High starting performance synchronous motor

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Abstract

With the advancement of technology, the area of applications for electric motors increases in a versatile manner. AC drives in industrial applications are rapidly increasing. It has replaced the DC motors in motion control applications and possibly makes DC motors relatively obsolete by the beginning of the next century.

For high performance drives that require very rapid dynamics and precise regulation, the need of vector control is becoming an urgent demand. In order to provide a method of decoupling the two components of stator current: one produces the air gap flux and the other producing the torque. Therefore, it provides an independent control of torque and flux, which is similar to a separately excited DC motor. Thus, vector controlled motor drive offers a number of attractive features such as smooth operation at a wide range of speeds, high torque capability, and high efficiency along with higher power factor.

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. Series DC motor has a high starting torque. Also separately excited DC motor can operate above the base speed in the field-weakening region by reducing the field current independently. However, due to commutators, DC motors are not most suitable for high-speed applications and require more maintenance than do AC motors .Therefore, in this paper a vector controlled drive system is suggested to run the synchronous 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. The synchronous motor vector 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__ synchronous motor- series DC motor- separately excited DC motor.

LIST OF SYMBOLS

R_f, R_a : field and armature resistance, Ω
L_{af} : field inductance, H
i_f, i_f^* : instantaneous and command control field current, A
i_d, i_q : d-and q-axis components of stator currents.
L_d, L_q :d-and q-axis inductances.

p	: differential operator.
P	: Number of pole pairs.
v_d, v_q	: d-and q-axis components of stator voltages.
ϕ_d, ϕ_q	: d-and q-axis flux-linkages.
T_L, T_e	: load and electromechanical torque, Nm
ω, ω *	: actual and command control signal speed, rad/sec
V_f, V_a	: steady state field and armature voltage, V
I_f, I_a	: steady state field and armature current, A

I. INTRODUCTION

DC motors were used for variable speed applications as they offer various control features of simplicity to control due to the decoupled nature of the field and armature magneto motive force (mmf). DC motor drives were proven to be excellent in both transient and steady state performances. However, disadvantages of DC motors such as high cost, the mechanical friction between the commutators and the brushes that require high maintenance, frequent changing of the brushes and the sparking that occurs by the brushes limit the power rating of the motor. These reasons make the DC drive system less attractive. That is why; AC motors have been favored for constant speed applications. The dynamic control of the AC drives is complex compared to the DC motor drive, but the recent developments in power electronics and in very large scale integrated [VLSI] circuits have simplified the system complexity to a large extend, leading to tremendous growth of AC drive technology. AC motors have several advantages over DC motors; higher efficiency, higher power density, lower cost, more reliable and almost maintenance free. Moreover, synchronous motors of wire-wound rotor type are common in high power AC drive systems because the field current can be controlled from the rotor side. Therefore, the synchronous motor has a wide range of applications. Its constant speed operation (even under load variation and voltage fluctuation) and high efficiency (92-96%, the highest of all motors) make it most suitable for constant-speed, continuous-running drives such as motor generator sets, air compressors, centrifugal pumps, blowers, crushers, and many types of continuous-processing mills [E.3]. In addition, a unique feature of synchronous motors is their power factor control capability. If the motor is overexcited, it draws leading reactive current .The overexcited synchronous motor can be used to compensate for a large number of induction motors that draw lagging reactive current. The leading reactive current drawn by the synchronous motor can improve the plant power factor, while at the same time such motors can act as prime movers for some drives in the plant. An unloaded synchronous motor may be used as a synchronous condenser (overexcited) or reactor (underexcited) to regulate the voltage at the receiving end of a long power transmission line [D.5].

The simple open-loop volt/Hertz (v/f) control method has been popularly used for long time in low performance drives. Closed-loop with flux control, torque control, slip control, and angle control have been used where better drive performance is demanded, but these scalar control techniques have drawbacks due to non-linearity of the motor model and inherent coupling between the direct and quadrature axis quantities. This causes sluggish responses which are unacceptable for high-performance drive applications with fast and precise torque response. In order to achieve these required characteristics, several methods have been proposed to obtain fast response. The vector or field oriented control techniques are being accepted almost universally for control of drive. Vector control technique displays good performance for variable speed AC drive, where, both the phase angle and the magnitude of the current have to be controlled. With the advancements of microcomputer era, VLSI, and high switching devices, such control is no longer a problem. As for machines, torque control in AC machines can also achieved by controlling the motor current. However, in contrast to the DC machines, in an AC machine, both the magnitude and phase angle of the stator current need to be controlled. This is achieved by defining a time-varying vector which corresponds to a sinusoidal flux wave moving in the air gap of the machine. When referring the mmf wave of the stator current to this flux wave, it is realized that only the quadrature axis component of the mmf wave is contributing to the torque, whereas the direct axis component affects the magnitude of the flux. Hence, the stator current phasor is defined in a frame of reference defined by the time-varying field or in field coordinates. This indicates a close correspondence to the DC machines, with the direct axis component of the stator current vector being analogous to the field current and the quadrature axis component to the armature current.

Consequently, the decoupled vector control technique can be used so that the synchronous motor can achieve the dynamic performance capabilities of the separately excited DC machine, while retaining the general advantages of AC over DC motors.

Moreover, vector control has several advantages over other control methods for AC machines drives. The decoupled torque and flux producing commands allow easy control, the fast torque response allows accurate torque, speed or position control. One further advantage of decoupled flux and torque control is operating the synchronous machine with a low load torque. Dynamic braking or regeneration is easily implemented. The torque command references simply reversed in polarity. This will produce a torque in the opposite direction and mechanical energy not dissipated in the winding resistance is returned to the supply. Under vector control operation, it should be mentioned that in addition to fast transient response due to the decoupling control, the conventional stability problem of synchronous motor does not exist anymore. The control can easily be designed to have four quadrants operation. Therefore, the vector controlled synchronous motor drives can be used for high performance application.

On the other hand, 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. However, 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. As for the separately excited DC motor, the speed control can be accomplished easily; it 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.

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. 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 are inversely proportional to the armature current. The series motor cannot run over base speed, as there is no individual control on the field 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. However, due to commutators, DC motors are not most suitable for high-speed applications and require more maintenance than do AC motors. Therefore, this paper proposes a synchronous motor drive system that merges the advantages of the separately excited DC motor and the series DC motor. The basic configuration of the proposed vector control drive system consists of a synchronous motor fed by PWM voltage source inverter and connected with the load as shown in Fig. 1. The optical incremental encoder is mounted on the rotor shaft. From the optical incremental encoder the actual position and the speed can be obtained.

Below base speed, within constant torque region, this synchronous motor drive will operate 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 synchronous 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. The basic idea is explained and vector 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.

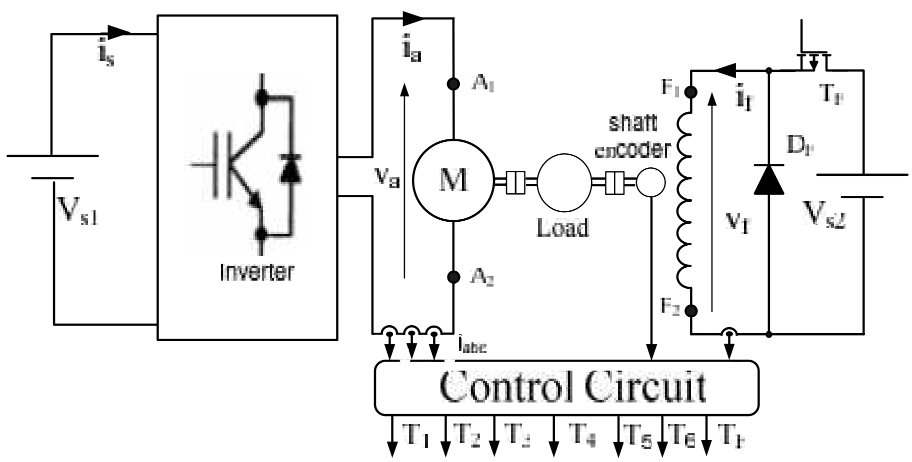

Fig. 1 Connection diagram of the proposed high starting synchronous motor

II. DYNAMIC MODEL OF VECTOR CONTROLLED SYNCHRONOUS MOTOR

The vector control results in control of the spatial orientation of the electromagnetic fields in the machine and has led to the term field orientation. Usually, this term is reserved for controllers which maintain a 90° spatial orientation between critical field components.

The vector control separates the torque and flux channels in the machine through its stator-excitation inputs. The concept of rotor position feedback and vector control of the machine stator current to maintain the space angle between the field winding and stator mmf results in stator currents which translate to controlled values of i_q and i_d in the rotor reference frame. This is a result of the instantaneous control of the phase of the stator current to always maintain the same orientation of the stator mmf vector relative to the field winding in the d-axis of the dq model. The concept of the field orientation is that the controlled current supply to the machine maintains this condition for transient changes in machine speed as well as under steady state conditions. The current i_d is therefore, the stator current component in the rotor flux axis. The current i_q is the torque component of stator. In vector control, it is assumed that the stator current to the machine is directly controlled such that i_q and i_d are independent variables. So that, the field or direct-axis current is made to be zero ($i_d = 0$), leaving only the torque or quadrature-axis current in place. Under this condition the stator voltage equation will be given by:

$$v_d = -\omega L_q i_q + pL_{af} i_f \tag{1}$$

$$v_q = R_a i_q + pL_q i_q + \omega L_{af} i_f \tag{2}$$

And the stator flux linkage relations will be:

$$\phi_d = L_{af} i_f \tag{3}$$

$$\phi_q = L_q i_q \tag{4}$$

And the torque expression will be:

$$T_e = \frac{3}{2}\frac{P}{2} L_{af} i_f i_q \tag{5}$$

Note that, because of the absence of d-axis stator current there is no reluctance torque and only the q-axis reactance is involved in finding the terminal voltage, i.e. there is no direct magnetization or demagnetization of the d-axis, only the field winding acts to produce flux in this direction. Thus, the torque response for field orientation is instantaneous and follows the commanded value of i_q exactly. This result is represented in block diagram shown in Fig. 2. Note that, this is the same as for a DC machine in fact it is a result of exactly the same physical phenomena, the reaction between two fixed current distributions. In the DC machine both are stationary. In the field orientation synchronous machine both rotate in fixed relation to one another at rotor speed.

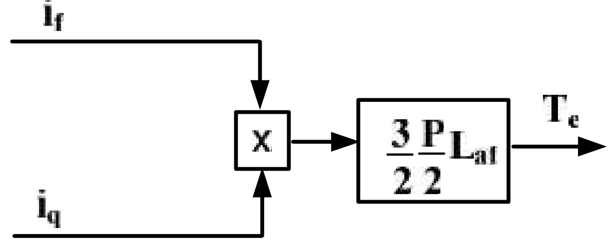

Fig. 2 Torque production-field orientation with constant field excitation.

For this situation, the field current in the d-axis and the stator current in the q-axis are 90° apart as is the case in the DC machine. Because of the absence of d-axis stator current there is no reluctance torque and only the q-axis reactance is involved in finding the terminal voltage i.e. there is no direct magnetization or demagnetization of the d-axis, only the field winding acts to produce flux in this direction.

MATLAB-SIMULINK software may be used to simulate the dynamic model of the motor as shown in Fig. 3. The actual speed ω is compared with the reference speed ω^*. The error between them is processed by the speed controller to generate the torque reference. This torque reference signal is processed through the torque current calculator to define the reference current i_q^*. The actual current from the motor is converted by Park's transformation to generate the d-q axis currents i_d and i_q rotating reference frame. The currents i_q and i_d are compared with the reference i_q^* and i_d^* respectively. The error is utilized by the current controller to generate v_q^* and v_d^* voltage commands. This goes through the inverse Park's transformation to generate a, b, and c voltage commands. These commands are compared with the triangular waveform to generate the PWM signals, which will fire the power transistors to produce the actual voltages to the motor.

Consequently, the decoupled vector control technique can be used so that the synchronous machine can achieve the dynamic performance capabilities of the separately excited DC machine, while retaining the general advantages of AC over DC motors.

III. OPERATING MODES

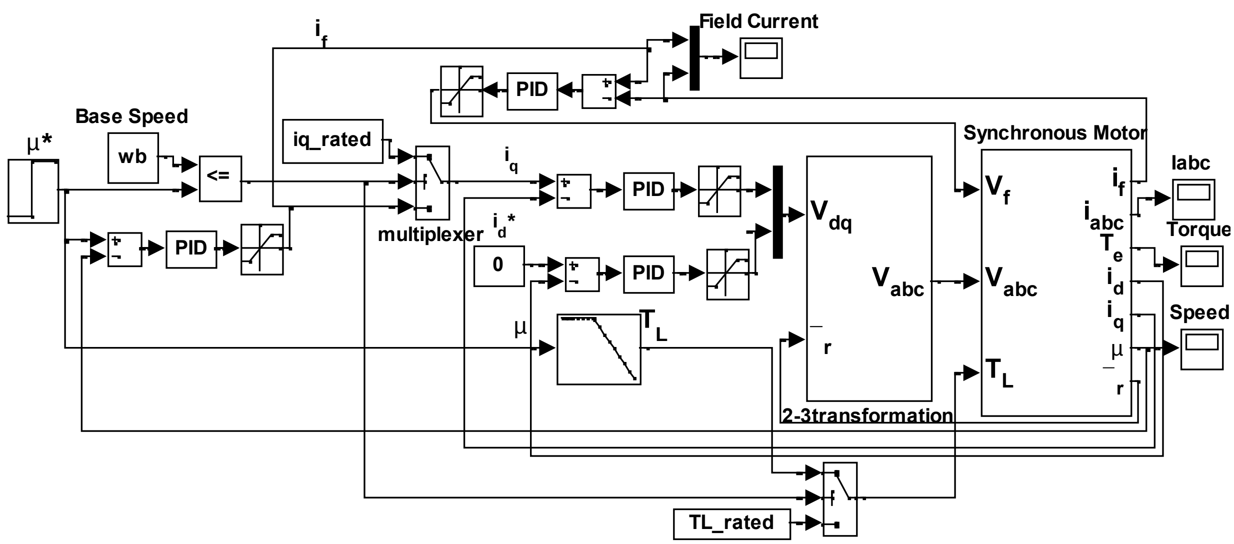

Fig. 3 Schematic diagram of the proposed high starting synchronous motor decoupled vector control scheme.

Fig. 3 shows the schematic diagram of the vector control system of the proposed high starting performance synchronous motor. The absolute value of the motor speed ω is compared with the base speed ω_b of the machine i.e the value of the motor speed at which the voltage reaches its maximum permissible value that can be supplied to the motor. 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 q-axis current i_q, meaning that the synchronous machine acts exactly like a series DC motor. In such case, the torque available is constant without exceeding the rated current of the machine as shown in Fig. 4. Above the base speed, the field current predetermined from the command rotor speed is compared with the actual field current fed from the motor, and the error signal passes through a PID controller that gives the required field voltage v_f. This field voltage enables the synchronous motor to operate in the field weakening mode of operation. According to the field voltage, the flux level is inherently adjusted and the flux weakening operation is accomplished automatically. This means that, 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 weakening mode of operation within the constant power region. In such case, the power available is constant, without exceeding the voltage rating of the machine as shown in Fig. 4. The decision of the command signal of the field depends on the absolute value of both the speed and the q-axis current. Therefore, controlling the field current is completely decoupled with speed direction and vise-versa.

It is clear from Fig. 4 that, below the rated speed, there is constant torque available without exceeding the rated current of the machine. Above the base speed, the power available is constant, without exceeding the voltage rating of the machine. Such field winding algorithm has the advantage of simplicity. As, the field current i_f is predetermined only by the rotor speed ω. The control drive system with both constant-torque and constant-power operation is presented in Fig. 3.

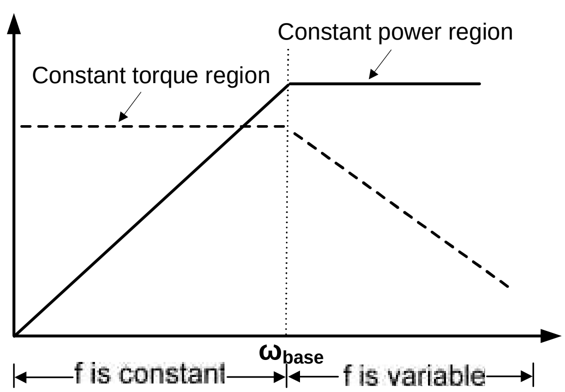

Fig. 4 Constant torque and power region operation.

Equation (1) to (5) can be arranged depending on the motor speed to develop the motor performance characteristics curves at the rated armature voltage as shown in Fig. 5. It is seen that the synchronous machine is driven in a way such that its characteristic is similar to the series DC motor before base speed and similar to the separately excited DC motor characteristics in the field-weakening region during constant power region. See Appendix for motor parameters.

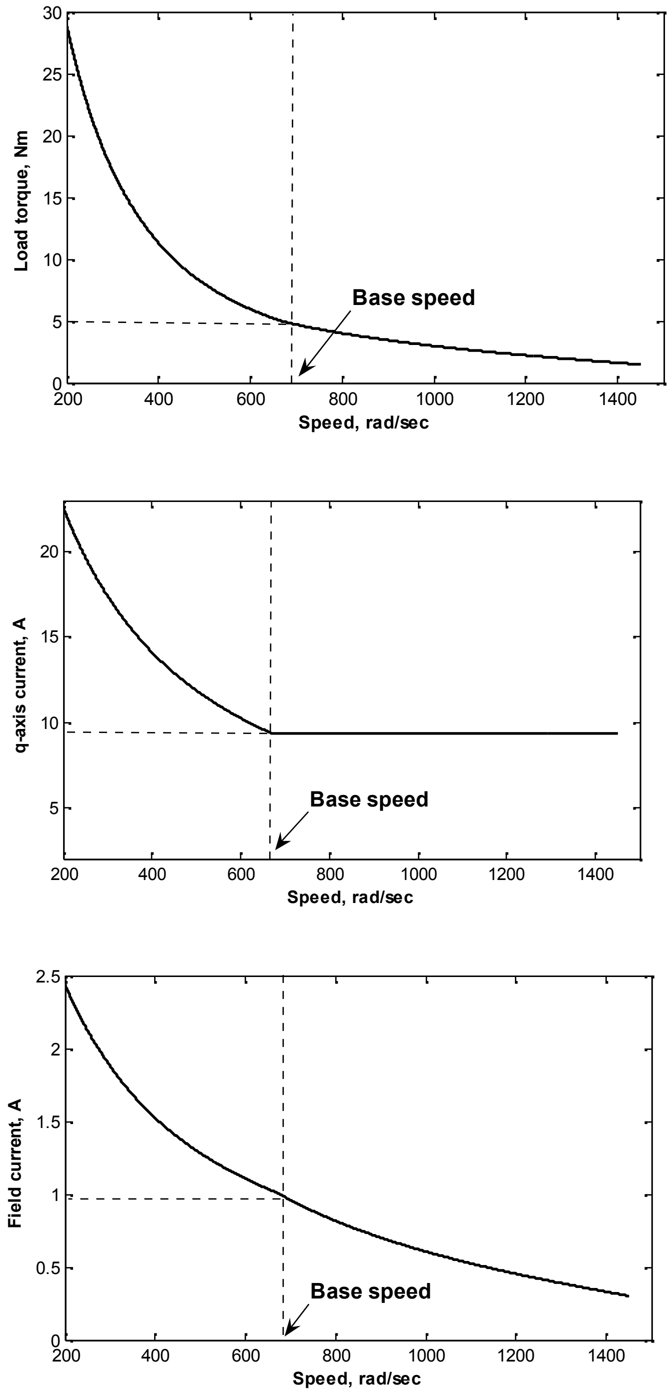

Fig.5 Steady state characteristics of the proposed high starting synchronous motor at rated voltage, speed versus (a) load torque, (b) q-axis current and (c) field current

IV. TRANSIENT RESPONSE

The model depicted in Fig. 3 has been simulated to conclude the transient response of the proposed set. The speed command signal is increased from 500 to 850 rad/sec at time t_1 1sec. (Note that the base speed is 672 rad/sec). Fig. 6 shows the instantaneous waveforms of step speed command below and above the base speed. This means that before time t_1, the machine runs at rated load torque in the constant torque region. It is clear that the machine has a high starting torque like a series DC motor, while current limiters have been adjusted to limit the field current at its rated value.

Whereas, after time $t_{1,}$ the speed will increase about 26% above the base speed, which will consequently lead to the decrease of the field current and hence the decrease of the torque about 20% below the full load value in order to maintain q- axis current at its rated value. The q-axis 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).

Fig. 6 Transient Response for step speed command from 75% to 126% base speed: (a) speed, (b) torque, (c) Field current, (d) q-axis currents, (e) d-axis currents, and (f) d-q axis voltages.

V. DISCUSSION

The synchronous motor proposed in this paper is driven like the series DC motor before the base speed, such that the field winding is principally designed to carry about 10% of the rated q-axis armature current. That is why; the field winding is composed of a small number of turns with a large cross section wire like that of the series DC motor which is designed to carry large currents and is connected in series with the armature winding.

The average value of the armature voltage is controlled by controlling the duty ratio of the inverter switching T_1 to T_6, while the field current is controlled through a single switch T_f. It should be noted that, the value of the field current is about 0.1 of the q-axis armature (in order to avoid magnetic saturation), also the instantaneous waveform of the two currents may not be typical during transient period due to difference in time constant of the two circuits but at steady state they are typical as can be seen from Fig. 6 (c) and (d).

VI. CONCLUSION

In this paper, a drive system for the synchronous 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 synchronous motor as a series DC motor below base speed then run it as a separately excited DC motor above base 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.

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IX. APPENDIX

The parameters of the 220 V, 1.1 kW synchronous machine are:

$R_a = 2.875\ \Omega$	;	$R_f = 220\ \Omega$	;
$L_q = Ld = 8.5mH$	;	$L_{af} = 0.175H$	;
$J = 0.008$	;	$P = 4$	;
$T_L = 5Nm$	;	$\omega_b = 672$ rad/sec	;