DIGITAL SPEED CONTROL SYSTEM WITH INTEGRAL-PROPORTIONAL CONTROL

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Abstract. A microprocessor based speed control system for a dc motor drive is described. The motor is fed by a three phase fully controlled bridge the delay angle of which is set directly by the microprocessor. To control the speed of the drive a PI control algorithm is implemented first and the experimental results are obtained for changes in the load torque and the reference speed. The proportional term of the PI controller is then moved from the forward loop to the feedback loop, resulting in an I-P control algorithm. Experimental results are obtained and compared with the previous ones. It is seen that the I-P controller results in a better dynamic performance.

Keywords. Motor control, direct digital control, controllers, thyristors.

INTRODUCTION

For speed control of dc motor drive systems, most commonly used control algorithm is proportional-plus-integral control. The parameters of the controller are tuned to the system in hand to obtain the desired response. However, a comprimise has to be reached between the speed of response and the amount of overshoot. A set of controller parameters which results in an acceptable amount of overshoot, might not give a satisfactory speed of response. The parameters can be adjusted such that no overshoot occurs, but then the system response becomes rather sluggish in case of a load disturbance.

Recently a novel method of control, called integral-proportional control, is suggested (Takahashi, 1978; Harashima and Kondo, 1982) to overcome the above mentioned contradiction. In this type of controller, the proportional term of the conventional PI controller is moved to the feedback loop from the forward loop. I-P controller is therefore a type of feedback compensation and Harashima and Kondo (1981) has shown that such a method is superior to the methods of forward loop compensation in achieving deadbeat performance, i.e. a fast response without overshoot.

This paper reports the results of some theoretical and experimental investigations on the performance characteristics of PI and I-P controllers. A dc motor drive system fed from a three-phase fully controlled bridge is used for the experimental investigations. The control algorithms are implemented digitally by means of a microcomputer and its output is utilized directly to control the delay angle of the bridge.

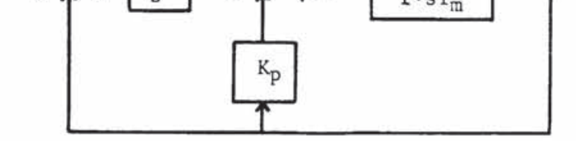
THEORETICAL INVESTIGATIONS

The continuous-time models for a seperately excited dc motor speed control system with a PI controller and an I-P controller are shown in Fig. 1.a and Fig. 1.b respectively, the dc motor being represented as a first order system. From these, the discrete-time models of Fig. 2.a and Fig. 2.b can be obtained, where

$$A = \exp(-T/T_m)$$
$$B = K_m\{1 - \exp(-T/T_m)\} \qquad (1)$$

and T is the sampling period.

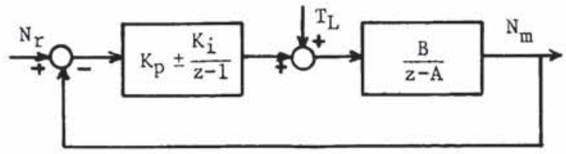
The following transfer functions can easily be obtained from Fig. 2.



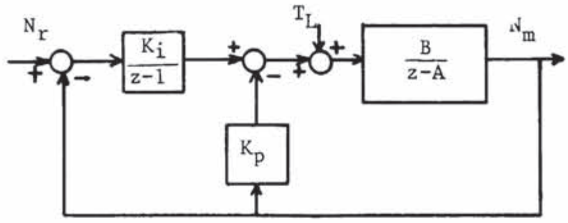
a. PI control system

b. I-P control system

Fig. 1. Continuous time models



a. PI control system



b. I-P control system

Fig. 2. Discrete-time models

With a PI controller:

$$\frac{N_m(z)}{T_L(z)} = \frac{K_i B z}{G_o(z)} + \frac{K_p B(z-1)}{G_o(z)} \quad (2)$$

$$\frac{N_m(z)}{N_r(z)} = \frac{B(z-1)}{G_o(z)} \quad (3)$$

With an I-P controller:

$$\frac{N_m(z)}{N_r(z)} = \frac{K_i B z}{G_o(z)} \quad (4)$$

$$\frac{N_m(z)}{T_L(z)} = \frac{B(z-1)}{G_o(z)} \quad (5)$$

where

$$G_o(z) = z^2 + \{B(K_i + K_p) - A - 1\}z + A - K_p B \quad (6)$$

Since Eqs. (3) and (5) are exactly the same, the same response should be obtained when a change in load torque occurs. However, for a change in the reference speed, the I-P control system should result in a better dynamic response due to the absence of the second term of Eq. (2) in Eq. (4). This term is analogous to a zero in the continuous-time case and Harashima and Kondo (1982) have discussed the effects of its absence in detail. In essence, this allows us to use higher values of K_i and K_p in I-P controllers to obtain a fast response without an overshoot. If the same set of values is used for a PI controller, a large overshoot would be experienced, requiring a higher capacity from the power converter.

DESCRIPTION OF THE SYSTEM

The block diagram of the experimental set-up is shown in Fig. 3. A seperately excited dc motor is driven by a 3-phase fully controlled thyristor bridge. The speed of the drive is sensed by a dc tachogenerator whose dc output is converted into digital form by a 10 bit tracking type A/D converter (Datel ADC-856). It is adjusted such that the speed is sensed with a resolution of 1.2 rpm/bit. The drive is loaded by a dc generator connected to the same shaft.

The microcomputer used is Z-80 based with a clock frequency of 2.5 MHz. It has 2x8 bit input ports and 2x8 bit output ports which were organized as shown in Fig. 4. The reference speed is stored in the microcomputer memory. Provision is however made to increase or decrease this by checking whether certain keys of the keyboard are pressed or not.

For controlling the delay angle of the bridge an approach similar to that of Tang, Lu and Wu (1982) is used with some refinements.

The blocks shown in Fig. 4 are all necessary for the correct operation of the bridge. Their functions are explained below without going into the details of operation.

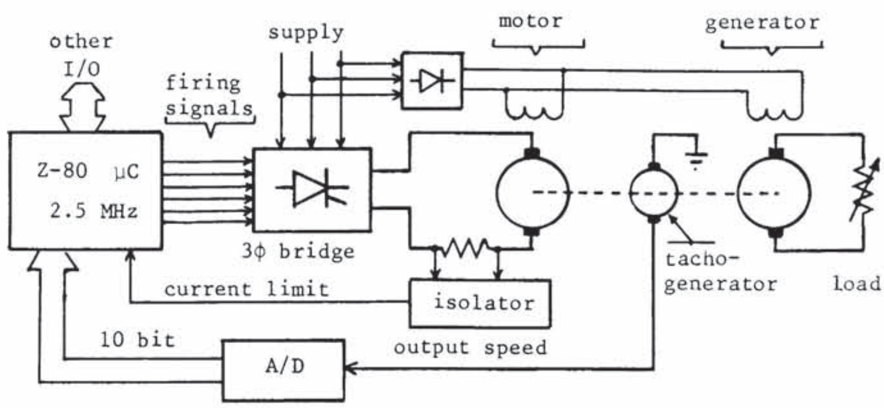


Fig. 3. Block diagram of the experimental set-up

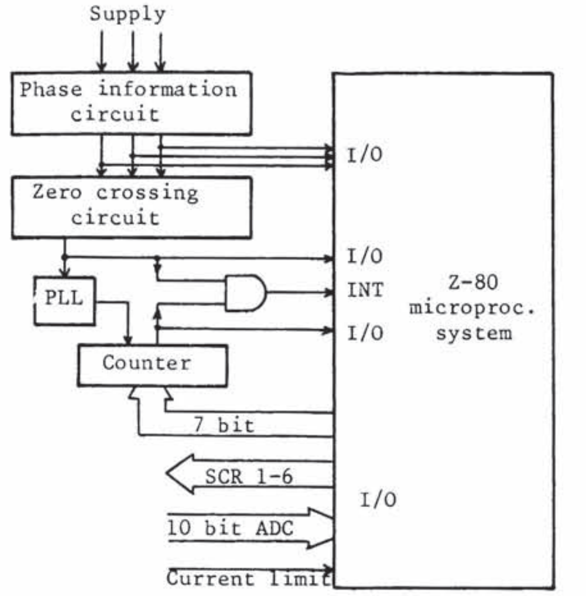


Fig. 4. I/O signals of the microcomputer.

Phase information circuit: This is a circuit consisting of a number of transformers and comparators to provide the microcomputer with the information on the status of the phases of the 3-phase supply.

Zero crossing circuit: This senses the zero crossings of the phases and outputs a pulse train with a nominal frequency of 300 Hz. It is used as an interrupt signal and also as the input to the PLL circuit.

PLL circuit: This generates the clock signal for the counter. The output frequency is synchronised to the supply.

Counter: This is a 6 bit programmable down counter. The control word in the microcomputer for the firing delay angle is 8 bits. The most significant two bits are stored in the memory as the information on whether the firing delay angle is between 0^0-60^0 or 60^0-120^0 or 120^0-180^0. The other 6 bits are loaded into the counter. The zero count output of the counter is used as an interrupt signal to inform the microcomputer that it is time to fire the thyristors. In this way, a firing delay angle resolution of $60^0/64$ is obtained.

In the actual realization, end stops are put by limiting the control word to Ø2H-AØH, corresponding to 2^0-150^0. Additionally, the counts around 60^0 and 120^0 are prohibited to prevent the occurrence of the zero crossing interrupt and the count zero interrupt signals simultaneously.

Current limit: This is used to protect the bridge against overloads. A signal proportional to the armature current is picked up by means of a small resistor and it is isolated from the power circuit by a photo transistor. The maximum current is set to 6 A.

The microcomputer is operated in the interrupt mode 1. An interrupt therefore results in a restart to location ØØ38H. There can be two sources of interrupt, one due to the zero crossing signal and the other due to the count zero signal. As shown in the flowchart of Fig. 5, when an interrupt is sensed, the count value corresponding to control word calculated in the previous cycle is loaded into the counter and the counter is enabled. Seven bits (six for the count value, one as enable signal) of one of the output ports is therefore reserved for this purpose After the loading of the counter, the internal interrupt flip-flop of the microprocessor is enabled, ready to receive the count zero interrupt. The speed information is then inputted and the main program for the implementation of the control algorithm is entered. When the external counter counts down to zero either before or after the completion of the main program, an interrupt is generated and a restart to ØØ38H is made. The outcome of the test shown in Fig. 5 causes the program to branch into the firing program. The status of the phases is loaded in and by use of this information and the information about the firing delay angle range (which is in the memory) the thyristors to be fired are determined by consulting a look-up table. A return is then made back to the main program or to the HALT state.

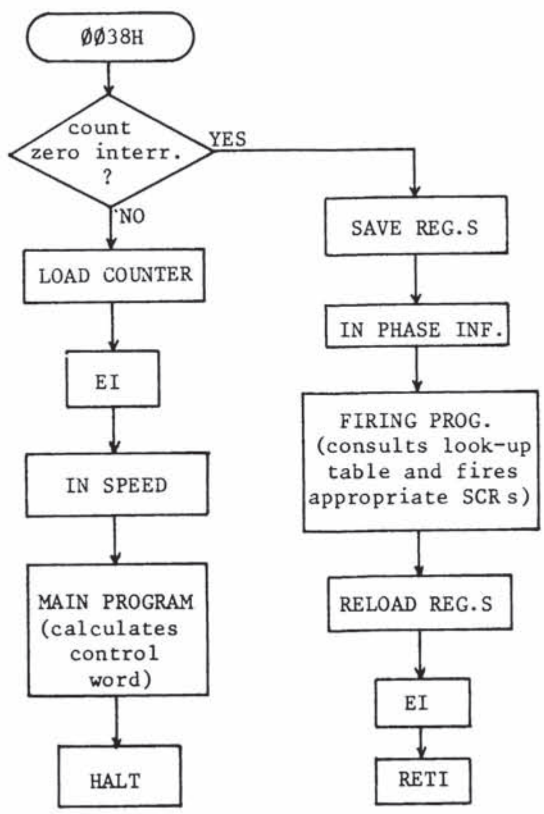


Fig. 5. Flowchart of the interrupt service routine.

CONTROL ALGORITHMS IN DISCRETE FORM

PI controller: In the case of a PI controller, the voltage to be applied to the bridge is of the form

$$u(t) = K_p e(t) + K_i \int e(t)dt \quad (7)$$

where e(t) is the error.

The integral in the last equation can be written as

$$x(t) = \int_{t_o}^{t} e(\tau)d\tau + x(t_o) \quad (8)$$

where t_o is the initial time and $x(t_o)$ is the initial value of x(t).

To approximate the integral by a digital model, the trapezoidal integration rule is used. Defining t kT and t_o (k-1)T, where T is the sampling period, the definite integral of Eq. (8) can be approximated to

$$\int_{(k-1)T}^{kT} e(kT)dt \simeq e[(k-1)T]T + \frac{T}{2}\{e(kT) - e[(k-1)T]\}$$

$$= \frac{T}{2}\{e(kT) + e[(k-1)T]\} \quad (9)$$

Since the integral evaluated in the interval k is used in the next interval, Eq. (8) becomes

$$x[(k+1)T] = \frac{T}{2}\{e(kT) + e[(k-1)T]\} + x(kT) \quad (10)$$

and Eq. (7) becomes

$$u[(k+1)T] = K_p e(kT) + K_i x[(k+1)T] \quad (11)$$

It should be noticed that in Eq. (10) x(kT) is used instead of x[(k-1)T].

I-P controller: For an I-P controller, the control voltage in analog form is given by

$$u(t) = K_i \int e(t)dt - K_p N_m(t) \quad (12)$$

Following a similar approach to that used for the PI controller, the control voltage in digital form is given by the following equations:

$$u[(k+1)T] = K_i x[(k+1)T] - K_p N_m(kT) \quad (13)$$

$$x[(k+1)T] = \frac{T}{2}\{e(kT) + e[(k-1)T]\} + x(kT) \quad (14)$$

EXPERIMENTAL INVESTIGATIONS

As a prelimenary step to the experimental investigations, a number of simulations were carried out on the microcomputer system used for different values of K_i and K_p, using the equations developed in the earlier sections. The simulation results, which are not presented here, indicated as expected that the dynamic performance of the I-P controller would be better. Based on the simulation results, a range of values for the parameters K_p and K_i were decided upon and implemented.

The execution time of the program has to be less than the sampling period (3.3 ms) of the system. The control algorithms involve a number of multiplication steps and if they are carried out by software, the execution time is likely to exceed the limit. Since the microcomputer system used did not have a hardware multiplier, the values of K_i and K_p were chosen in such a way that shift right or shift left instructions executed the necessary multiplications. The oscillograms for some sets of K_p and K_i values are shown in Figs. 6 and 7.

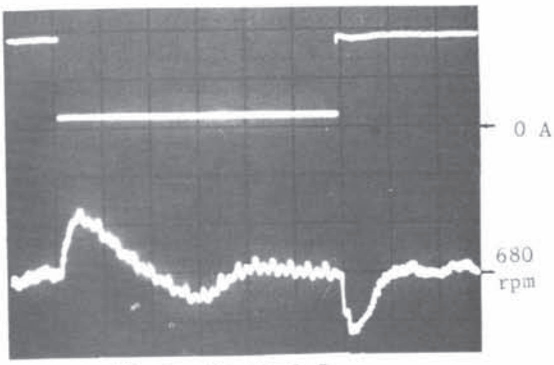
The values of K_p and K_i quoted in these figures includes the gains in the microcomputer and the thyristor bridge. The gain of the bridge is in fact non-linear since the output voltage is a cosine function of the firing delay angle. It can be linearized by use of a inverse cosine look-up table, but this was not implemented. The gain was taken as the average values of the gains at firing delay angles of 30^0 and 60^0 since the bridge operates mainly in this range.

The oscillograms of Fig. 6 indicate that the responses to a sudden change in the load torque are the same for PI and I-P controllers. This is to be expected from Eqs. (3) and (5). However, it is seen from the oscillograms of Fig. 7 that a set of values which causes an appreciable amount of overshoot in the PI controller, gives no overshoot in the case of the I-P controller and the response is very fast.

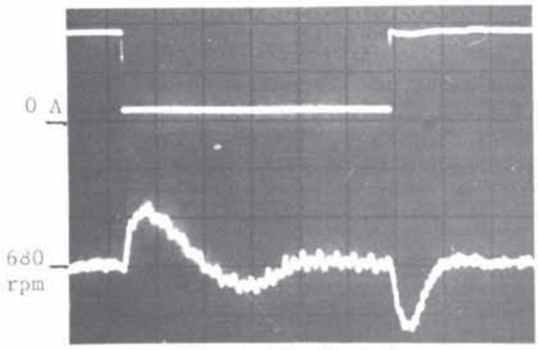
The parameters of the machine are given in TABLE 1.

TABLE 1 Parameters of the machine

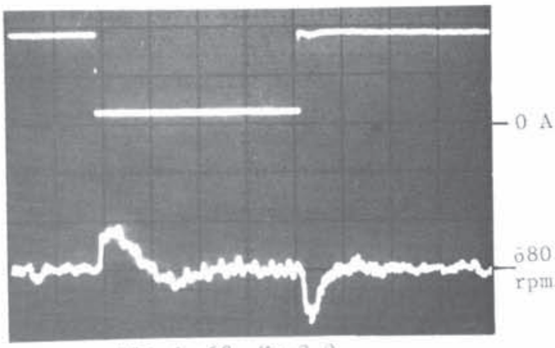
Rating:		3/4 kW 1450 rpm 125 V
K_m	:	0.93 rad/V.s.
T_m	:	0.46 s.
R_a	:	3 ohm
L_a	:	24 mH



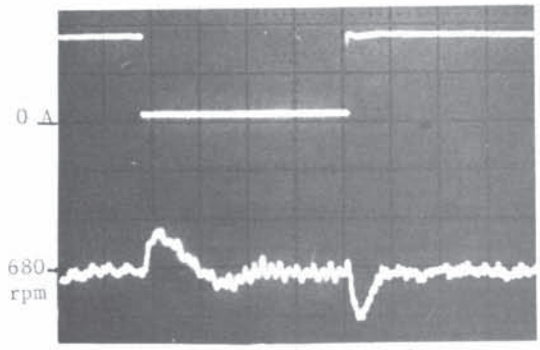
PI: K_p=30, K_i=1.5



I-P: K_p=30, K_i=1.5

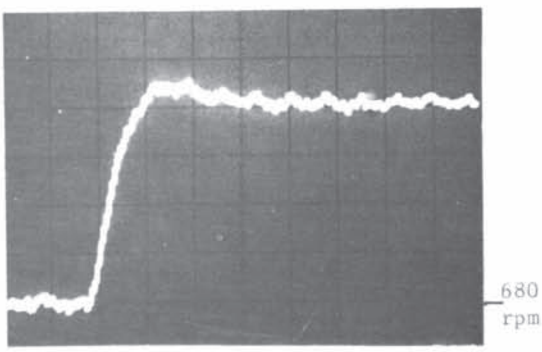


PI: K_p=60 K_i=3.0

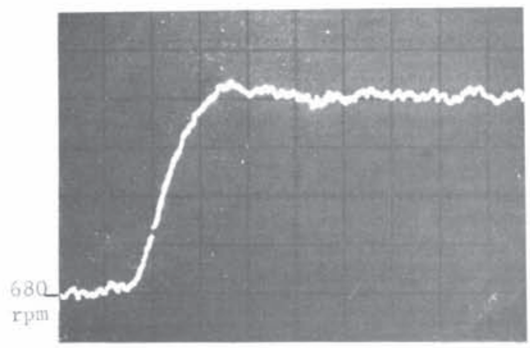


I-P: K_p=60, K_i=3.0

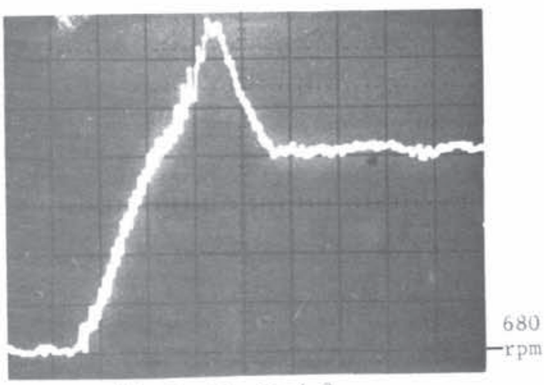
Fig. 6. Responses to a sudden change in load
Upper traces: Load current. Lower traces: Output speed.
1 div = 1 A, 20 rpm, 0.1 s.



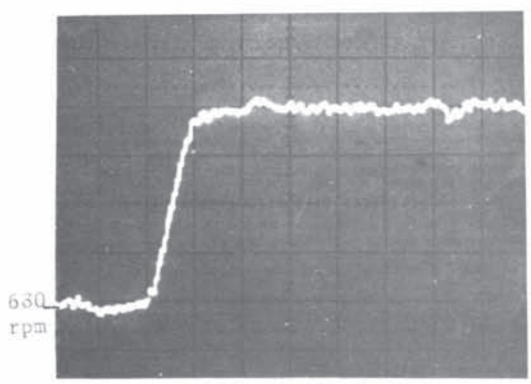
PI: K_p=30, K_i=1.5



I-P: K_p=30, K_i=1.5



PI: K_p=60, K_i=3.0



I-P: K_p=60, K_i=3.0

Fig. 7. Responses to a sudden change in reference speed.
1 div = 20 rpm, 0.2 s. (Load current: 1.5 A.)

CONCLUSIONS

This paper has demonstrated that I-P controllers can effectively be used when a fast response without any oversnoot is a requirement. Howver, the price paid for this is the higher dynamic range required from the controller (Harashima and Kondo, 1982).

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