	1.00	0.15	0.15	2.35	1.00	0.16	0.15

5.2. **Loading condition.** The same performance can be observed even in loaded case as shown in Table 1. Both PI and SIPIC have shorter settling time at loading condition and higher speed. Table 1 entails that the damping ratio changes drastically in PI while SIPIC only encounters slight changes on the damping ratio regardless of the tuning parameters. Favourably, SIPIC solves the issue commonly encountered in conventional PI where if high PI gains are used for fast dynamics, an undesirable high overshoot can however, occur in the speed response and the settling time becomes very slow on the contrary. Since a very high gain cannot be used to obtain fast dynamics, the response to a step command or load disturbance becomes very slow when the system is designed without any overshoot.

6. **Conclusion.** The proposed new control method, SIPIC, exhibits tuning gains decoupling effect. The tuning of k_p and k_i will be less dependent and flexible which allows the individual tuning of each gain without affecting their respective contribution. This allows the SIPIC to have shorter settling time while maintaining no overshoot performance as compared to the conventional PI control which shorter settling time will introduce overshooting. The shorter settling time has insignificant effect on the damping state for

SIPIC as shown in the simulation result. SIPIC shows better performance regardless of no load or loading conditions and this gives a wider range of tuning for desired motor speed control. Future work will focus on its implementation in different applications.

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REFERENCES

[1] R. A. Gupta, R. Kumar and A. K. Bansal, Artificial intelligence applications in permanent magnet brushless DC motor drives, *Artificial Intelligence Review*, vol.33, pp.175-186, 2010.
[2] S. M. Gadoue, D. Giaouris and J. W. Finch, Artificial intelligence-based speed control of DTC induction motor drives – A comparative study, *Electric Power Systems Research*, vol.79, no.1, pp.210-219, 2009.
[3] F. Haugen, Comparing PI tuning method in real benchmark temperature control system, *Modeling, Identification and Control*, vol.31, no.3, pp.79-91, 2010.
[4] D. D. Ruscio, On tuning PI controllers for integrating plus time delay systems, *Modeling, Identification and Control*, vol.31, no.4, pp.145-164, 2010.
[5] C. L. Hoo, S. M. Haris, E. C. Y. Chung and N. A. N. Mohamed, New integral antiwindup scheme for PI motor speed control, *Asian Journal of Control*, vol.17, no.6, pp.2115-2132, 2015.
[6] C. L. Hoo, S. M. Haris, E. C. Y. Chung and N. A. N. Mohamed, Steady-state integral proportional integral controller for PI motor speed controllers, *Journal of Power Electronics*, vol.15, no.1, pp.177-189, 2015.
[7] C. L. Hoo, E. C. Y. Chung, S. M. Haris and N. A. N. Mohamed, Steady-state integral proportional integral controller for PI motor speed controllers: A theoretical approach, *ICIC Express Letters*, vol.9, no.6, pp.1777-1782, 2015.
[8] C. L. Hoo, S. M. Haris, E. C. Y. Chung and N. A. N. Mohamed, The generalisation and decoupling mode of PI-based control: Theoretical approach, *ICIC Express Letters*, vol.9, no.7, pp.1991-1996, 2015.