High starting performance separately excited DC motor

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Abstract__Electric motors have a variety of speed-torque characteristics during steady state and transient operations. For a given drive applications, motors are often selected to match the characteristics of the required operation, determined by the mechanical load characteristics and the available power supply. Due to advances in power electronics, such restrictions no longer exist where the characteristics of most motors can now be altered to match the desired performance when external power converters are used and advanced control strategies are employed. Series DC motor has a high starting torque. Reversing its speed direction is normally done using a relay arrangement, which requires an off time interval and results in waste of energy during braking. Also DC series motor doesn't run above base speed because there is no separate control on the field current unless a field diverter is used which causes losses. Separately excited DC motor can operate above the base speed in the field-weakening region by reducing the field current independently. Also its speed direction can be reversed by reversing the armature voltage. In this paper a DC drive control system is suggested to run the DC motor so as to obtain the performance of the series DC motor below base speed and the performance of the separately excited DC motor above base speed and to change speed direction in a regenerative braking mode at any motor speed. The model of the DC motor including the saturation is reviewed. The control strategy is explained and the control circuit is proposed. A steady state and transient analysis of the motor is performed below and above base speed.

Index terms__ series DC motor- separately excited DC motor- DC drives

LIST OF SYMBOLS

R_f, R_a : field and armature resistance, Ω
L_f, L_a : field and armature inductance, H
E, e : steady state and instantaneous induced emf, V
V_f, V_a : steady state field and armature voltage, V
I_f, I_a : steady state field and armature current, A
v_f, v_a : instantaneous field and armature voltage, V
i_f, i_a : instantaneous field and armature current, A
i_f^*, i_a^* : field and armature command control signal
J, B : inertia constant, Nm.s^2/rad, friction constant, Nm.s/rad
T_L, T_e : load and electromechanical torque, Nm
ω_r, ω_r*: actual and command control signal speed, rad/sec

I. INTRODUCTION

DC motors have variable torque/speed characteristics and are used extensively in variable speed drives. DC motors can provide a high starting torque and it is also possible to obtain speed control over a wide range. The methods of speed control are normally simpler and less expensive than those of AC drives [1]. DC motors still play a significant role in modern industrial drives. Both series and separately excited DC motors are normally used in variable speed drives, but series motors are traditionally employed for traction applications. Due to commutators, DC motors are not most suitable for high-speed applications and require more maintenance than do AC motors. With the recent advantages in power conversions, control techniques, and microcomputers, the AC motor drives are becoming increasingly competitive with DC motor drives [2]. Although the future trend is toward AC drives, DC drives are currently used in many industries. It might be a few decades before the DC drives are completely replaced by AC drive. Due to their ability to supply a continuously variable DC voltage, controlled rectifiers and DC-DC converters made a revolution in modern industrial control equipment and variable-speed drives, with power levels ranging from fractional horsepower to several megawatts [3]. For the separately excited DC motor, the flux created by the field winding is kept constant below base speed, hence the torque developed by the motor is proportional to the armature current and then the motor speed can be controlled by armature voltage. While above base speed, the speed is controlled by controlling the field current keeping the armature voltage, and hence the power, constant at rated voltage. Also, the speed direction can be reversed by reversing the polarity of supply voltage across the armature in both constant torque and power operation zones. In series DC motor, as the armature current, which equals the field current, changes with the load, the flux produced by the field winding also changes. Therefore, the torque developed by the motor is proportional to the square of the armature current as long as the motor is operating in linear region. Since the torque developed by a series motor is also proportional to the square of the applied voltage, its torque developed can be controlled by controlling the applied voltage. The typical speed characteristics of a series motor is inversely proportional to the armature current. The series motor cannot run over base speed, as there is no individual control on the field current. Also the direction of speed cannot be reversed by reversing supply voltage because reversing armature voltage will reverse both field and armature current. Series DC motor has a high starting torque therefore it is used where the load demands a high initial torque such as cranes, hoists, electric vehicles and electric tractions. Researches are still being carried out to enhance the performance and operation of DC motors [4-9]. This paper proposes a drive system for the DC motor that merges the advantages of the separately excited DC motor and the series DC motor. As shown in fig. (1), the armature coil is fed from a DC supply via a class-E chopper and the field coil is fed from a DC supply via a class A-chopper. Feed back signals from the speed, field current and armature current are fedback to the control circuit, which produces the control signals of the two chopper switches. Below base speed, within constant torque region, this drive will operate this motor so as to get a performance exactly like the series DC motor having the advantage of high starting torque of the series DC motor where the speed is controlled using armature voltage. While above the base speed, the motor will operate as a conventional separately excited DC motor allowing field weakening operation in the constant power region where the speed is controlled by controlling the field current. Moreover, the control circuit can change the direction of rotating at any speed through regenerative braking mode. The basic idea is explained and control strategy is illustrated. The drive is simulated using MATLAB SIMULINK and theoretical results are obtained to show the transient and steady state performance of the machine.

II. DYNAMIC MODEL OF DC MOTOR

Equations describing the characteristics of separately excited motor can be concluded as follows [1]:

$$L_a \frac{di_a}{dt} + R_a i_a + e = v_a \tag{1}$$

$$L_f \frac{di_f}{dt} + R_f i_f = v_f \tag{2}$$

$$J \frac{d\mu_r}{dt} + B\mu_r = T_e - T_L \tag{3}$$

$$T_e = \frac{e i_a}{\mu_r} \tag{4}$$

$$\frac{e}{\mu_r} = a_4 i_f^4 + a_3 i_f^3 + a_2 i_f^2 + a_1 i_f + a_0 \tag{5}$$

where a_0, a_1, a_2, a_3 and a_4 are factors of the curve fitting 4th order equation. Equation (5) expresses the relationship between the field current and the back emf per unit speed as can be concluded from the no load characteristics of the machine including the saturation. MATLAB-SIMULINK software may be used to simulate the dynamic model of the motor as shown in fig. (2).

III. OPERATING MODES

Fig. (3) shows the schematic diagram of the closed loop control system of the proposed high starting performance separately excited DC motor. For both clockwise or anticlockwise speed directions, the absolute value of the motor speed (ω_r) is compared with the base speed (ω_b) of the machine. Accordingly, the field multiplexer determines the field current signal (i_f^*) such that below the base speed, the command signal of field current equals to the absolute value of the armature current, meaning that the machine acts exactly like a series DC motor. Above the base speed, the command signal of field current is calculated so as to run the machine as a separately excited DC motor using field

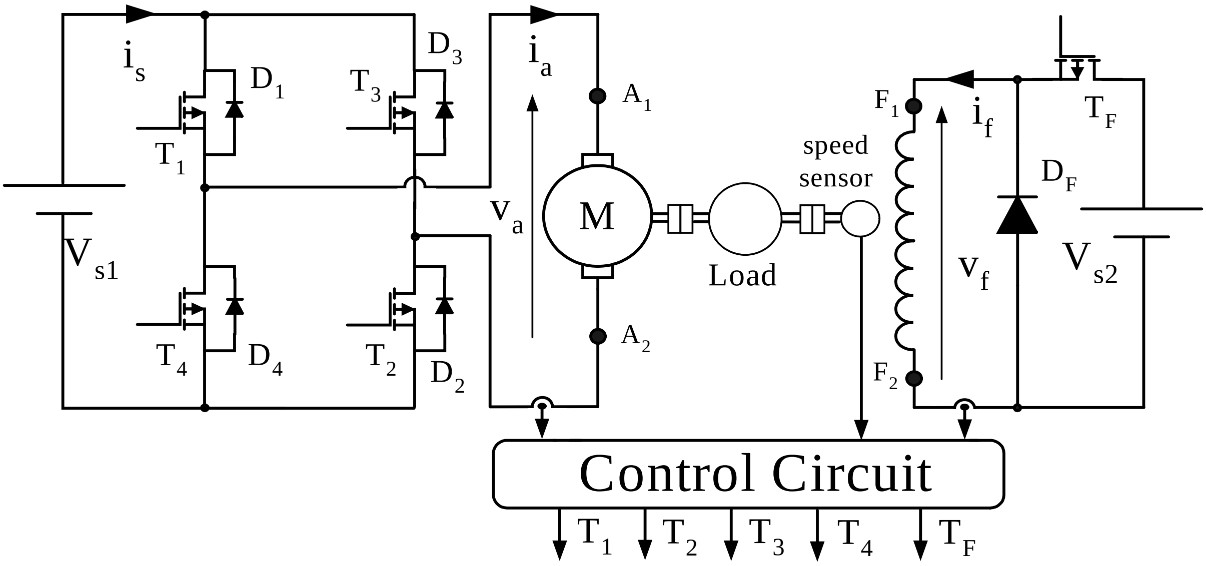


Fig. (1) : Connection diagram of the proposed high starting separately excited DC motor

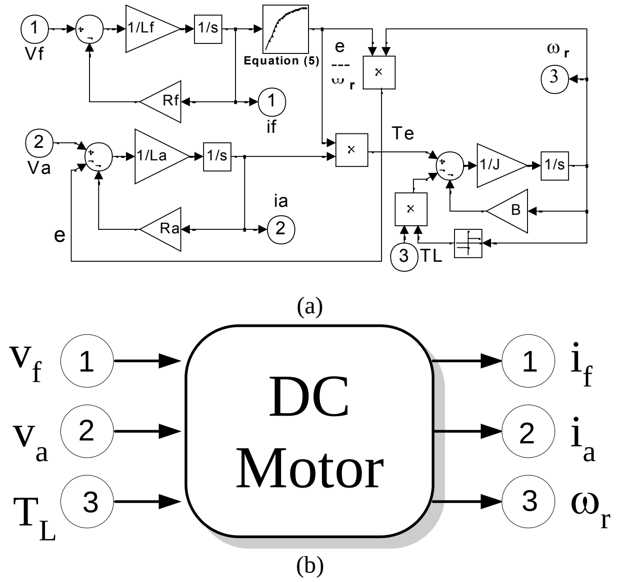


Fig. (2) : DC motor model (a) Equation schematic diagram, (b) a single block diagram

weakening mode of operation within the constant power region. Moreover, if the polarity of the command signal of the speed is reversed, the direction of the motor speed will be reversed either above or below base speed regardless of operation mode of the machine. The decision of the command signal of the field depends on the absolute value of both the speed and the armature current. Therefore, controlling the field current is completely decoupled with speed direction and vise-versa.

IV. STEADY STATE ANALYSIS

The motor performance characteristics at steady state can be concluded below and above base speed. Equation (1) to (5) can be reduced to express the motor model at steady state as follows:

$$R_a I_a + E = V_a \tag{6}$$

$$R_f I_f = V_f \tag{7}$$

$$T_e = \frac{E I_a}{\mu_r} \tag{8}$$

$$\frac{E}{\mu_r} = a_4 I_f^4 + a_3 I_f^3 + a_2 I_f^2 + a_1 I_f + a_0 \tag{9}$$

Equations (6) to (9) can be arranged depending on the motor speed to develop the motor performance characteristics curves at the rated armature voltage as shown in fig. (4). It is seen that the machine has series characteristic before base speed and separately excited characteristics in the field-weakening region during constant power region. See Appendix for motor parameters.

V. TRANSIENT RESPONSE

The model depicted in fig. (3) has been simulated to conclude the transient response of the proposed set. Figures (5), (6) and (7) show the instantaneous waveforms of step speed command below base speed, above base speed and reversing speed direction, respectively. In fig. (5), the machine runs at rated load torque where the speed command is step changed to base speed at 0.1 second, then reduced to 50% of base speed at 1.5 second, then reduced to zero speed at 3 second. It can be seen that the machine has a high starting torque like a series DC motor, while current limiters have been adjusted to limit the armature and field current at twice the rated current. In fig. (6), the command speed is step changed from 80% base speed to 120% base speed at 2 second. At steady state, the armature current is controlled to equal the rated current while the field current is determined to run the machine in the constant power region and therefore the torque is decreased (field weakening). In fig. (7), the speed direction is step reversed with in regenerative baking mode. With respect to fig. (7-c), it could be seen that the armature voltage in immediately reversed during the time between t_o to t_1 to force the armature current to change direction, then during the time between t_1 to t_2, the armature voltage is positive while the armature current is negative and the power is pumped back to the supply through the two diodes D_1 and D_2.

VI. DISCUSSION

The DC machine used in this drive is essentially series

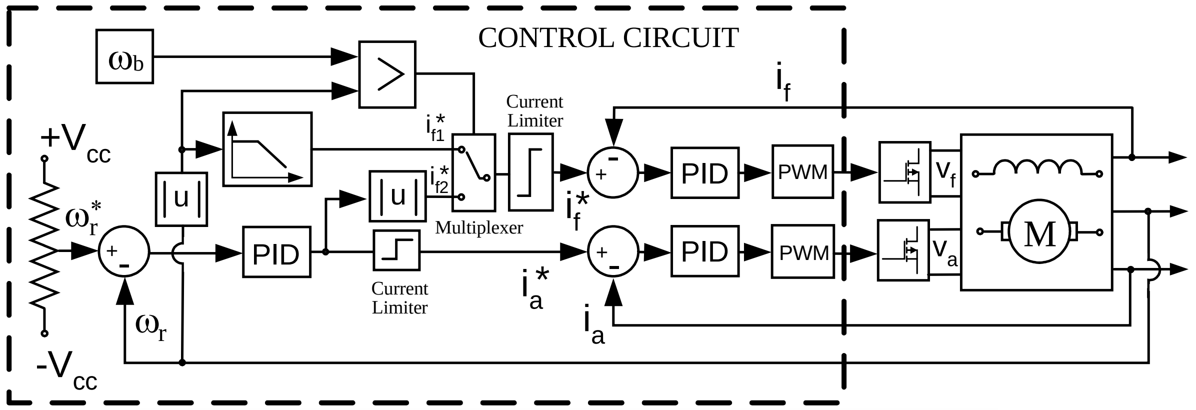
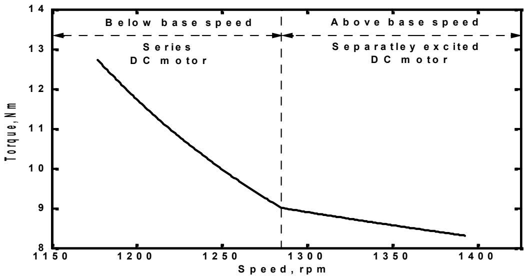
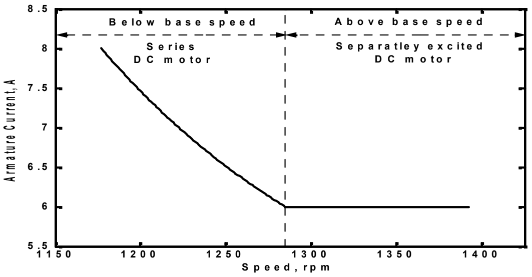


Fig. (3) : Closed loop control circuit of high starting separately excited DC motor



(a)



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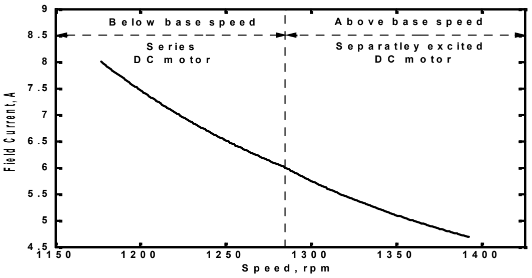
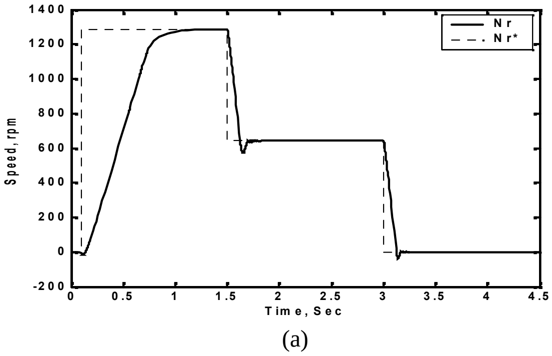
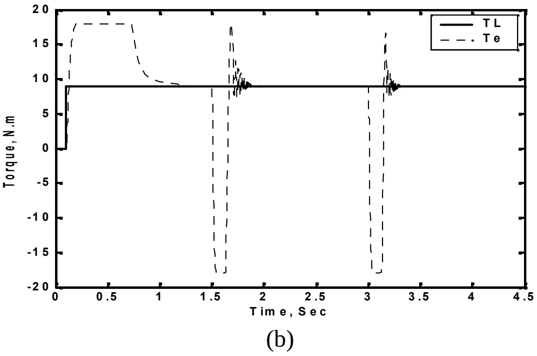


(c)

Fig.(4) : Steady state characteristics of high starting separately excited DC motor at rated voltage, speed vesus (a) load torque, (b) armature current and (c) field current



(a)



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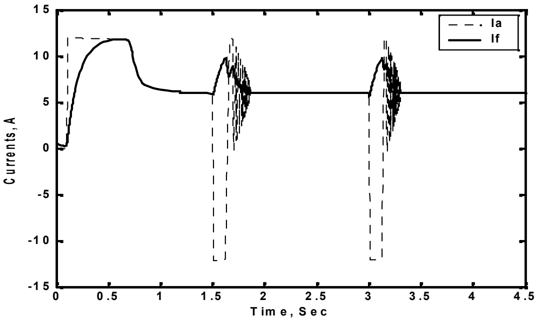
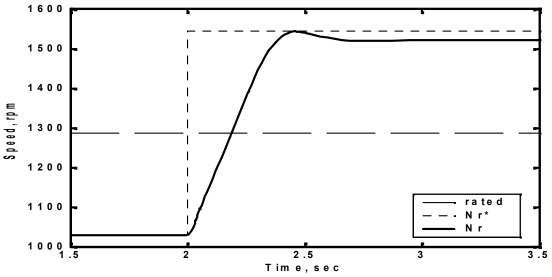
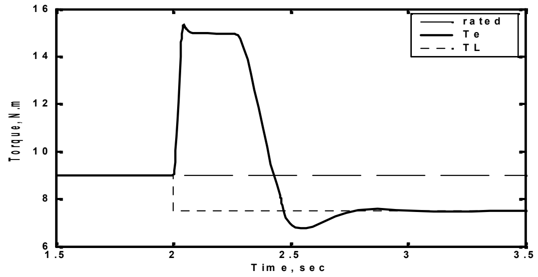


(c)

Fig. (5) : Transient response for step speed command: (a) speeds, (b) torques and (c) currents below base speed



(a)



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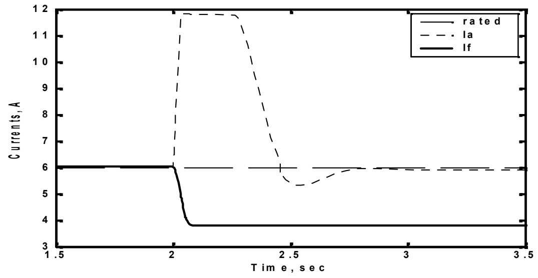
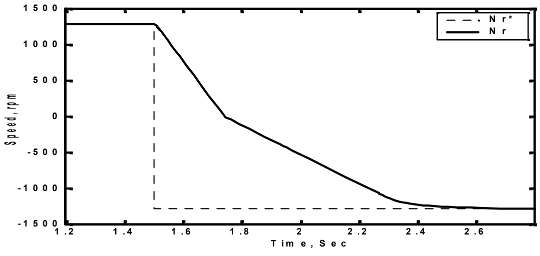
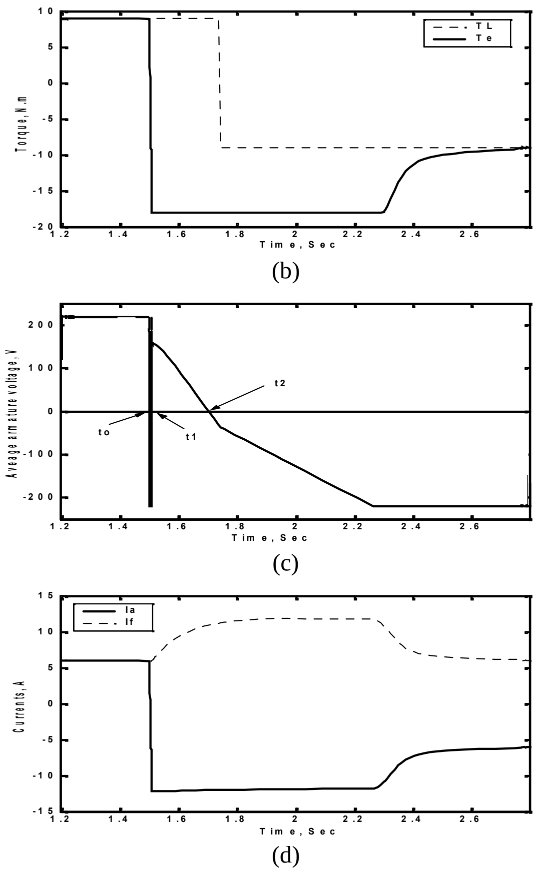


(c)

Fig. (6) : Transient Response for step speed command from 80% to 120% base speed: (a) speed, (b) torque and (c) currents



(a)



(b)

(c)

(d)

Fig. (7) : Transient response for speed reverse command: (a) speeds, (b) torques , (c) average armature voltage and (d) currents at base speed

type such that the field winding is principally designed to carry the armature current. In the series DC motor, since the series field winding carries the rated armature current, it has few turns of heavy wire. The field winding is composed of a small number of turns with a large cross section wire. This type is designed to carry large currents and is connected in series with the armature winding. The field resistance is normally small. Therefore, the voltage level of the field circuit should be small and the chopping frequency is low enough to allow continuous mode of current in the field circuit. In industry, for this 6 A field current machine, a 24 VDC voltage can be obtained from a single-phase 220V supply, 220/24, 100 VA transformer and uncontrolled bridge rectifier. The control circuit operates such that the voltage across the armature is positive and the motor is running in the clockwise direction by chopping T_1 and T_2 together. Conversely, the voltage across the armature is negative and the motor is running in the anti-clockwise direction by chopping T_3 and T_4 together. In both directions, the average value of the armature voltage is controlled by controlling the duty ratio of switching T_1 to T_4, while the field current is controlled through a single switch T_f. It should be noted that, the instantaneous waveform of the field and armature currents may not be typical during transient period due to difference in time constant of the two circuits but at steady state they are equal as can be seen from fig. (5-c) and fig. (6-c).

VII. CONCLUSION

In this paper, a drive system for the DC motor, which merges the advantages of both the separately excited DC motor and the series DC motor was introduced. The control system proposed is designed so as to run the DC motor as a series DC motor below base speed then run it as a separately excited DC motor above base speed. The proposed drive system was also used to change the speed direction in a regenerative braking mode at any motor speed. The steady state analysis of the motor below and above the base speed was performed. The transient analysis was also performed with the aid of MATLAB-SIMULINK model. Such system can cover a wide range of speed applications with different torque/speed characteristics such as traction, cranes and electric cars.

VIII. REFERENCES

[1] B.S.Guru and H.R.Hiziroglu, Electric Machineryand Transformers. Oxford University Press, New York, 1988.

[2] M.H.Rashid, *Power Electronics: Circuits, Drives and Applications.* Prentice Hall, New Jersey, 1988.

[3] N.Mohan, T.M.Undeland and W.P.Robbins, *Power Electronics: Converters, Applications and Design.* Wiley Press, New York, 1989.

[4] P.B.Schmidt and R.D.Lorenz, "Design principles and implementation of acceleration feedback to improve performance of DC drives", *IEEE Transactions on Industry Applications*, Volume 28, Issue 3, pp. 594 – 599, May-June 1992.

[5] G.Jang and M.G.Kim, "A bipolar-starting and unipolar-running method to drive a hard disk drive spindle motor at high speed with large starting torque", *IEEE Transactions on Magnetics,* Volume 41, Issue 2, pp. 750 – 755,Feb. 2005.

[6] I.Avitan and V.Skormin, "Mathematical modeling and computer simulation of a separately excited DC motor with independent armature/field control", *IEEE Transactions on Industrial Electronics,* Volume 37, Issue 6, pp. 483 – 489, Dec. 1990.

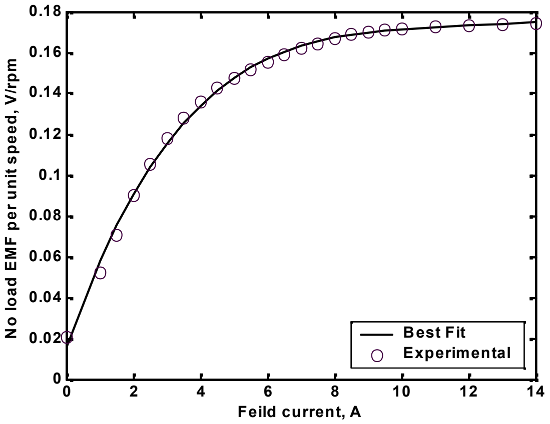
[7] J.Chiasson, "Nonlinear differential-geometric techniques for control of a series DC motor", *IEEE Transactions on Control Systems Technology,* Volume 2, Issue 1, pp. 35 – 42, March 1994.

[8] Zuo Zong Liu, Fang Lin Luo and M.H.Rashid, "Speed nonlinear control of DC motor drive with field weakening", *IEEE Transactions on Industry Applications,* Volume 39, Issue 2, pp. 417 – 423, March-April 2003.

[9] S.Mehta and J.Chiasson, "Nonlinear control of a series DC motor: theory and experiment", *IEEE Transactions on Industrial Electronics,* Volume 45, Issue 1, pp. 134 – 141, Feb. 1998.

IX. APPENDIX

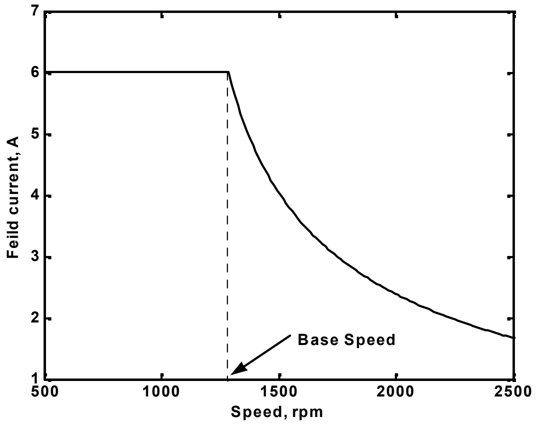
The parameters of the 220 V, 1.2 kW DC series machine is
$R_a = 3$; $R_f = 1.8$;
$L_a = 0.2$; $L_f = 0.2$;
$J = 0.05$; $B = 0.001$;



(a)

$\omega_b = 1280$

Fig. (8) shows the no load characteristics and the predicted relationship between the field current and motor speed for both constant torque and constant power region.



(b)

Fig. (8) : (a) No load characteristics (b) Relationship between field current and speed