Analog and Digital Speed Control of DC-Drive by Using Different Control Schemes

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Abstract

A comparative study for the speed control of a dc-drive, in both analog and digital systems, using proportional and integral (PI), integral-proportional (I-P), and proportional-integral (P-I) control schemes is presented here. The current and the speed responses to a step changes in the speed references and the load torque by using the different control schemes are compared to evaluate the merits of each control scheme.

The sensitivity to the controller gains is discussed in briefly in this paper. The simulation results are presented for each control scheme based on Matlab-7 release-14, where the (I-P) control scheme offers some distinctive advantages over other control schemes. The P-I control scheme offers undesirable speed response where the steady-state error is very large in this control scheme.

الخلاصة:

دراسة مقارنة للسيطرة على سرعة سواقة تيار مستمر بأستخدام كل من الأنظمة الكمية والرقمية ومسيطرات تناسبي وتكاملي (PI) وتكاملي-تناسبي (I-P) وتناسبي-تكاملي (P-I) وضّحت في هذا البحث. أستجابة التيار والسرعة نتيجة التغير المفاجئ في السرعة المرجعية وعزم الحمل بأستخدام طرق سيطرة مختلفة ثبتت وقورن فيما بينها لتقييم فوائد كل طريقة.

الحساسية بالنسبة لثوابت المسيطر نوقشت بأختصار في هذا البحث. نتائج المحاكات وضحت لكل طريقة سيطرة بالأعتماد على برنامج (Matlab-7)، حيث طريقة السيطرة بالمسيطر التكاملي-التناسبي (I-P) تقدم بعض الميزات المفضلة على طرق السيطرة الأخرى. طريقة السيطرة بالمسيطر التناسبي-التكاملي (P-I) تقدم أستجابة للسرعة غير مناسبة حيث خطأ حالة الأستقرار جداً كبير في هذه الطريقة.

1. Introduction

Variable speed drives have become wide spread in the home appliance and industrial fields. The closed loop, variable-speed dc drives are widely used because of the ease of control and versatility of the dc separately excited motor. These systems have been studied widely [1]. In many cases, absolute precision in movement is not an issue, but precise speed control is, for example, a dc motor in a cassette player is expected to run at a constant speed. It does not have to run for precise increments which are fractions of a turn and stop exactly at a certain point.

The functional and performance improvements are expected in plants which utilizes a speed regulator for motor drive. Because of this, control performance is required which realizes high accuracy and high-speed response over a wide speed range for a speed regulator for motor drive [2]. Therefore, a system has been tested which utilizes one times the digital control and to compare the responses of system using other times the analog control.

The digital control system uses the microprocessor, as the brain of a system, can digitally control the angular velocity of the motor, by monitoring the feedback lines and driving the output lines. In addition it can perform other tasks which may be needed in the application [3].

In many cases, the appliance driven by the motor includes some kind of user interface: buttons, counters, LED displays. If the analog approach is used, more circuitry will be needed to interface them with the motor drive [4], more cost, higher power consumption, and reduced reliability of the system. Most modifications of the digital control system can be achieved by simple software modifications, therefore the digital control techniques much faster than analog control techniques.

Two control loop design for speed-control of dc drive; the first open-loop and the second closed-loop. Open-loop control is sending a signal to the motor, but not sensing the operation of the motor, hence, the control system can not verify the exact operation of the motor (i.e. make it moves at a certain speed or to certain location). A closed-loop control system senses the rotation of the motor shaft, and/or the voltage and current delivered to the motor. This type of control-loop (closed-loop) make the dc-motor rotate at the required speed, and makes the system response relatively insensitive to external disturbances and internal variations in system parameters. In this paper the second control-loop design is used.

The controller designs are fundamental and important problems in the speed control of dc-drives. The controller design is usually accomplished by using a linear model of the system and classical control theory. Despite huge advances in the field of control systems engineering, PID still remains the most common control algorithm in industrial use today. It is widely used because of its versatility, high reliability, and ease of operation [5, 6]. The speed controls of dc-drive systems usually use proportional-plus-integral (PI) controllers. In this paper proportional-plus-integral (PI), integral-proportional control (I-P), and proportional-integral (P-I) control schemes have been analyzed, using both analog and digital control techniques. Such a comparative study of these different control schemes, provides a viewpoint into the working of each of those control schemes, also show the various advantages and disadvantages of analog and digital controls. The current and speed responses to a step change in speed reference for the different control schemes in both analog and digital control system are discussed in section 3 and 4 respectively. The speed response to a step change in load torque is presented in section 5. In section 6, the sensitivity of speed response to the controller gains is studied.

2. Traditional Closed-Loop Control System

In this paper, the dc-drive is operated as closed-loop system with an outer speed control loop and an inner current control loop. The internal current loop allows better safety where maximum current value is concerned. Further advantages of inner current control loop is giving fast response and overcoming the adverse effects of supply disturbances [7]. Current overshoots preventing will be useful where frequent stops and starts are necessary in an application. On the other hand it increases the system order, leading to extra effort in practical implementation [8].

The separately excited dc-motor is used in this work because the speed control of this type of dc-motor is relatively easy. From the functional block diagram of separately excited dc-motor that shows in Fig. 1, the change in speed $W(s)$ due to disturbances in applied voltage $E_a(s)$ and load torque $T_L(s)$ can be expressed in the following expression [9].

$$W(s)=\frac{k_a\phi}{(k_a\phi)^2+R_aB(1+s\tau_a)(1+s\tau_m)}E_a(s)+\frac{R_a(1+s\tau_a)}{(k_a\phi)^2+R_aB(1+s\tau_a)(1+s\tau_m)}T_L(s) \quad (1)$$

If we neglect the load torque term, from equation (1)

$$\frac{W(s)}{E_a(s)}=\frac{k_a\phi}{(k_a\phi)^2+R_aB(1+s\tau_a)(1+s\tau_m)} \quad (2)$$

If $\tau_a \langle\langle \tau_m$ (which is almost always the case), then τ_a can be neglected, and the expression simplifies to

$$\frac{W(s)}{E_a(s)}=\frac{k_a\phi}{(k_a\phi)^2+R_aB+sR_aB\tau_m}=\frac{k_d}{1+s\tau_d} \quad (2a)$$

Where

$$\tau_d=\frac{R_aB}{(k_a\phi)^2+R_aB}\tau_m \quad (2b)$$

$$k_d=\frac{k_a\phi}{(k_a\phi)^2+R_aB} \quad (2c)$$

$\tau_d \langle \tau_m$

From Fig. 1b

$$\frac{W(s)}{I_a(s)}=\frac{k_a\phi/B}{1+s\tau_m}=\frac{k_f}{1+s\tau_m} \quad (3)$$

Therefore, from equations (2a) and (3)

$$\frac{I_a(s)}{E_a(s)} = \frac{W(s)}{E_a(s)} \times \frac{I_a(s)}{W(s)}$$

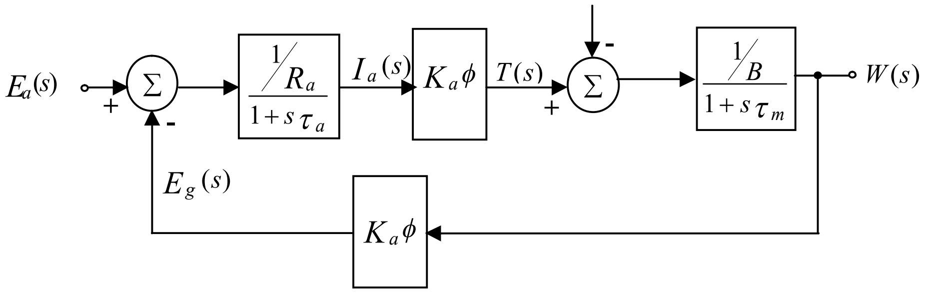
$$= \frac{k_d B(1+s\tau_m)}{k_a \phi(1+s\tau_d)} = \frac{k_m(1+s\tau_m)}{(1+s\tau_d)} \quad (4)$$

Thus the motor can be represented, for the purpose of analyzing it for armature voltage control, as two blocks as shown in Fig. 1b. The gain constants k_m, k_f and k_d shown in Fig. 1b are as follows.

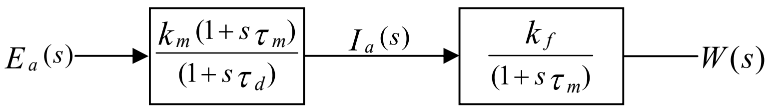
$$k_m = \frac{B}{(k_a\phi)^2 + R_a B} \quad (4a)$$

$$k_f = \frac{k_a \phi}{B} \quad (4b)$$

$$k_d = k_m k_f \quad (4c)$$



(a)



(b)

Fig. 1: (a) Functional block diagram of separately excited dc motor (b) Simplified functional block diagram

3. Current Response

3.1 Analog Control Technique

It is interesting to note that more than half of the industrial controllers in use today utilize PID or modified PID-control schemes [10]. The usefulness of PID-controller lies in their general applicability to most control systems.

Fig. 2 shows a block diagram of a dc-drive with a PI-speed control. The reference current of the motor is;

$$E_I(s) = \varepsilon_w(s)(K_{Pw} + \frac{K_{Iw}}{s}) \quad (5)$$

Since;

$$\varepsilon_w(s) = W_r(s) - W(s) \quad (6)$$

By substituting eq (6) in eq (5):

$$E_I(s) = W_r(s)(K_{Pw} + \frac{K_{Iw}}{s}) - W(s)(K_{Pw} + \frac{K_{Iw}}{s}) \quad (7)$$

Its clear from eq (7) at the starting state or when a step change in the reference speed, the output of the PI-controller, $E_I(s)$, shows an abrupt change and its clamped at the maximum allowable current value (3A). Therefore when the reference current jumps abruptly, the armature motor current also shows a sudden change as shown in Fig.3, where the later shows the simulation starting current response with an analog PI-control technique.

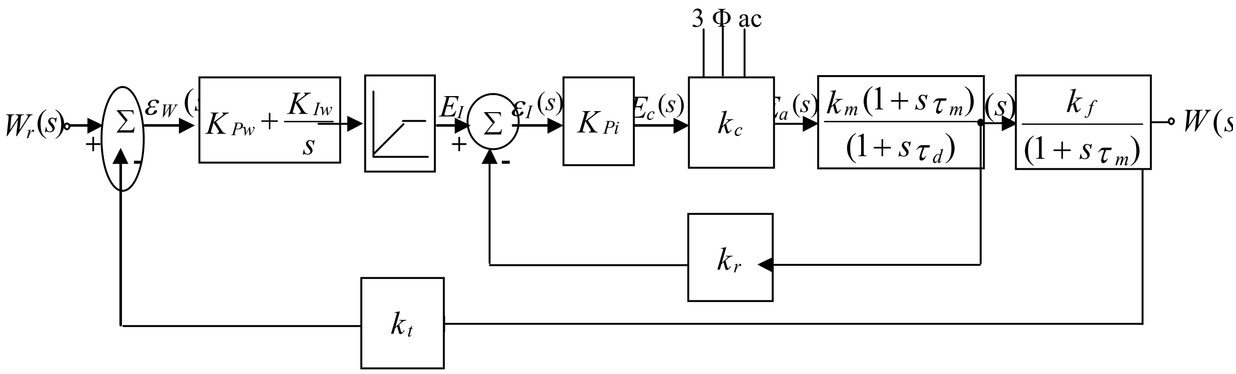


Fig. 2: Block diagram of the dc-drive with a PI-controller

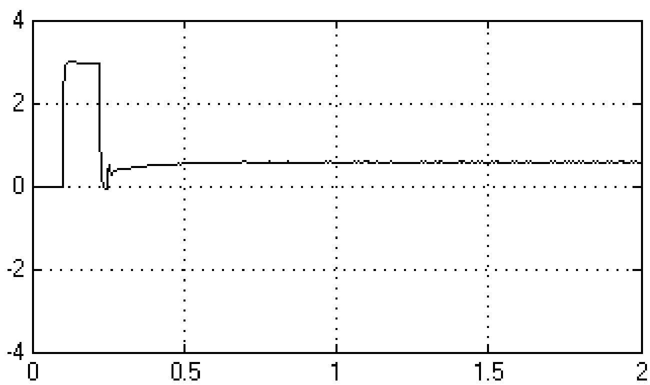


Fig. 3: Simulation starting current response for analog PI-control scheme

The block diagram of a dc-drive with an I-P control scheme is shown in Fig.4. In this scheme, an integral part of controller acts on the speed error $\varepsilon_w(s)$, while the proportional part of controller acts on the motor speed (feedback). The reference current can be computed from Fig. 4 as following:

$$E_I(s) = \varepsilon_w(s)\frac{K_{Iw}}{s} - W(s)K_{Pw} \quad (8)$$

by substituting eq (6) in eq (8):

$$E_I(s) = W_r(s)\frac{K_{Iw}}{s} - W(s)(K_{Pw} + \frac{K_{Iw}}{s}) \qquad (9)$$

From eq (9) the outputs of the integral and proportional parts don't change suddenly and the current reference $E_I(s)$ will not show an abrupt change. Consequently, even with large step changes in the reference speed, the armature current will never overshoot as it does in PI-control scheme. Fig. 5 shows the simulation starting current response of dc-drive with I-P control scheme.

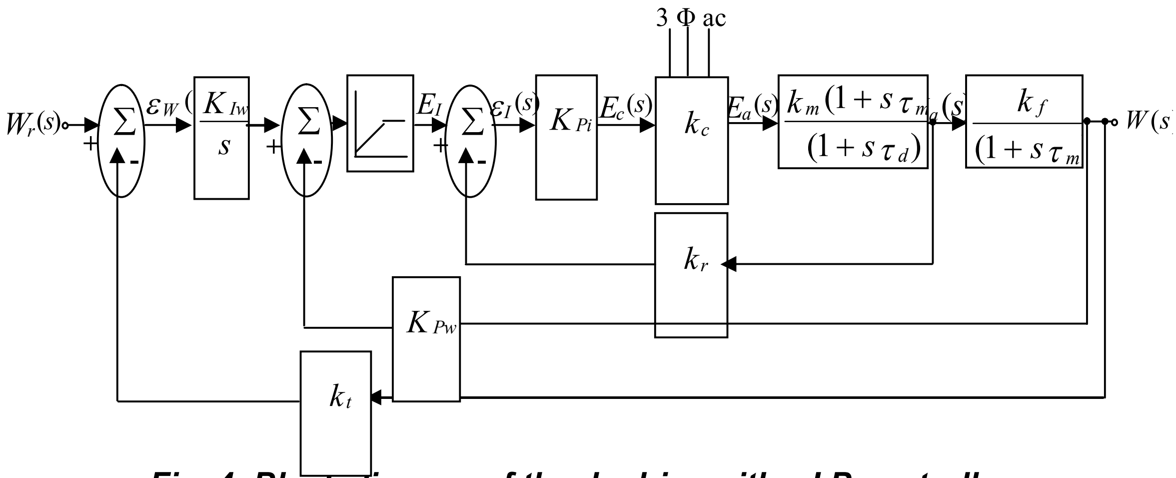


Fig. 4: Block diagram of the dc-drive with a I-P controller

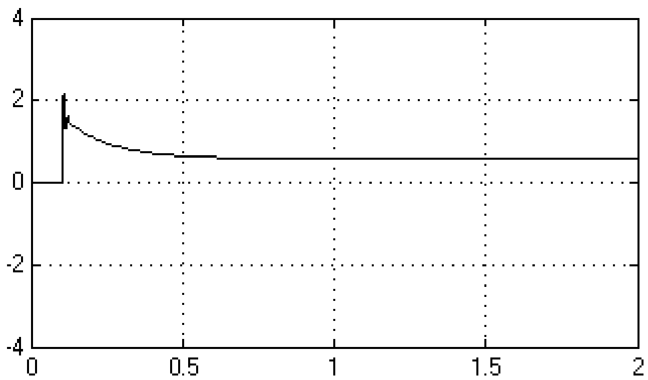


Fig. 5: Simulation starting current response for analog I-P control scheme

The block diagram of a P-I control scheme is shown in Fig. 6. In this scheme, a proportional part controller acts on the speed error, while the integral part acts on the feedback speed. The reference current in this scheme is;

$$E_I(s) = W_r(s)\,K_{Pw} - W(s)(K_{Pw} + \frac{K_{Iw}}{s}) \qquad (10)$$

Eq (10) different slightly from eq (7), therefore the starting current response of P-I control scheme expected similar to the response of PI-control scheme. Fig. 7 shows the similarity in the transient response only, but in the steady-state response is different. Fig. 8 shows the modified current response of a P-I control scheme with modified values of speed controller constants. The response of Fig. 8 similar to the response of Fig. 3 in both transient and steady states responses.

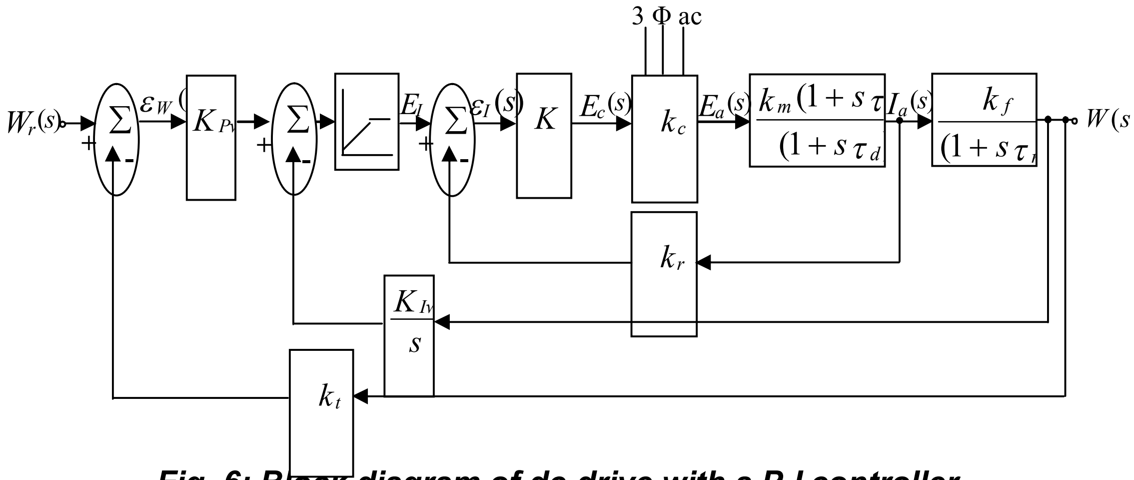


Fig. 6: Block diagram of dc-drive with a P-I controller

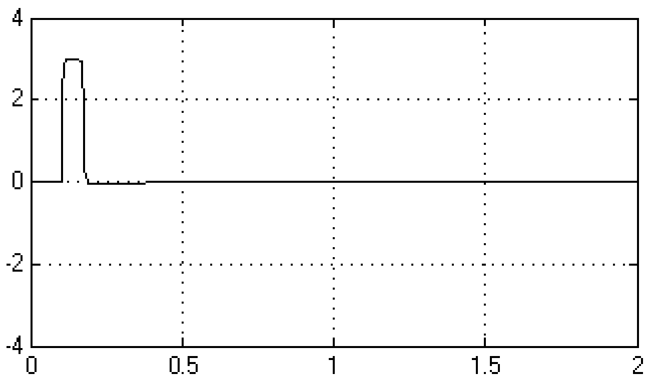


Fig. 7: Simulation starting current response for analog P-I control scheme

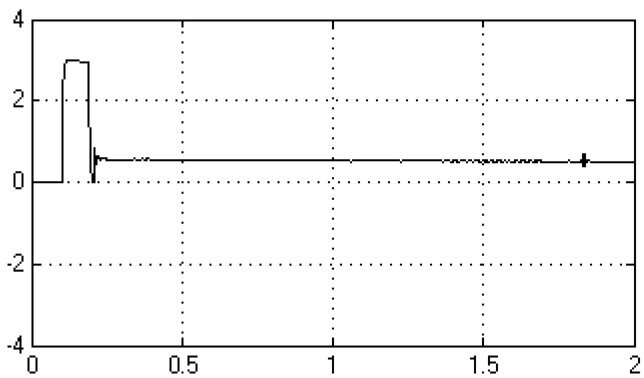


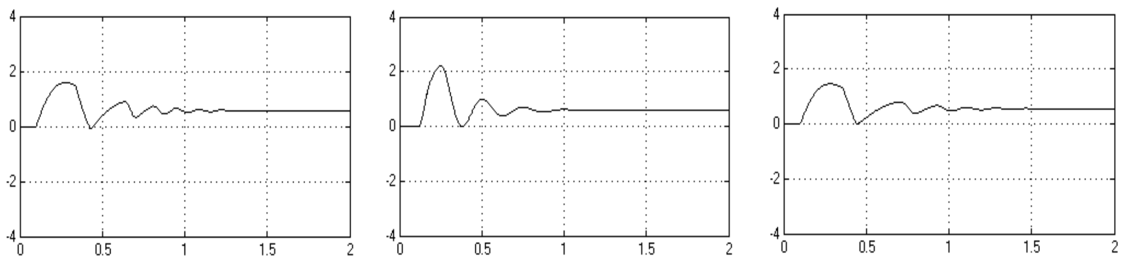
Fig. 8: Modified simulation starting current response for analog P-I control scheme

It's clear from the previous discussions that the dc-drive with an I-P control scheme is better than the other two schemes. The I-P control scheme prevents the armature current overshoot as well as has the advantages of PI-control scheme.

3.2 Digital Control

The advantages of replacing hardware circuits by microcontroller (is a single-chip computer means that the entire computer system lies within the confines of the integrated circuit chip [11]) controllers for a variable speed drive are reducing the size, cost of the hardwired electronics, and having more precise, stable and easy to maintain dc-motor drives. Since microprocessor based control schemes have the advantage of flexibility, higher reliability, and lower cost, but the demanding control requirements of modern power conditioning systems will overload most of the general purpose microprocessors and the computing speed of microprocessor limits the use of microprocessor in complex algorithms [12, 13].

The role of microprocessor in the digital control scheme may be either to replace the logic circuits that control the SCR firing angle or it performs the control law computations [14] and in addition command control signals. The microprocessor-based digital controllers are more convenient than continuous-time controllers. Where the control scheme is implemented in software, it becomes a mathematical operation. The delay time of the system can be neglected if the software program is kept small and if a fast microprocessor is used. Therefore the starting current overshoot can be avoided in digital PI-control scheme. Fig. 9 shows the starting current of dc-motor for different control schemes by using digital control technique.



(a) (b) (c)

Fig. 9: Simulation starting current response for digital different control schemes (a) PI- control scheme (b) I-P control scheme (c) P-I control scheme

4 Speed Responses

4.1 Analog Control

The closed-loop transfer function of dc-drive with a PI-control scheme is derived as follows:

$$\frac{W(s)}{W_r(s)}=\frac{(K_{Pw}+\frac{K_{Iw}}{s})(K_{Pi})(k_c)(\frac{k_d}{1+s\tau_d})}{1+(K_{Pi})(k_c)(k_r)(\frac{k_m(1+s\tau_m)}{1+s\tau_d})+(K_{Pw}+\frac{K_{Iw}}{s})(K_{Pi})(k_c)(k_t)(\frac{k_d}{1+s\tau_d})}$$

$$=\frac{(K_{Iw}+K_{Pw}S)K_{Pi}k_c k_d}{(\tau_d+\tau_m K_{Pi}k_c k_r k_m)s^2+(1+K_{Pi}k_c k_r k_m+K_{Pi}k_c k_d k_{Pw})s+K_{Pi}k_c k_d k_t K_{Iw}}$$

$$=\frac{AK_{Iw}+AK_{Pw}s}{k_1 s^2+k_2 s+k_3} \qquad (11)$$

Where;

$A=K_{Pi}k_c k_d$

$k_1=\tau_d+\tau_m K_{Pi}k_c k_r k_m$

$k_2=1+K_{Pi}k_c k_r k_m+K_{Pi}k_c k_d k_{Pw}$

$k_3=K_{Pi}k_c k_d k_t K_{Iw}$

Eq (11) shows that the PI-controller introduces a zero and, therefore, an overshoot in the speed response is expected for a step change in the speed reference. This is undesirable effect of the PI-control scheme. Fig. 10 shows the simulation speed response to a step change in the reference speed (120 rad/sec) of a dc-drive with a PI-control scheme.

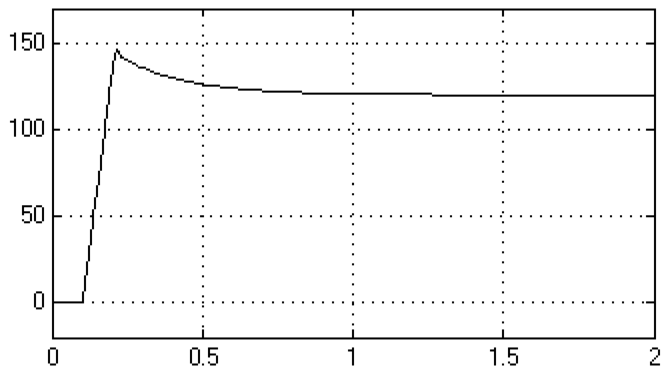


Fig. 10: Simulation speed response of a dc-drive with an analog PI-control scheme

The closed-loop transfer function of dc-drive with an I-P control scheme is derived as follows:

$$\frac{W(s)}{W_r(s)}=\frac{(\frac{K_{Iw}}{s})(K_{Pi})(k_c)(\frac{k_d}{1+s\tau_d})}{1+(K_{Pi})(k_c)(k_r)(\frac{k_m(1+s\tau_m)}{1+s\tau_d})+(K_{Pw})(K_{Pi})(k_c)(\frac{k_d}{1+s\tau_d})+(k_t)(K_{Pi})(k_c)(\frac{K_{Iw}}{s})(\frac{k_d}{1+s\tau_d})}$$

$$=\frac{K_{Iw}K_{Pi}k_c k_d}{(\tau_d+\tau_m K_{Pi}k_c k_r k_m)s^2+(1+K_{Pi}k_c k_r k_m+K_{Pi}k_c k_d k_{Pw})s+K_{Pi}k_c k_d k_t K_{Iw}}$$

$$= \frac{A K_{Iw}}{k_1 s^2 + k_2 s + k_3} \tag{12}$$

By comparing eq (11) and eq (12), it can be seen that, the characteristic equations are the same; but the zero introduced by the PI-controller is absence in the I-P controller. Therefore we expect the overshoot in the speed response of dc-motor with I-P control scheme is small. Fig. 11 shows the simulation speed response to a step changes in the reference speed of a dc-drive with an I-P control scheme.

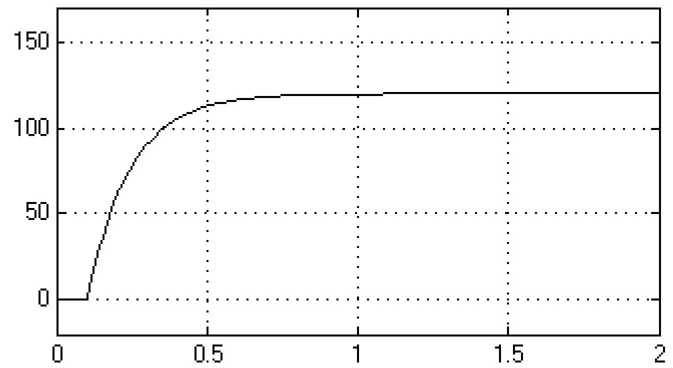


Fig. 11: Simulation speed response of a dc-drive with an analog I-P control scheme

The closed-loop transfer function of dc-drive with a P-I control scheme is derived as follows:

$$\frac{W(s)}{W_r(s)} = \frac{(K_{Pw})(K_{Pi})(k_c)(\frac{k_d}{1+s\tau_d})}{1+(K_{Pi})(k_c)(k_r)(\frac{k_m(1+s\tau_m)}{1+s\tau_d})+(K_{Pi})(k_c)(\frac{K_{Iw}}{s})(\frac{k_d}{1+s\tau_d})+(K_{Pw})(k_t)(K_{Pi})(k_c)(\frac{k_d}{1+s\tau_d})}$$

$$= \frac{K_{Pw} K_{Pi} k_c k_d}{(\tau_d + \tau_m K_{Pi} k_c k_r k_m) s^2 + (1 + K_{Pi} k_c k_r k_m + k_t K_{Pi} k_c k_d k_{Pw}) s + K_{Pi} k_c k_d K_{Iw}}$$

$$= \frac{A K_{Pw}}{k_1 s^2 + k_9 s + k_{10}} \tag{13}$$

The characteristic equation of a dc-drive with a P-I control scheme is different comparing with a PI-and I-P control schemes. Therefore the speed response of a P-I control scheme to a step change of reference speed is different. The speed response to a step change in the reference speed for a dc-drive with a P-I control scheme is shown in Fig. 12, where the values of the speed controller constants (K_{Pw} and K_{Iw}) are the same used in the previous control schemes (PI- and I-P control schemes). By changing the values of speed controller constants, the speed response can be modified to get response better than previous speed response (Fig. 12) as shown in Fig. 13. The steady-state error of the speed response is increased further and further because the feedback value (integral part of the speed controller) that subtracted from the speed error is increased further and further (see Fig. 13). However the speed response of P-I control scheme is bad, therefore the P-I control scheme is undesirable control scheme.

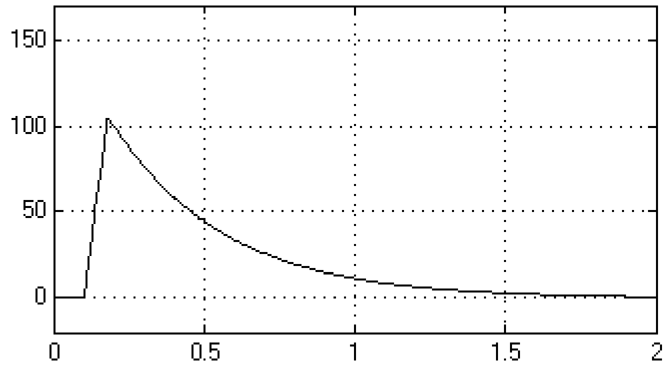


Fig. 12: Simulation speed response of a dc-drive with an analog P-I control scheme

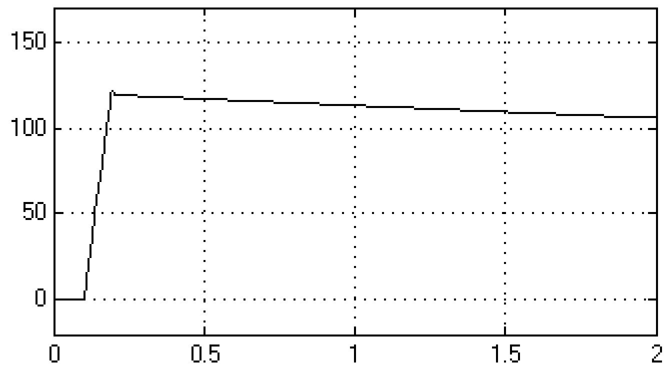


Fig. 13: Modified simulation speed response of a dc-drive with an analog P-I control scheme

4.2 Digital Control

The dc-drive with different control schemes by using digital control technique is discussed in this section. The pulse transfer function of a dc-drive with a PI-control scheme is:

$$\frac{W(z)}{W_r(z)} = \frac{K_{Pi} k_c G_c(z) G_1 G_2(z)}{1 + K_{Pi} k_c k_r G_1(z) + k_t K_{Pi} k_c G_c(z) G_1 G_2(z)}$$

Where; $G_c(s) = K_{Pw} + \frac{K_{Iw}}{s}$

$$G_1(s) = \frac{k_m(1 + s\tau_m)}{1 + s\tau_d}$$

$$G_2(s) = \frac{k_f}{1 + s\tau_m}$$

Since $G_c(z) = K_{Pw} + \frac{z}{z-1} K_{Iw}$

$$= K_{Pw} + G_{Iw}(z)$$

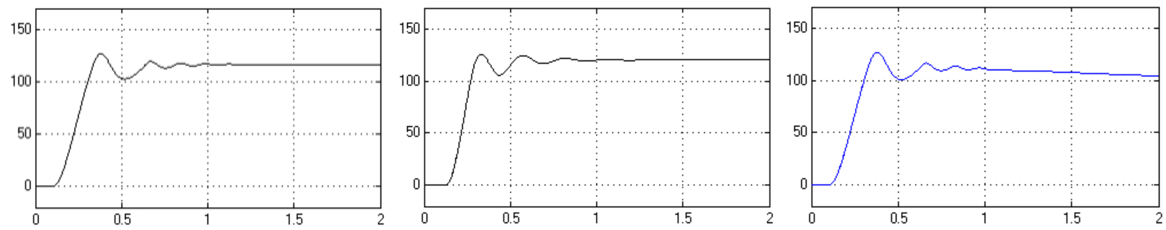
Then we can rewrite the previous pulse transfer function as follows:

$$\frac{W(z)}{W_r(z)} = \frac{(K_{Pi} k_c G_{Iw}(z) + K_{Pw} K_{Pi} k_c) G_1 G_2(z)}{1 + K_{Pi} k_c k_r G_1(z) + k_t K_{Pi} k_c G_c(z) G_1 G_2(z)} \tag{14}$$

While the pulse transfer function of a dc-drive with an I-P control scheme is;

$$\frac{W(z)}{W_r(z)} = \frac{K_{Pi} k_c G_{Iw}(z) G_1 G_2(z)}{1 + K_{Pi} k_c k_r G_1(z) + K_{Pw} K_{Pi} k_c G_1 G_2(z) + k_t K_{Pi} k_c G_{Iw}(z) G_1 G_2(z)} \tag{15}$$

By comparing eq (14) and (15), the denominator of the two equations approximately equivalent but the numerator term $K_{Pw} K_{Pi} k_c G_1 G_2(z)$, in eq (14) is not present in eq (15). Therefore the overshoot in the speed response to a step change in the reference speed for dc-drive with an I-P control scheme is expected small than with a PI-control scheme. Fig. 14 shows the speed response to a step change in the reference speed of a digital dc-drive with both PI- and I-P control schemes.



(a) **(b)** **(c)**

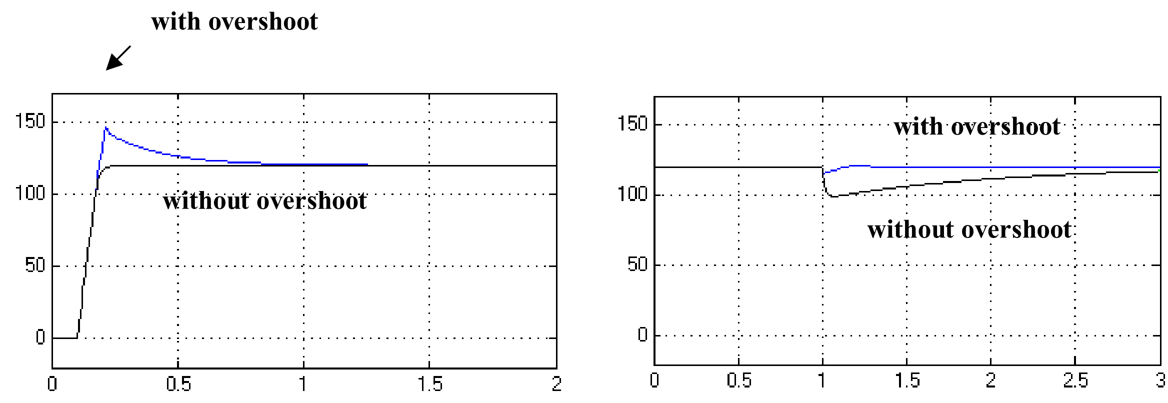
Fig. 14: Simulation speed response for a digital dc-drive (a) PI- control scheme (b) I-P control scheme (c) P-I control scheme

The pulse transfer function with a P-I control scheme

$$\frac{W(z)}{W_r(z)} = \frac{K_{Pi} k_c K_{Pw} G_1 G_2(z)}{1 + K_{Pi} k_c k_r G_1(z) + K_{Pi} k_c G_{Iw}(z) G_1 G_2(z) + K_{Pw} k_t K_{Pi} k_c G_1 G_2(z)}$$

The speed response with a digital modified P-I control scheme is similar to that with an analog P-I control scheme (Fig. 13).

It is possible to neglect the overshoot that appears in the speed response of dc-drive with PI-control scheme, as shown in Fig. 15a, but the response to load disturbances with such PI-control scheme design becomes very slow as shown in Fig. 15b.



(a) (b)

Fig. 15: Simulation speed response for dc-drive with PI- control scheme (a) without load (b) with load disturbance

5. Speed response to a step change in Load Torque

If a load torque is applied to the motor, a dynamic speed variation will occur in the SCR-driven dc-motor due to the load torque disturbances. One of the important properties of variable speed drives applications that the systems respond quickly to a load disturbances and recovery the speed response to a steady speed [15]. The closed-loop transfer function between the speed $W(s)$ and the load torque $T_L(s)$ for PI-control scheme is:

$$\frac{W(s)}{T_L(s)} = \frac{-R_a s}{\tau_m(R_a + K_{Pi} k_c k_r)s^2 + ((k_a\phi)^2 + \beta K_{Pi} k_c k_r + \beta R_a + k_t K_{Pi} k_c k_{Pw} k_a \phi)s + K_{Pi} k_c k_t K_{Iw} k_a \phi}$$

$$= \frac{-k_4 s}{k_1 s^2 + k_2 s + k_3} \qquad (16)$$

Where k_1, k_2, and k_3 are defined in the previous sections. While k_4 is equal to armature resistance (R_a).

When the I-P control scheme is used in the dc-drive, the closed-loop transfer function with load disturbance becomes;

$$\frac{W(s)}{T_L(s)} = \frac{-R_a s}{\tau_m \beta(R_a + K_{Pi} k_c k_r)s^2 + ((k_a\phi)^2 + \beta K_{Pi} k_c k_r + \beta R_a + K_{Pi} k_c k_{Pw} k_a \phi)s + K_{Pi} k_c k_t K_{Iw} k_a \phi}$$

$$= \frac{-k_4 s}{k_1 s^2 + k_5 s + k_3} \qquad (17)$$

The characteristic equation of both PI- and I-P control schemes approximately are equivalent. Therefore the speed responses due to load disturbance are the same for both schemes as shown in Fig. 16. The negative sign in eq (16) and (17) indicates that a drop in speed response for a step increase in load torque.

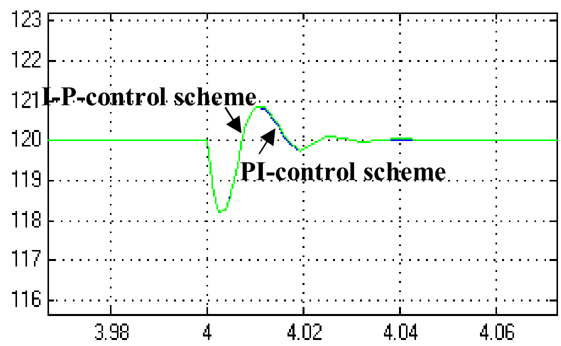


Fig. 16: Simulation speed response to a load disturbance for analog PI- and I-P control schemes.

6. Sensitivity of Speed Response to Integral-Controller Gain

The sensitivity to any changes in the controller gains is different for both PI- and I-P control schemes. Fig. 17 and Fig. 18 are showing the speed responses for a step change in speed reference, for both PI- and I-P control schemes with different controller gains. When the controller gain K_{Iw} is changed, it's clear from figures, the I-P control scheme tends to be more sensitive than PI-control scheme.

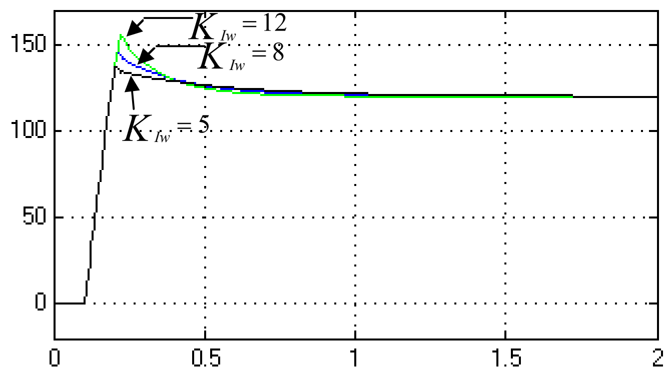


Fig. 17: Simulation speed response to a step change in reference speed for analog PI- control scheme with K_{Pw} constant and varying K_{Iw}

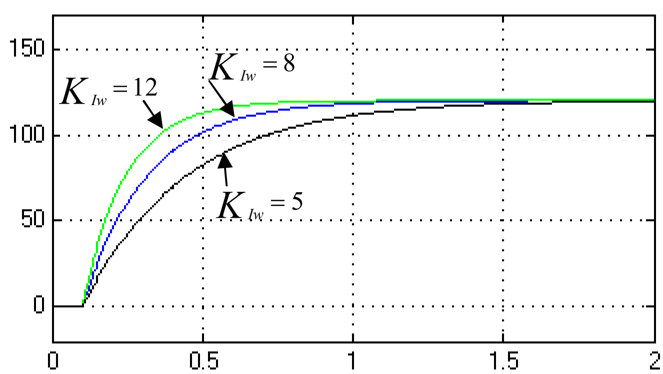


Fig. 18: Simulation speed response to a step change in reference speed for analog I-P control scheme with K_{Pw} constant and varying K_{Iw}

In PI-control scheme, when the controller gain K_{Iw} increased; the overshoot increased, the rise time approximately the same, and the steady-state error decreases. While in I-P control scheme; the rise time and steady-state error are decreased, and the overshoot is increased slightly when the controller gain K_{Iw} increased. The above discussion is demonstrated in the following table.

Table 1: Effective of integral controller gain on the transient and steady state responses

	PI-control scheme	I-P control scheme
	K_{Iw}	K_{Iw}
Overshoot %	↗	↗
Rise time	—	↘
Steady-state error	↓	↓

7. Conclusion

This paper brings out that I-P control scheme has some definite advantages over PI-control scheme. The good features of PI-control scheme is retained in the I-P control scheme, such as zero steady-state error. The overshoot problem in the current response to a step change in the reference speed in PI-control scheme is eliminated in the I-P control scheme. This elimination of overshoot is usefulness in the applications that required frequent stopping and starting and also for the protection of semiconductor devices in the power converters. The digital control based-microprocessor is more reliable, flexible, immune to noise, and easy to implement the complex control scheme.

The speed response to a step change in the reference speed that gets by using P-I control scheme is very bad, therefore the P-I control scheme is not useful. In the last this paper reveals that the I-P control scheme may be useful for implementation in high-performance or precision-drive application.

8. References

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