PERFORMANCE CHARACTERISTICS OF AN ARMATURE VOLTAGE CONTROLLED D.C. MOTOR

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ABSTRACT

In this paper, the performance study of a separately excited d. c. motor whose speed is controlled by armature voltage variation is presented. Both the open loop and the closed loop steady state and transient characteristics are reported. The speed controllers considered in the closed loop mode are the proportional and the proportional plus integral types. To each of these two control arrangements is added an inner current controller loop. Using developed motor equations, the performance characteristics of a test motor are obtained by digital computer analysis. The results show that closed loop operation, with appropriate control gains, give improved speed regulation and response characteristics for the d. c. drive system.

1. INTRODUCTION

The good control properties of the d.c. motor have made possible its initial large scale application in industry [1]. In spite of the present superiority of the solid state squirrel cage induction motor drive, especially at supply voltages of 750V and above, the d. c. machine still remains the dominant drive system in industry [2]. This paper therefore presents the open loop and the closed loop steady state and transient characteristics of an armature voltage controlled separately excited d.c. motor.

Using digital computer analysis, the driver characteristics of a test motor is investigated. In the closed loop mode, appropriate control gains are selected by analysis to give desired realizable steady state and transient performance characteristics. Results obtained with two speed controller types proportional and proportional plus integral controllers) and a proportional current controller in the inner feedback loop show that the closed loop control provides considerable improvement in motor speed regulation, speed of transient response and transient armature current duration. Illustrative steady state and transient performance characteristics are given.

2. OPEN LOOP OPERATION

The open loop block diagram of the separately excited d. c. motor can be shown to be represented by fig. 1. From this figure, the motor speed w and the armature current l_a are given by the expressions:

$$w(s) = \frac{\frac{K\phi}{R_a TJ} V_a(S) + \frac{1}{TJ}(Ts+1) T_L(S)}{S^2 + \frac{TB_m R_a + JR_a}{TR_a J} S + \frac{B_m R_a + (K\phi)^2}{TR_a J}} \qquad (1)$$

$$I_a(s) = \frac{\frac{B_m + Js}{R_a TJ} V_a(s) + \frac{K\phi}{TR_a} J T_L(S)}{S^2 + \frac{TB_m R_a + JR_a}{TR_a J} s + \frac{B_m R_a + (K\phi)^2}{TR_a J}} \qquad (2)$$

where

s is the Laplace operator

$K\phi$ is a motor constant related to the field excitation

B_m is the coefficient of air viscous friction

T is the motor electrical time constant, L_a/R_a

L_a is the armature inductance

V_a is the armature terminal voltage

T_L is the load torque

2.1 Open loop transient characteristics

From equations 1 and 2, the time responses of the motor speed and armature current to a step change in the armature voltage at constant load torque can be readily determined. Time response curves for the test motor whose parameters are specified in Appendix A are given in figures 2 and 3 for zero load torque.

Analysis for the test motor shows that the open loop speed response is highly overdamped with the characteristic roots being -10.71 and -89.38 respectively. The speed response, though second order therefore approximates to a first order system with a characteristic pole of -10.71 or a time constant of 0.093 secs. The response speed (fig. 2) with settling time of 0.36 secs is relatively sluggish. Also, fig. 3 shows relatively high transient current (90 p.u.) peak- value of relatively long duration. The high I^2t value associated with this high transient current of relatively long duration can cause drive system circuit failure especially with respect to the semiconductor devices that may be used in varying their armature terminal voltage unless appropriate protection mechanism, such as a current limiting circuit, is incorporated.

2.2 Open loop steady state characteristics

The open loop steady state expressions for the motor speed and armature current are obtained by setting the Laplace operators equal to zero in equations 1 and 2. This gives the steady state equations as:

$$W(\infty) = \frac{k\emptyset v_a - R_a T_L}{B_a R_a + (k\emptyset)^2} \qquad (3)$$

$$I_a(\infty) = \frac{B_a V_a + K\emptyset t_L}{B_a R_a + (k\emptyset)^2} \qquad (4)$$

When the parameters of the test motor of Appendix A are submitted in equations (3) and (4), the result is:

$$W(\infty) = 1.362V_S - 1.124T_L \qquad (5)$$

$$I_a(\infty) = 0.015V_a + 1.362T_L \qquad (6)$$

Figures 4 and 5 show the plots of the motor speed and the armature currents against the motor terminal voltage with the load torque as parameter

The results show that, over the entire range of the armature terminal voltage variation, there is a general decrease in speed as the load torque is increased. It is found that for a given armature terminal voltage V_a, the test motor speed changes by 4 rad/sec for every change in load torque by 25 % of the motor rated torque $T_{LR.}$

This gives the percentage speed regulation at rated armature voltage and rated load torque as 10.4 % which is relatively very high.

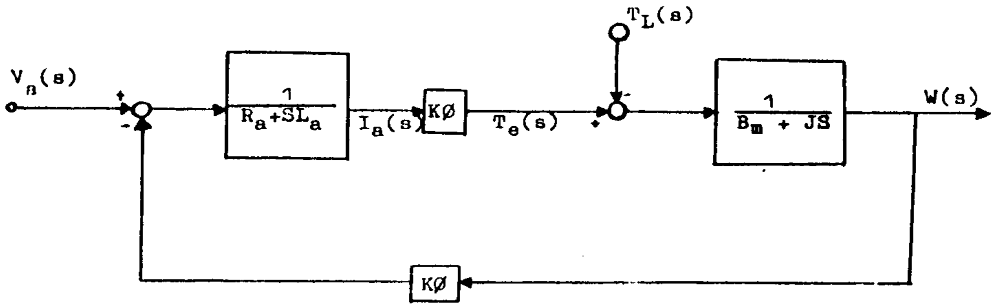

Fig. 1: Open Loop block diagram of a Separately excited d.c motor (DCM)

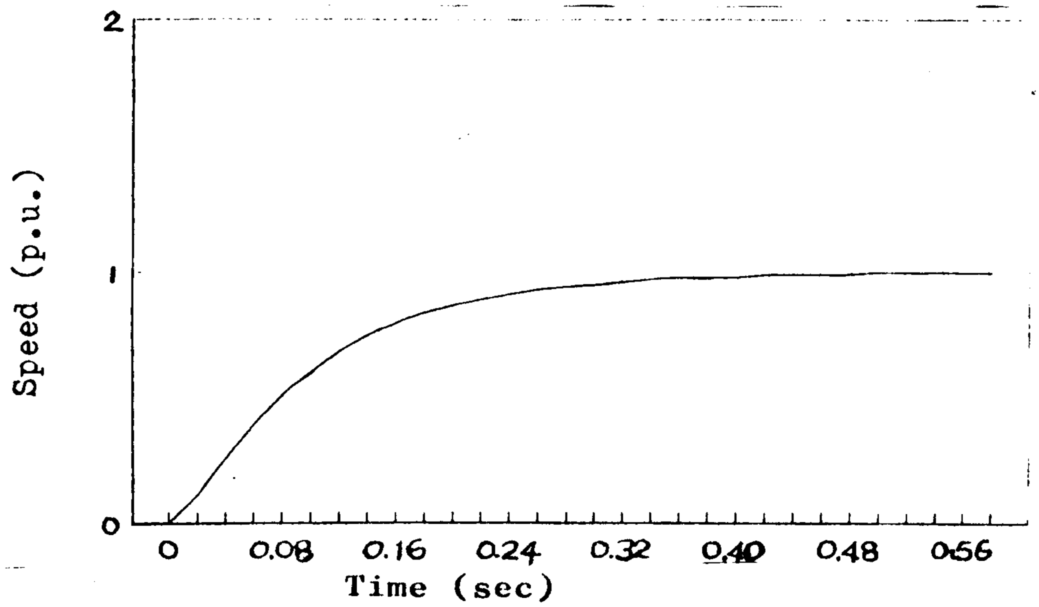

Fig. 2: Open loop transient speed response of DCM for unit step change in Voltage

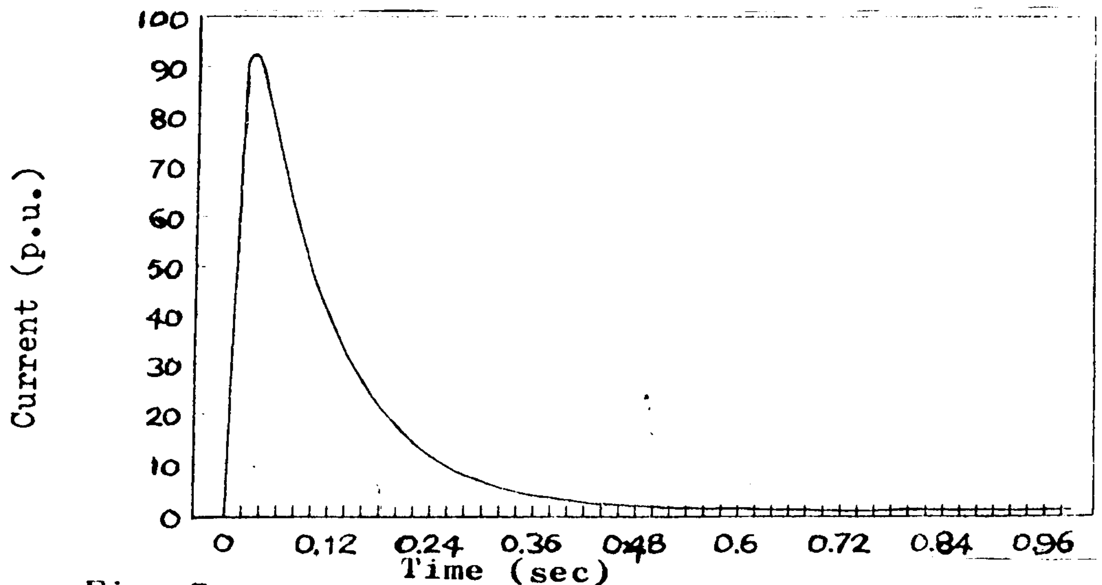

Fig. 3: Open loop transient current response of DCM for unit step change in voltage Va.

3. CLOSED LOOP CONTROL

Closed loop control of the d.c. motor is used to obtain improved motor speed regulation and transient response. In the closed loop mode, two speed controllers (proportional and proportional plus integral controllers) with an inner proportional current controller loop will be discussed.

3.1 Motor performance with proportional speed controller

The block diagram of the controlled d.c. motor with proportional speed controller and an inner proportional current controller loop is shown in Fig. 6. In this figure, K_A is the armature current sensor gain, K_s, is the speed sensor gain, K_c, is the gain of the power supply conditioner (controlled a.c. to d.c. or d.c. to d.c. converter), K_{p1}, is the proportional gain of the speed controller, K_{p2} is the current controller gain while V_r is the motor speed setpoint voltage.

From figure 6, the expressions for the motor speed and armature current in Laplace domain can be shown to be as follows:

$$\begin{bmatrix} W(S) \\ I_a(S) \end{bmatrix} = \begin{bmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{bmatrix} \begin{bmatrix} V_r(S) \\ T_L(S) \end{bmatrix} \qquad (7)$$

Where,

$$G_{11} = \frac{(K_{p1}K_{p2}K_cK\emptyset)}{R_aJ(s^2+As+B)} \qquad (8)$$

$$G_{12} = \frac{(K_{p1}K_{p2}K_c(Js+B_m)}{R_aJ(s^2+As+B)} \qquad (9)$$

$$G_{21} = \frac{-R_a(Ts+1)+K_AK_{p2}K_C}{R_aJ(s^2+As+B)} \qquad (10)$$

$$G_{22} = \frac{K\emptyset+K_SK_{p1}K_{P2}K_c}{R_aJ(s^2+As+B)} \qquad (11)$$

$$A = (R_aJ + R_aB_mT + K_AK_{p2}K_CJ)/(R_aTj) \qquad (12)$$

$$B = [K_{p1}K_{p2}K_cK\emptyset K_s + (K\emptyset)^2 + R_aB_m + k_aK_{P2}K_cB_m]/R_aTJ \qquad (13)$$

3.1 Selection of control gains

The control gain K_{p1} K_{p2} K_A, K_s and K_C can be determined from the ratings of the d.c. motor, the desired maximum electronic control voltage level and the desired motor response characteristics. In power engineering environment, high threshold logic family chips requiring bias voltages of about ± 15 V are common thus making the maximum circuit sensor and controller output voltage levels of ± 10 volts common practice

For the test motor of Appendix A, the control gains can therefore be obtained by assuming that the sensor and controller output voltages are limited to ± 10 V.

Limiting the motor speed to 1.5 times its rated value, the speed sensor gain is

$$K_A = 0.279V/A \qquad (15)$$

If ±2 v error voltage to the input of the armature current controller produces rated armature voltage of ± 125 V at the power supply conditioner output, the product of the current controller and the power supply conditioner gain is given by:

$$K_cK_{p2} = 62.5 \qquad (16)$$

Limiting the motor armature voltage to 1.25 times its rated value, the power supply conditioner gain is:

$$K_c = 15.625 \qquad (17)$$

Equations 14 to 17 give the values of all the control gain constants except the speed controller gain. Using digital computer analysis, $K_{P1,}$ is varied until the desired reliable transient and steady state performance characteristics are obtained. The analysis show that a value of K_{p1}, equal to 1320 is about the optimal value for the specified values of other control gains:

$$K_{P1} = 1320 \qquad (18)$$

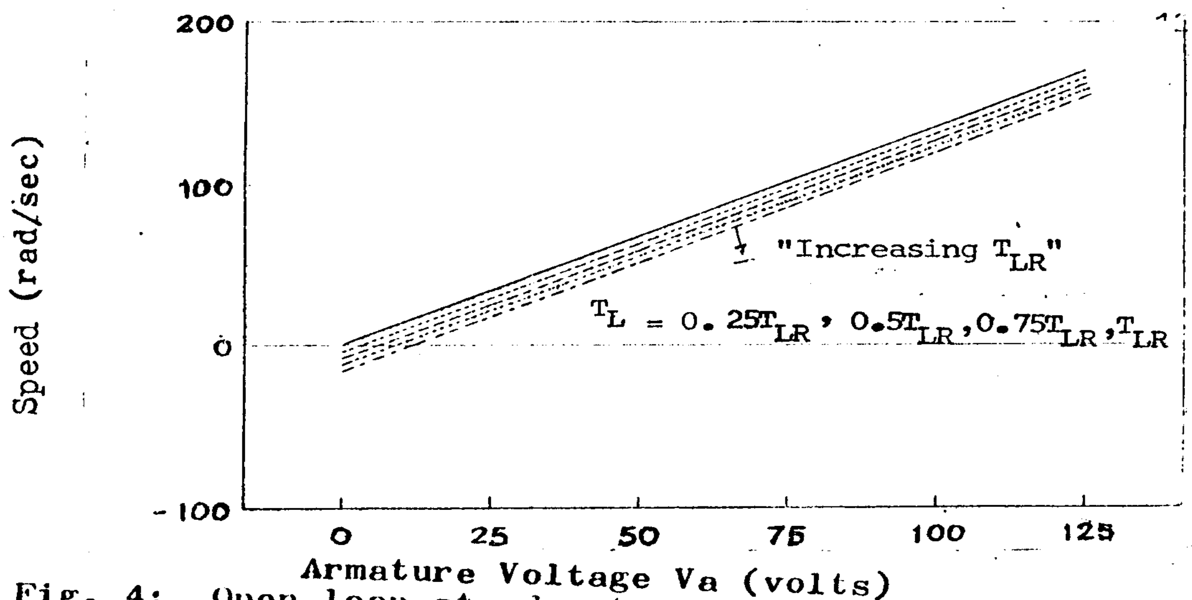

Fig. 4: Open loop steady state speed characteristic of DCM.

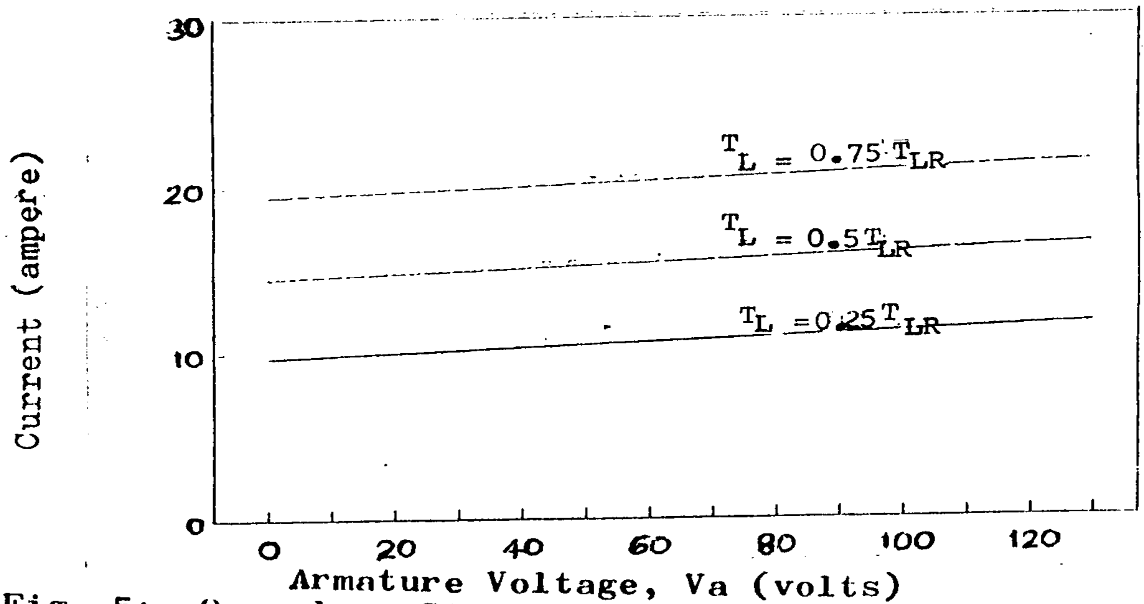

Fig. 5: Open loop Steady State Current Characteristics of DCM.

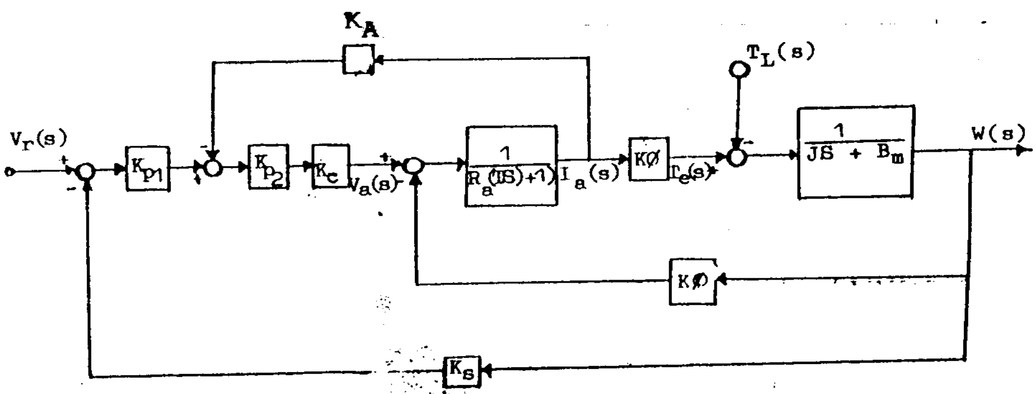

Fig. 6: Closed loop block diagram of DCM.

3.1.2 Transient characteristics with proportional speed controller

For the control gains determined in section 3.1., figures 7 and 8 show the responses of the motor speed and armature current to a unit step change in the armature voltage at zero load torque.

The speed response (fig. 7) has a damping ratio of 0.707 as against the 1. 62 obtained for the open loop response. This result in the closed loop setting time of 0.0027 sees which is 133.3 times as fast as the open loop response. Also, the transient armature current peak duration (0.0027 secs) is considerably much less than the open loop value thus giving considerably reduced I^2t stresses on the circuit components.

3.1.3 Steady state characteristics with proportional controller

When the test motor parameters are substituted in equations 7 through 13 and the Laplace operators made equal to zero, the closed loop steady state motor equations become:

$$W(\infty) = 23.80V_r - 0.0072T_L \quad (19)$$

$$I_a(\infty) = 0.26V_r + 1.37T_L \quad (20)$$

Figures 9 and 10 show the motor speed and the armature current plotted against the speed setpoint voltage v_r, with the load torque as parameter. It is seen from Fig. 9 that, for a given speed command voltage v_r the motor speed is constant over the load torque range of zero to the rated value. This represents zero percentage speed regulation for any set command motor speed. This zero percentage speed regulation when compared with the 10.4 % at rated supply voltage and load torque for the open loop drive represents a major advantage of the closed loop drive.

3.2 Motor performance with proportional plus integral speed controller

The proportional speed controller of fig. 6 is replaced by a proportional plus integral speed controller of gain:

$$\frac{K_I}{S} + K_{p1}$$

and an analysis, as outlined in section 3.1 carried out. The resultant motor speed and armature current equations are:

$$\begin{bmatrix} W(S) \\ I_a(S) \end{bmatrix} = \begin{bmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{bmatrix} \begin{bmatrix} V_r(S) \\ T_L(S) \end{bmatrix} \quad (21)$$

Where,

$$G_{11} = \frac{K_1 K_{p2} K_c K\emptyset + K_{p1} K_{p2} K_c K\emptyset}{R_a J(s^3 + As^2 + Bs + C)} S$$

$$G_{12} = \frac{(Js + B_m)(K_1 K_{p2} K_c + K_{P1} K_{p2} K_c S)}{R_a J(s^3 + As^2 + Bs + C)}$$

$$G_{21} = \frac{[R_a(Ts + 1) + K_A K_{p2} K_C]S}{R_a J(s^3 + As^2 + Bs + C)}$$

$$G_{22} = \frac{(K\emptyset + K_S K_{p2} K_{P1} K_c)S + K_1 K_s K_{p2} K_C}{R_a J(s^3 + As^2 + Bs + C)}$$

and

$$A = \frac{[R_a J + B_m T R_a + K_A K_{P2} K_C J]}{R_a T J}$$

$$B = \frac{B_m R_a + K_{p1} K_{p2} K_c K\emptyset K_S + (K\emptyset)^2 + K_A K_{p2} K_C B_m}{R_a T J}$$

$$C = \frac{K_1 K_{p2} K_c K\emptyset K_S}{R_a T J}$$

With all other control gain constants as specified in sections 3. 1. Figures 11 and 12 show the transient response characteristics of the controlled motor for k_1 = 36000 and K_{p1} = 1015.38. The motor speed response has settling time of 0.008 secs which is 45 times as fast as the open loop speed response

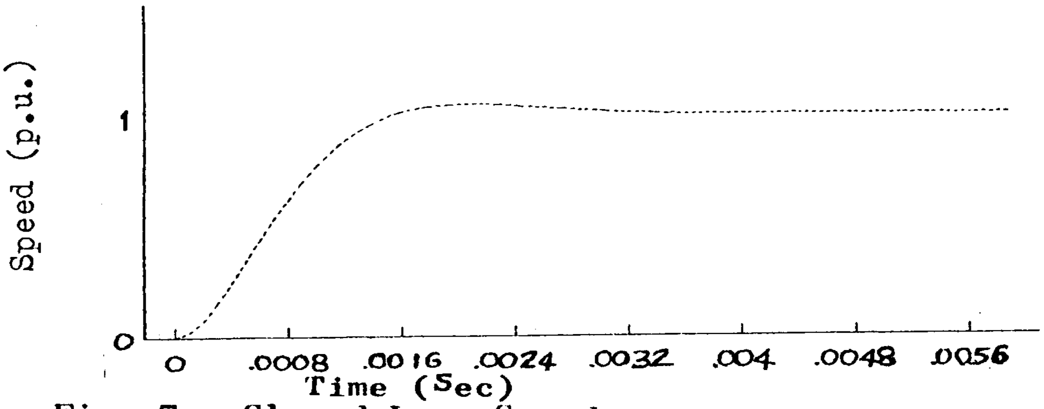

Fig. 7: Closed Loop Speed response of DCM With Proportional Speed Controller.

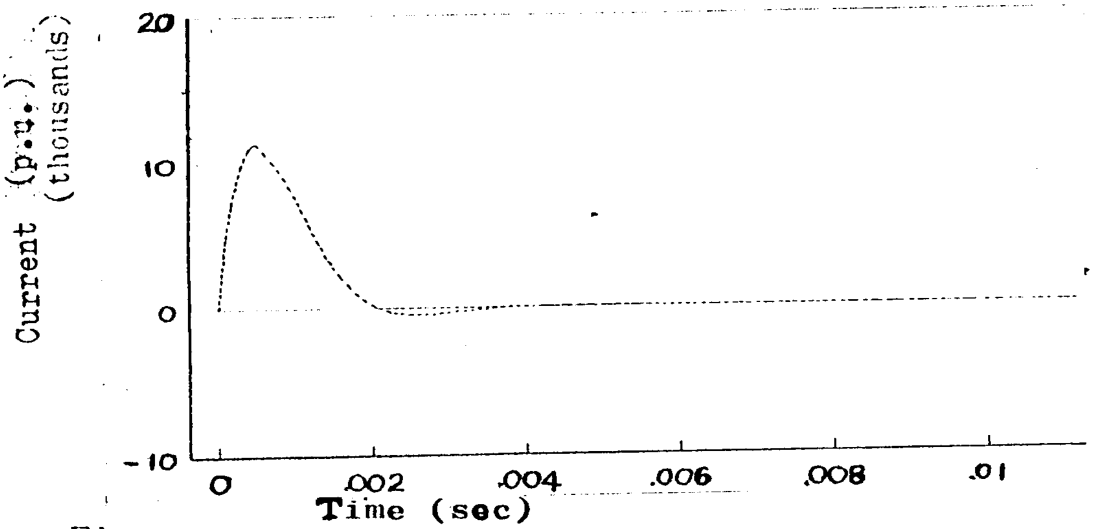

Fig. 8: Closed Loop Current response of DCM With Proportional Speed Controller.

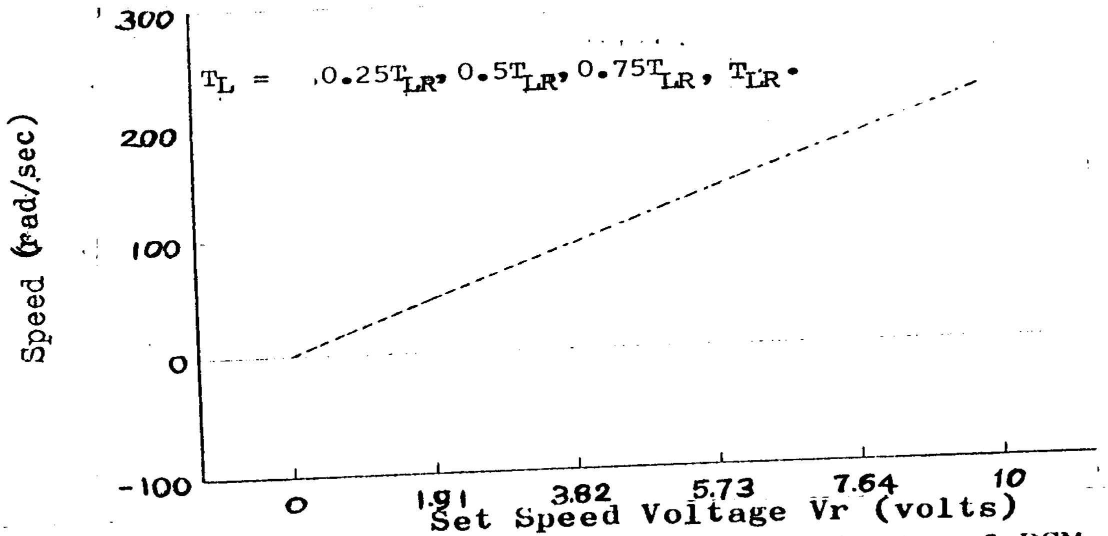

Fig. 9: Steady State Speed Characteristic of DCM with Proportional Speed Controller.

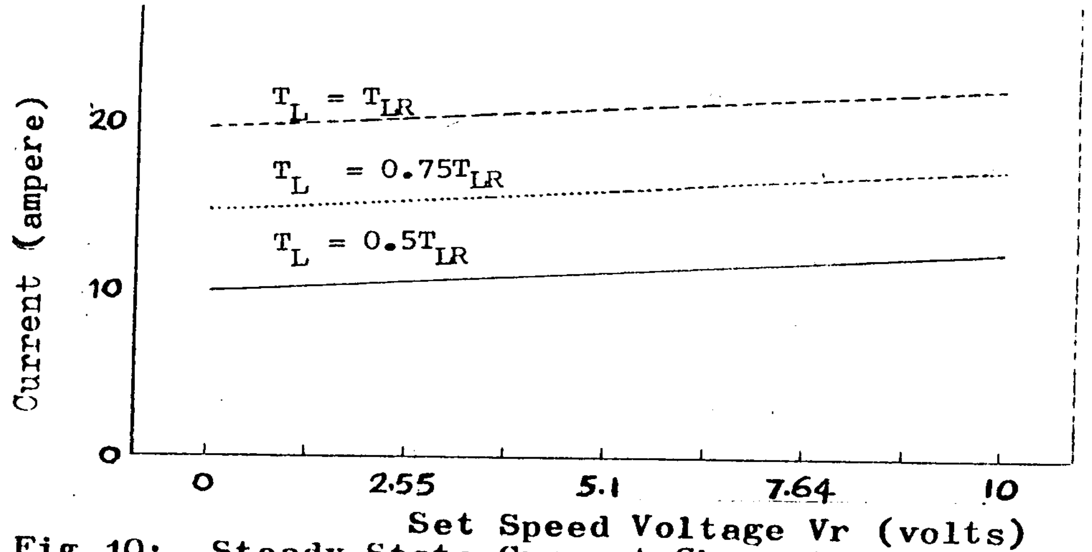

Fig. 10: Steady State Current Characteristic of DCM with Proportional Speed Controller.

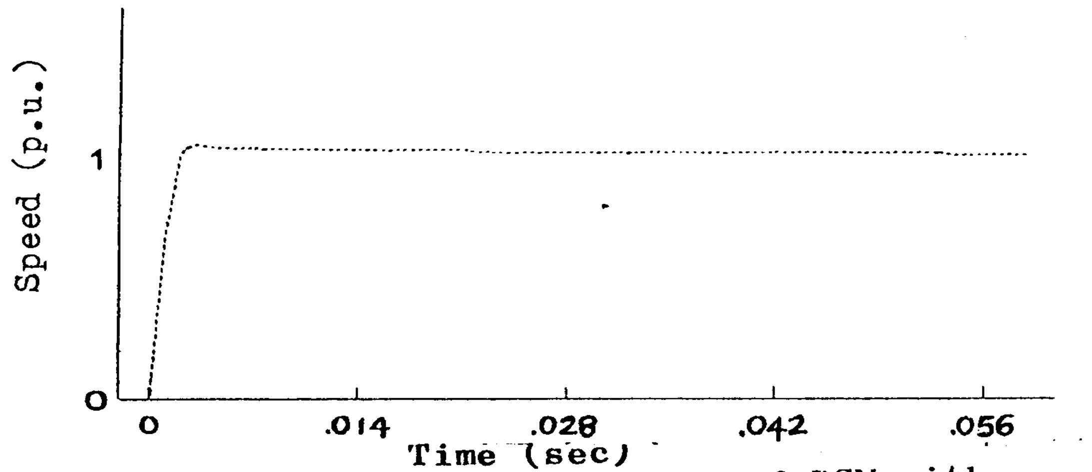

Fig. 11: Speed Transient response of DCM with Proportional plus integral Speed Controller.

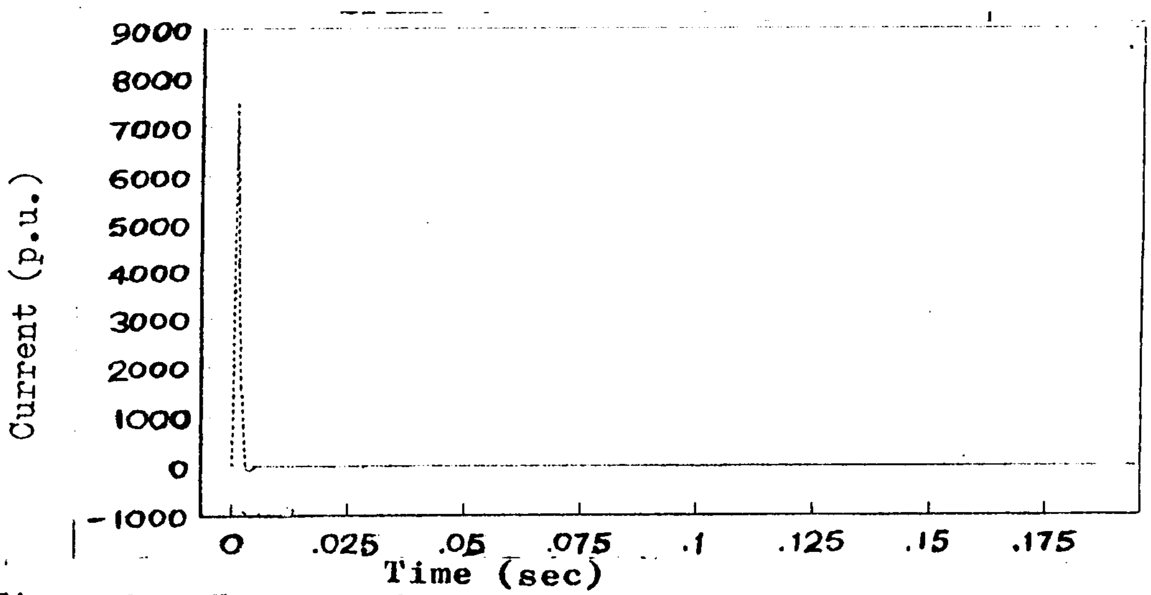

Fig. 12: Current Transient response of DCM with Proportional plus integral speed controller.

Though the current response shows considerable theoretical peak value but of relatively short duration, the actual current peak is limited by the maximum allowable supply voltage values (l56.25v for the armature terminal voltage V_a and 10 volts for control voltages) so that transient armature current in excess of twice the rated value will tend to be clipped off by the closed loop control action. Steady state characteristics obtained by analysis also show that the speed regulation over the entire range of load torque variation is essentially maintained at zero by closed loop action.

CONCLUSION

The transient and steady state characteristics of a separately excited d.c. motor which has its speed controlled by varying the armature terminal voltage at constant field excitation has been presented. In the study, two speed controller types namely the proportional and the proportional plus integral types are used. To each speed control arrangement is incorporated an inner proportional current controller loop. In the closed loop mode. both the motor variables (speed, current and terminal voltage), and the control circuit voltages are limited to predetermined safe values by the choice of appropriate gain constants.

APPENDIX A

Test motor dater:

a) Specification: 3hp, 125v, 1500 rpm separately excited d.c motor.
b) Parameters: R_a = 0.6 ohm
   L_a=6mh
   J = 0.093 Kgm
   B_m = 0.008 Nm/rad/s
   $k\phi$ = 0.7274
   T = 0.01 secs

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2. Sen, P. C. and Macdonald, M. L."Thyristorized D.C. Drives with Regenerative Braking and Speed Reversal", *IEEE Trans. On Industrial Electronics and Control Instrumentation*, Vol. IECI-25, No.4. Nov. 1978, pp. 347- 353.