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DIGITAL SPEED CONTROL AND ANALYSIS OF PERFORMANCE OF THYRISTORIZED DC MOTORS

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Abstract

A PID speed controller for a thyristorized dc motor has been designed, implemented, and tested. The controller is mainly composed of a DEC PDP 11/10 minicomputer together with the firing control circuit, and the necessary interfaces.The control algorithm and all of the relevant subroutines have been implemented in order to minimize the overall execution time of the control program. Thyristor control of dc motor is investigated with more emphasis on the problem associated with firing of the control circuit. A solution to these problems is developed using optocouplers to isolate the thyristor gate from the motor side. A discussion of the experimental results is presented and the performance analysis of the adopted controller is analyzed. A thorough study for different types of errors such as the roundoff errors, quantization errors and inherent errors showed a satisfactory performance of the proposed controller within the acceptable limits.

1. Introduction

In recent years significant progress has been made in the discrete data computer control systems. These systems gain its popularity and importance in all industries due to the advances made in microprocessors coupled with their diminishing cost as well as the advantage found in working with digital controllers [8,9]. In many cases the microprocessor controllers have successfully replaced the conventional analog controllers [10,11,12]. There are several good reasons to account for this invasion. Some advantages of digital control are improved sensitivity, better reliability, more compact and light weight, more flexibility in programming, less cost, and less effects due to noise and disturbances [1].

This paper presents a method of controlling the speed of an SCR dc motor drive using a full wave single phase ac supply. A digital PID controller is used to determine the firing angle. The control algorithm is based on a finite difference equation relating the error signal to the controller output, and is implemented using a DEC PDP 11/10 minicomputer and an interface circuit. The computer performs both the control algorithm execution and the necessary logic for firing the SCR. The control algorithm is simple and meets the real-time requirements.

2. Description of the control system

Fig. 1 depicts an SCR driven dc motor with a full wave single phase ac power supply. The armature circuit of the motor is controlled using natural commutation circuit. During the positive half-cycle of the supply voltage, the first SCR namely SCR1 is forward biased, the transformer secondary S1 carries the load current, and the second SCR namely SCR2 is reverse-biased. During the negative half-cycle SCR2 is forward biased, and the tranformer secondary S2 carries load current, and SCR1 is reverse-biased. The output amplitude of the average dc control voltage E is controlled by adjusting the firing angle, output current I is therefore supplied in turn by SCR1 and SCR2.

DC Motor Transfer Function

A linear model for the motor will be assumed through the following discussion. Thus the following equations can be written in the s-domain relating the electromechanical effects on the motor. The equations characterizing this system are as follow (see Fig. 1).

$$E_a(s) = E_b(s) + R_a I_a(s) + sL_a I_a(s) \tag{1}$$

$$E_b(s) = k_b W(s) \tag{2}$$

$$T(s) = k_q I_a(s) = JsW(s) + B W(s) \tag{3}$$

where

R_a = armature motor resistance

L_a = armature motor inductance

$E_b(S) = L(E_b(t))$, where $E_b(t)$ is the back emf voltage

k_b = motor back emf constant,

k_q = motor torque constant

$I_a(s) = L(I_a(t))$, where $I_a(t)$ is the armature current

$E_a(s) = L[E_a(t)]$, where $E_a(t)$ is the armature voltage

$W(s) = L[W(t)]$, where $W(t)$ is the speed of motor

J = moment of inertia at motor shaft,

B = viscous friction

In general, the armature circuit time constant (L_a/R_a) can be assumed relatively small with respect to motor time constant (J/B), i.e. $L_a/R_a \ll J/B$. Considering E (s) as the input and W(s) as output. The transfer function of the motor becomes [2]:

$$W(s)/E(s) = K_m \,/\, (1 + s\, T_m) \qquad (4)$$

where

$$K_m = K_b \, (k_b \, K_q + R_a \, B)$$

$$T_m = R_a B \,/\, [(K_b K_q + R_a B)\; J/B]$$

The model of the thyristors circuit is considered as a sampler and partial zero hold device of amplitude proportional to the firing angle with conduction period T. The SCR model can be described by equation (5).

$$E_a(s) \,/\, E_i(s) = [K_\alpha \, (1 - \mathrm{EXP}\,(-T_c \, s))]/s \qquad (5)$$

where

E_i = the input supply voltage

$K_\alpha = E_i /\pi \int_\alpha^\beta \sin\,(wt)\; dwt$

α = the firing angle

β = the distinction angle

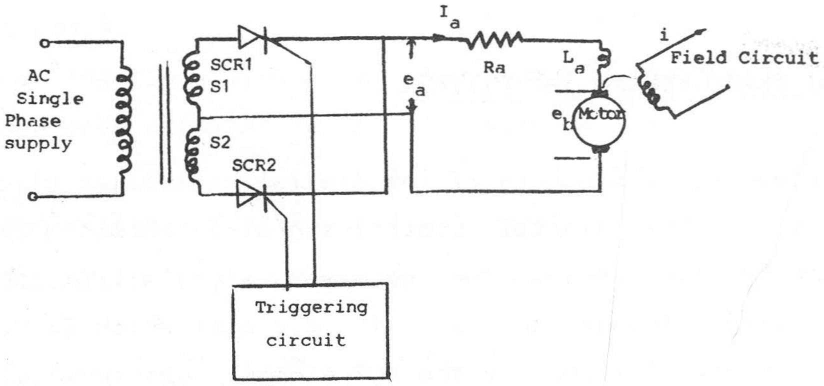


Fig. 1. AN SCR DRIVEN DC MOTOR

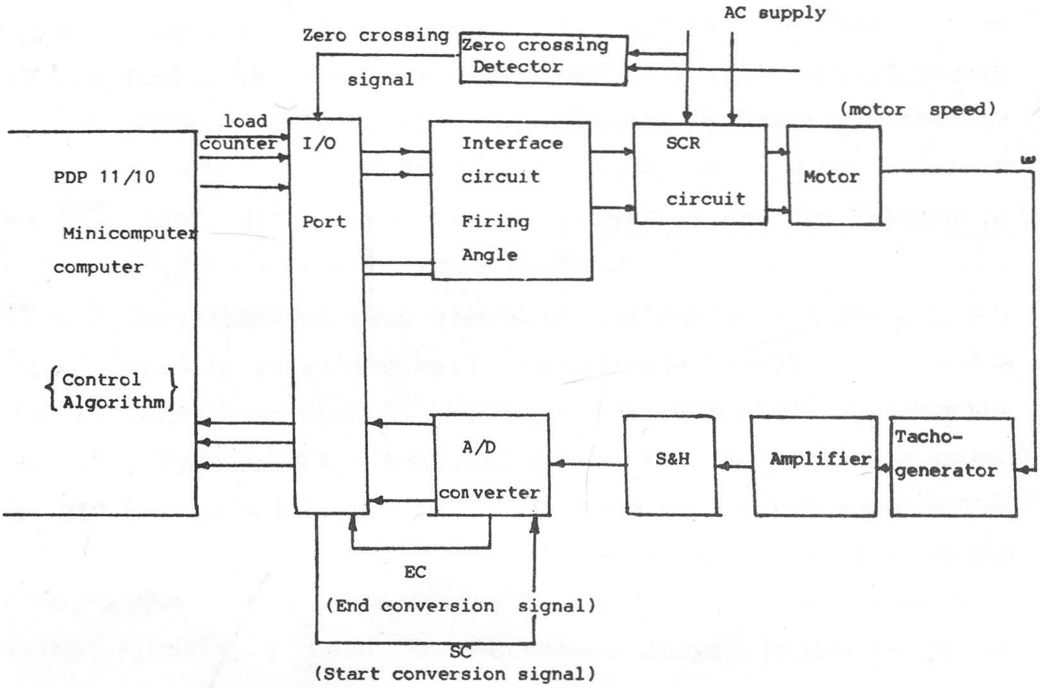


Fig. 2. Computer Based control system

T_c = conduction period

Digital Speed Controller Circuit

The necessary components of the digital controller circuit are shown in Fig. 2. The digital control signal is obtained from a PDP11/10 minicomputer as shown. The necessary signals from the computer are communicated through an I/0, 16 bit port which feeds an interface firing circuit, followed by the SCR elements driving motor circuit. On the feedback side, the tachogenerator measures the motor actual speed, w, feeding it to an amplifier, then **to a** sample and hold circuit. The sampled signal is then converted to digital information using A/D converter, which provides the binary form of the feed back signal. The zero crossing detector is fed from the ac supply and produces a synchronizing signal to the computer. The later signal is used by the control algorithm to start a new cycle of execution .

A. Digital PID Controller

The digital PID controller is widely used in industrial systems of any order. It offers significant flexibility by allowing tuning of its parameters. The discrete version of the controller is obtained by using z'-transform and the difference equation approach. The overall Z-transform expression chataceterizing the action of the PID controller can be written in the form [1].

$$G_c(z) = M(z)/E(z)$$

$$= K_p + K_i T\ (z+1)/(2(z-1)) + K_d(z-1)/T \qquad (6)$$

where K_p , K_i, and K_d are the proportional, integral and derivative constants.

The difference equation, relating the control signal to the error signal which has been obtained in Eq. (7), written as:

$$H(n) = M(n-i)+C1E(n)+C2E(n-1)+C3\,E(n-2) \qquad (7)$$

where

$C1 = (\,2\,K_p + K_i\,T + 2K_d)/2T$

$C2 = (-2\,K_p T + K_i T - 4K_d)/2T$

$c3 = (K_d/T)$

$T =$ the sampling period

B. Firing Angle Interface Circuit

The firing circuit is designed to operate in parallel with the computer. The main function of the circuit is to receive the digital information representing the value of the firing delay and to trigger the proper thyristor. The datails of the circuit are shown in Fig. 3. It consists of a 25 KH clock generator, an 8 bit firing counter, a zero crossing detector, and an isolation circuit feeding SCR circuit.

The binary counter is used as a firing delay timer [3] which decodes the firing angle produced by the control algorithm. The counter is driven by a synchronized clock. The function of the zero crossing detector is to send a synchronizing signal to the computer when the ac voltage changes its sign from possitive to negative or vice-versa. The synchronizing signal is used to determine which thyristor will be fired. Provisions have been made to insure sufficient amplitude and duration for turning on the thyristor as well as a good accuracy over the required range of operation. Measures have been taken to insure

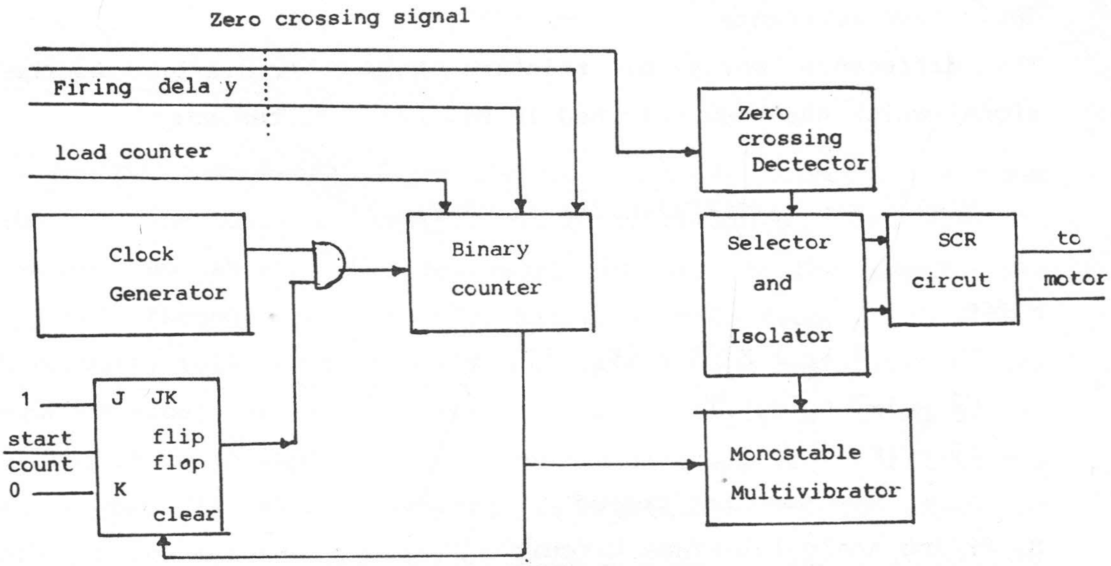
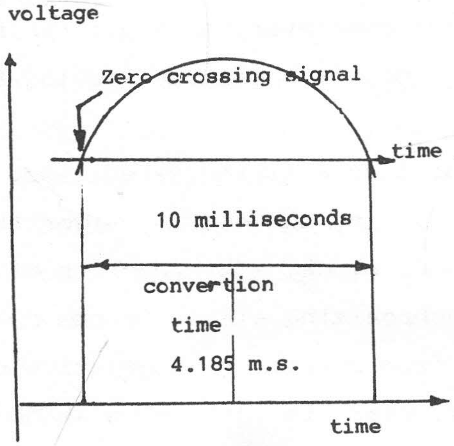


Fig. 3 Firing Angle circuit



1. start A/D converter
2. Load the counter
3. Start counter

Fig. 4 Timing diagram

the proper isolation of the thyristor gate during turn-on process by using optocouplers. The operation of the thyristor firing is as follows. The digital output of computer representing the firing delay is stored in a temperary storage; when the computer receives the zero crossing signal. It issues a load signal to load the counter with the firing delay signal. The later signal is followed by a start count signal, counting down starts which will ended up with a borrow signal that will trigger a monostable multivibrator. The monostable output is transmitted to the proper thyristor providing the necessary firing signal. The zero crossing output will also cause the computer to start a new cycle of calculating a new firing delay.

Referring to Fig. 4; after the computer receives the zero crossing signal it will send a load counter signal followed by a start count signal. Also it sends a start A/D conversion signal to the A/D converter. Then the computer starts the calculation of the control signal. The firing delay is obtained from the firing angle look up table which is established off-line [6] the execution of the control algorithm.

C. Software Description

The controller software is organized according to the flow chart shown in Fig. 5. The flow chart includes a description of the initialization and starting procedures, which involves waiting for the moment when the zero crossing signal changes from zero to one and subsequently a load counter and a start count signal are sent to the counter, then a start converge signal is sent to the A/D converter. Thereafter, the computer performs the tasks of preparating the next firing cycle.

The design of the digital PID control algorithm is a four step process as follow:

(1) Obtain the Z-transform of the PID controller G_c (z).

(2) Find the finite difference equation relating the PID control signal to the input error signal.

(3) Write a computer program to sample the error and produce the correcting signal according to the finite difference equation [5].

(4) The firing angle corresponding to the generated control signal is obtained from a lock up firing angle table.

Design of The PID Control Algorithm

An assembly language program is developed to implement the control algorithm to minimize the response time of the controller. Since the minimum distance time between two consequetive firing instances are 180 degree or 10 milliseconds for a 50 HZ supply, thus the time allowed for the control algorithm should be less than 10 milliseconds. The fixed point arithmetic is used to achieve these requirements, the format of the fixed point numbers is 16-bits to represent the fractional part, 15-bits for the integer part and one bit for sign, and the 2's complement is used to store negative numbers. The addition, subtraction and multiplication subroutines are written using assembly language.

The control algorithm consists mainly of three segments namely, initialization segment, firing angle calculation segment, and subroutines and table segment. The first segment provides initialization parameters and coefficients necessary for the operation of the controller algorithm. The second segment utilizes the PID control algorithm to obtain a correcting signal based on the input error signal, also this segment performs the handshaking operation between the computer and the firing circuit. The third segment comprises of multiplication, subtraction and addition subroutines and functions to be used by the control algorithm in data processing as well as the firing angle table. The PDP 11/10 minicomputer control program flow chart is completely shown in Fig. 5.

The length of the computer control algorithm program, subroutines and firing angle table is 820 bytes, and the total execution time is 4.145 milliseconds[7].

3. Controller Analysis

a. Stability Analysis

In this section we examine the stability of the controller as well as its performance in the steady state under step and ramp inputs. Consider Fig. 6 which shows the closed loop block diagram of a control system including controller.

The SCR model can be approximated by rational expression like Pade expansion [4].

$$(1 - EXP(-T\ S))/s = T/(1 + sT / 2) \tag{8}$$

The Z-transform of SCR and motor becomes.

$$G(z) = B1\ (B2 - B3)/[(Z - B2)(Z - B3)] \tag{9}$$

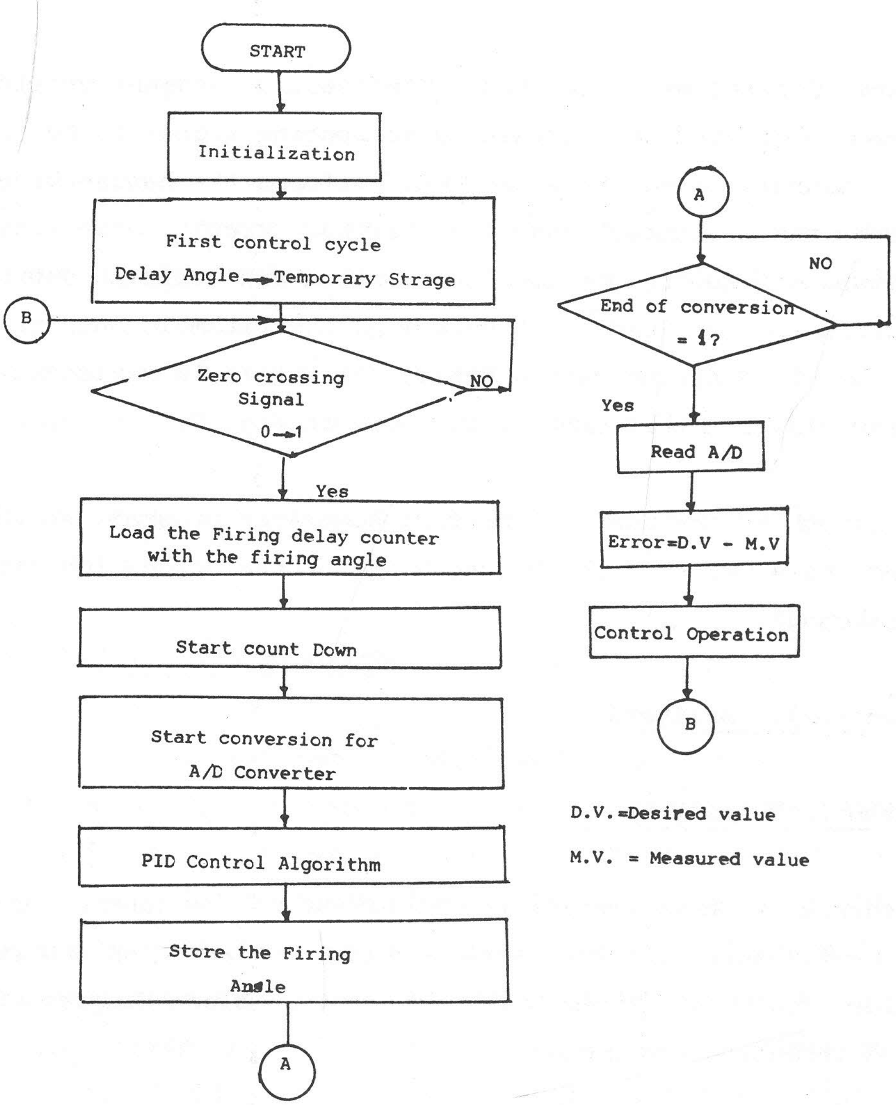


Fig. 5 The control Program Flowchart

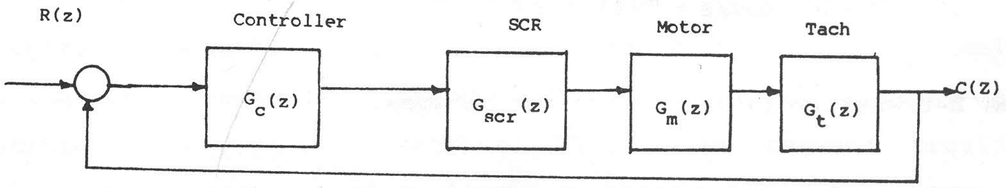


Fig. 6. Closed loop control system including the PID controller.

where

$B1 = 2 K_{\alpha} \; K_m /(1 + 2T_m/T_c)$

$B2 = EXP\ (- 2T/T_c)$

$B3 = EXP\ (- T/T_c)$

the overall closed loop transfer function is given by:

$$C(Z)/R(Z) = G_c(Z)G(Z)K/(1+G_c(Z)G(Z)K) \qquad (10)$$

The controller parameters can be determined in such a way that the PID zeros cancels the two poles of the controlled process at Z=B2 and Z=B3. Then the controller constants can be determined.

By applying the Jury's test [1] to the characteristic equation

$$F(Z) = 1 + G_c\ (Z)\ G(Z) \qquad (11)$$

The system is stable and all roots lie inside the unit circle

b. Error Analysis

Rounding of a binary number to C-bits is accomplished by discarding all bits less than the least significant bit. For the fixed point arithmetic the error made by rounding is the same for all three types of number representations (sign-magnitude, 1's complement and 2's complement). In case of fixed point and if the fractional part in C-bits, the error is less than 2^{-C}.

The propagation of the round error depends on the control algorithm and the system transfer function. The error propagated by any succeeding arithmetic operation, is very important to be in terms of an expression of the absolute value and relative error of the four arithmetic operations. Such an expression is a function of the bound on the total error in calculations containing any number of arithmetic operations.

Let us now apply the process graph techniques to the controller expression Eq. (7). To be completely safe, a worst case will be assumed where the error could be as large as the bound. The bound on the relative error is indpendent of the size of numbers, rather the bound depends on the number of digits in the fractional part, and the method of rounding. In our case the round off error is always less than 2^{-16}. Let: r be the relative error in addition subtraction, multiplication, and division.

r1- be the inherent error in E(n), E(n-1), E(n-2), M(n-1),

r2 - be the inherent error in the A/D

Since all numbers are represented in fixed point format the maximum error due to roundoff and inherent errors are 2^{-16}.

By applying the process graph techniques to Eq. (12) the absolute error in the controlled signal M(n) is :

$$e = r[\,(4\ C1\ E(n)+4\ C2\ E(n-1)+3\ C3\ E(n-2)+M(r)+1]+r1[C1\ E(n) + C2\ E(n-1)+ C3\ E(n-2)] = .045 \text{ volt} \qquad (12)$$

The error in firring angle due to these errors is (0.045 volt), which is less than the minimum value required to change the firing angle by 1 degree.

4. Experimental Results

The relation between the input armature voltage to the motor and its output speed is obtained as shown in figure (7). A tachogenerator is used to measure the speed of the motor. Under armature control it can be seen that for any given input voltage the motor settles at a steady speed and it can be controlled over a wide range of input armature voltage. The system constants are taken as follows: $T_m = 1$ sec, $K_m = 1.714$, $T_c = 0.004$ sec, $T = 0.1$ sec, $K_t = 0.00275$ volt/rad, and $J = 0.00003$ Kg. m^2. Different responses of the tachogenerator are shown in figure 8.

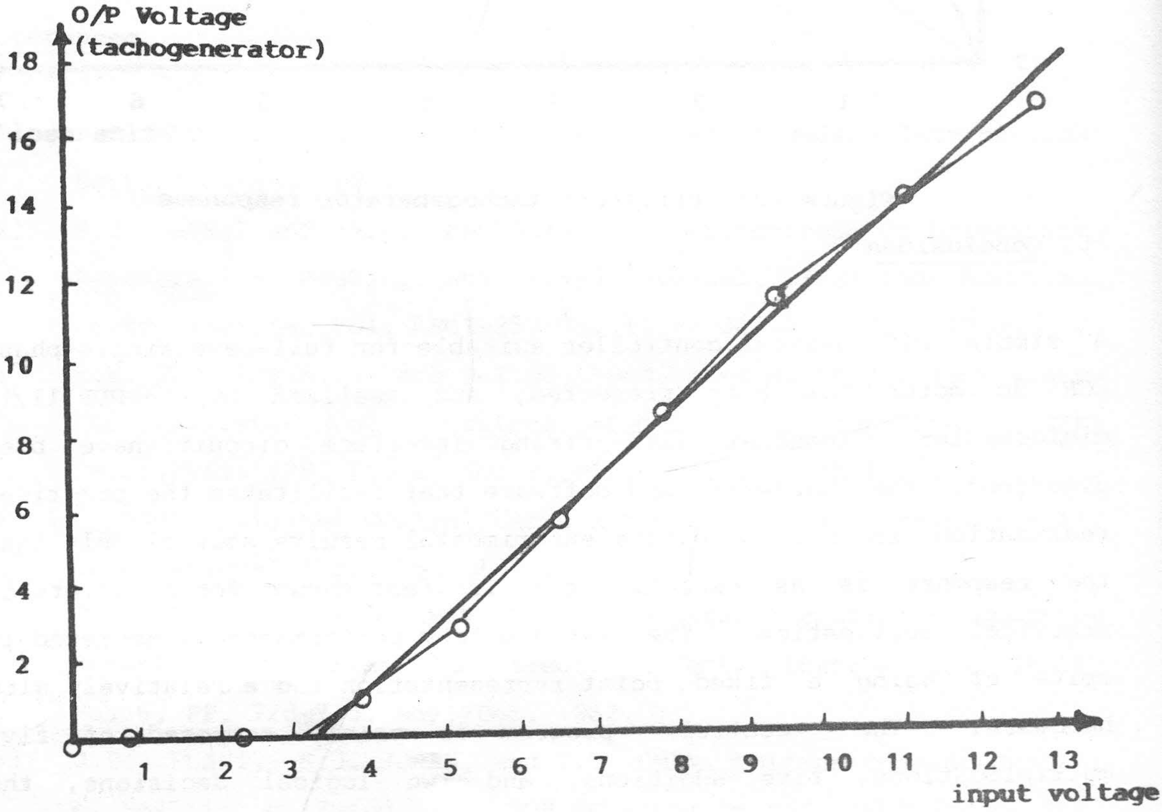


Figure (7) Motor speed versus input characteristic

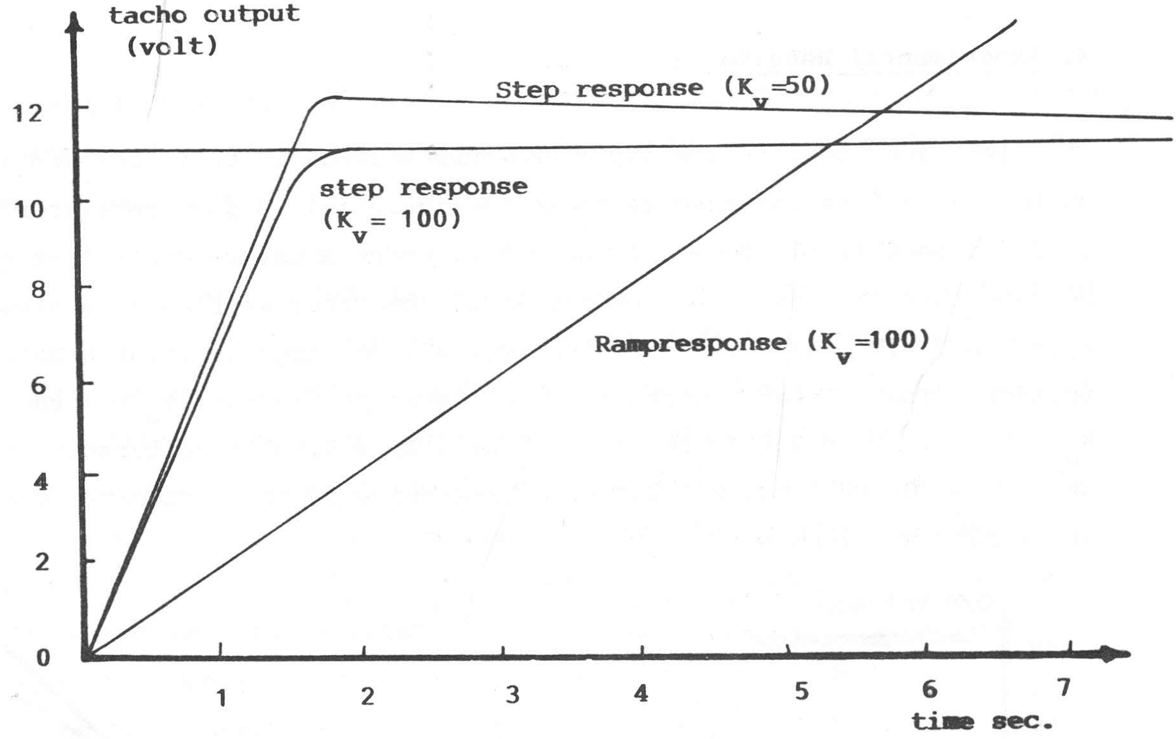


Figure (8) Different tachogenerator responses

5. Conclusions

A simple PID digital controller suitable for full-wave single-phase SCR dc motor has been presented, and realized by the PDP 11/10 minicomputer together with firing interface circuit have been discribed, the hardware and software that facilitates the practical realization is discussed. The experimental results show clearly that the response is as expected and is fast enough for a variety of practical applications. The satisfactory performance is achieved in spite of using a fixed point representation and a relatively slow hardware. The control program is mainly composed of five multiplications, five additions, and two logical decisions, the control scheme is simple enough to be represented on the most contemporary realtime on-line systems.

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