Steady State Analysis of Commutatorless DC Shunt Motor

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ABSTRACT

This paper presents steady state analysis of a line commutated inverter (LCI) fed synchronous motor (equivalent to commutatorless d.c. shunt motor) by using rotor position sensor technique. The firing pulses for thyristor of the inverter are generated in proper sequence with the help of rotor position sensor of the synchronous machine. The performance characteristic of LCI fed synchronous motor in shunt mode is computed from the mathematical model. The steady state characteristics of the system is found to be similar to the characteristics of conventional DC shunt motor.

1. INTRODUCTION

Recently variable speed drives are widely used in modern industrial fields. From the very beginning, the conventional DC motor was used as variable speed drives in many industrial applications [1]. However, for reliable operation of the system, the DC motor drives are not advisable in many cases due to several drawbacks, such as, brush and commutator wear occurs due to friction and sparking, power loss due to both brush contact points, mechanical commutator needs regular maintenance, the commutator construction increases the cost of the DC motor drive, the mica insulation limits the voltage between the commutator segments.

A DC motor can be considered of as an AC synchronous machine in which the field is stationary and the armature with its multiphase AC winding is rotating. The armature receives AC power from a DC source through brushes and commutators. The brushes and the commutator constitute an inverter sensitive to the rotor position. In a similar way, a synchronous motor may be considered to operate as a DC motor. In a synchronous machine the field is rotating whereas the armature is stationary but it should be supplied by an inverter controlled by rotor position sensing signals. The line commutated inverter with rotor position sensitive controller can very well be regarded as an electronic commutator serving the same function as does the mechanical commutator. A line commutated inverter (LCI) fed synchronous motor can be used most economically as variable speed drives in place of conventional DC motor drives for a wide range of speed [2-4]. A synchronous motor supplied by a line commutated inverter acts like a commutatorless DC motors.The drives has several advantages. Like this, synchronous machines are rugged, reliable and free of trouble. A large volume of research has been performed on the series type commutatorless DC motors [6]. From literature review, it is however, found that no steady state and transient analysis has been reported on the field of commutatorless DC shunt motor.

2. SYSTEM DESCRIPTION

The block diagram of the commutatorless DC shunt motor is shown in Fig.1. It consists of an auto transformer, uncontrolled rectifier bridge, DC link smooth inductor, line commutated inverter and a three phase synchronous machine. The uncontrolled rectifier, together with the smoothing inductor, acts as DC current source. Its output I_{DC} is impressed at the DC input of the machine voltage commutated inverter.

The synchronous machine is interfaced with a DC power supply by a self control variable frequency static inverter, which switches the power to the appropriate stator winding of the synchronous machine. The excitation winding of the synchronous machine is connected in shunt with extra resistance (r_i) to the input of inverter. So the excitation winding is suitable for standard excitation voltages (i.e.50 volt).

For better understanding of the system operation, the major components are discussed briefly as follows:

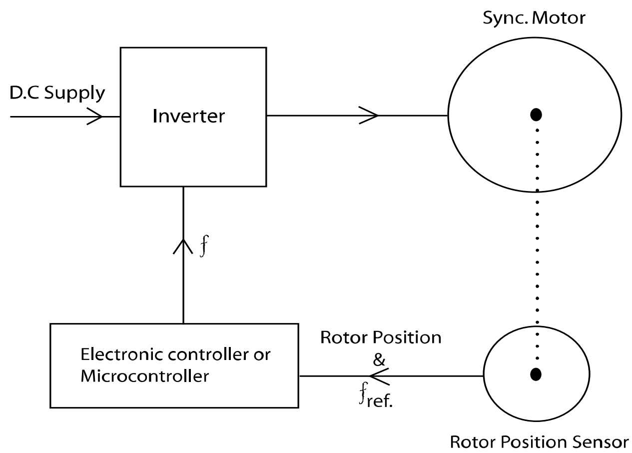

Fig. 1: Block diagram of commutatorless DC shunt motor.

(i) Uncontrolled diode bridge

The function of the diode bridge is to rectify the fixed frequency AC supply to DC voltage (V_D) and supply the active power for the synchronous machine.

(ii) DC Link inductor

The variable voltage is applied to the DC link choke, which blocks the voltage ripple and makes DC link current smooth and suppress the harmonics contained in the output of the bridge rectifier. DC link inductor acts as a current source.

(iii) Line commutated inverter (LCI)

It is a simple three-phase thyristor inverter bridge. The commutation of inverter thyristor is performed by the voltage induced in the stator winding of the synchronous machine, which is seen by the inverter as a three phase AC source of terminal voltage V_{SY}. The firing angle of the inverter is always greater than 90 degree and measured from the instant of crossing point two phase voltages .It is a self controlled inverter, which produces variable frequency in accordance to reference frequency (f_{ref}) of rotor position sensor.

(iv) Synchronous Machine

The synchronous machine is a conventional one and it is operated as a variable speed machine. The field winding of the machine is connected separately. The machine runs at synchronous speed corresponding to the speed of the rotor. Thus the inverter frequency is a function of the machine speed. When a synchronous motor is operating under steady-load conditions and an additional load is suddenly applied, the developed torque is less than that required by the load and the motor starts to slow down. A light reduction in speed decreases the frequency of the induced e.m.f [3]. The firing control scheme will generate the firing pulse for LCI at new frequency.

(v) Rotor Position Sensor

Rotor position sensor measures the value of displacement angle between stator pole axis and rotor pole axis of synchronous machine. It produces an analog signal with respect to displacement angle in between stator and rotor. Output signal is send to the controller or microcontroller based firing circuit to produce inverter frequencies.

Brushless derives are basically synchronous motor drives in self control mode. The armature supply frequency is changed in proportion to the rotor speed changes so that the armature field always moves at the same speed as the rotor. The self control ensures that for all operating points the armature and rotor fields move exactly at the same speed. This prevents the motor from pulling out of step, hunting oscillations, and instability due to a step change in torque or frequency. The accurate tracking of the speed is normally realized with a rotor position sensor [1].

(vi) Electronic Control Circuit based or Microcontroller based firing circuit:

The rotor position signal is fed to electronic control circuit or microcontroller for firing control of the inverter thyristor in proper sequence.

3. ANALYSIS

Here, steady state performance equation of a commutatorless DC motor is developed. Simple effective equivalent circuits are presented for commutatorless DC shunt motor system during conduction and commutation interval. The performance equation of the commutatorless DC shunt motor has been derived with the help of equivalent circuit (Fig. 2) and vector diagram (Fig. 3) [1]. The block diagram of the system shown in Fig. 1 consists of an auto-transformer, an uncontrolled bridge rectifier, a DC link inductor, a line commutated inverter, rotor position sensor and a conventional synchronous machine. The average DC output voltage of the rectifier is controlled by an auto transformer. This three phase uncontrolled bridge rectifier and DC link inductor act as a DC current source for the line commutated inverter. From the equivalent circuit diagram of commutatorless shunt motor shown in Fig. 2, it is found that the inverter Input voltage,

$$V_{DC} = V_D - I_{DC}\, r_d \tag{1}$$

General equation of synchronous motor,

$$V_{SY} = E_{SY} + I_{sy}\,(R_{SY} + j\,X_S) \tag{2}$$

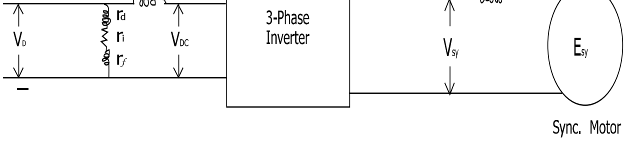

Fig. 2: Equivalent circuit diagram of commutatorless motor.

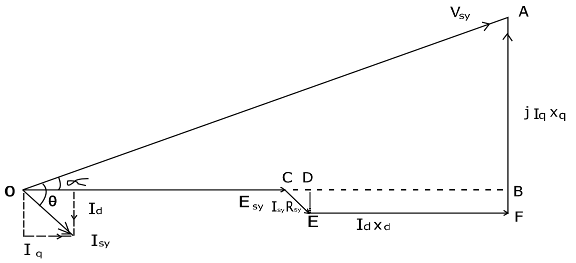

Fig. 3: Vector diagram of commutatorless DC motor.

From vector diagram

Δ OBA

$(OA)^2 = (OB)^2 + (BA)^2 = (OC+CD+DB)^2 + (FA-FB)^2$

If,

$\gamma = \theta - \alpha$, θ = p. f angle, α = Load angle, $I_d = I_{SY} \, Sin \, \gamma$, $I_q = I_{SY} \, Cos \, \gamma$

$OA=V_{SY}$, $OC=E_{SY}$, $CD=I_{SY}R_{SY} \, Cos \, \gamma$, $DB=EF=I_dX_d$,

$FA=I_qX_q$, $FB=ED=I_{SY}R_{SY} \, Sin \, \gamma$

Now, we get

$(V_{SY})^2 = (E_{SY} + I_{SY} R_{SY} Cos \gamma + I_d X_d)^2 + (I_q X_q - I_{SY} R_{SY} Sin \gamma)^2$

$(V_{SY})^2 = (E_{SY} + I_{SY} R_{SY} Cos \gamma + I_{SY} X_d Sin \gamma)^2 + (I_{SY} X_q Cos \gamma - I_{SY} R_{SY} Sin \gamma)^2$

$$E_{SY}=\sqrt{(V_{SY})^2 - (I_{SY} X_q Cos\gamma - I_{SY} R_{SY} Sin\gamma)^2} - (I_{SY} R_{sy} Cos\gamma - I_{SY} X_d Sin\gamma) \quad (3)$$

Inverter Relationship [12], [15]:

$$V_{DC} = \frac{3\sqrt{6}}{\pi} V_{SY} \, Cos\beta \quad (4)$$

(Here commutation reactance is neglected)

$\beta = 180 - \alpha^{/}$ $\quad \frac{\pi}{2} \leqslant \alpha^{/} \leqslant \pi$ (for LCI)

Where, V_{DC} = Inverter input voltage

β= Inverter lead angle in electrical degree.

$\alpha^{/}$ = Inverter firing angle in electrical degree.

$$I_{SY} = \frac{\sqrt{6}}{\pi} I_{DC} \quad (5)$$

Here,

No load current of motor, I_{SY}=1.09 A

No Load Inverter input Current, I_{DC}=1.40 A [From Eqn. (5)]

And Full load current of motor I_{SY}=10.8253 A

Full Load Inverter input Current I_{DC}=13.8840 A [From Eqn. (5)]

Speed or frequency of commutatorless motor is dependent on rotor position angle. The maximum displacement of load angle is 20 degree (elect) [13, 14]. The electronic controller circuit should have calibration of inverter frequency in according to load angle displacement.

Load Angle (α)	Inverter output frequency (*f*)	Current (I_{DC})
0 Degree	50 Hz	1.40A
20 Degree	45 Hz	13.95A

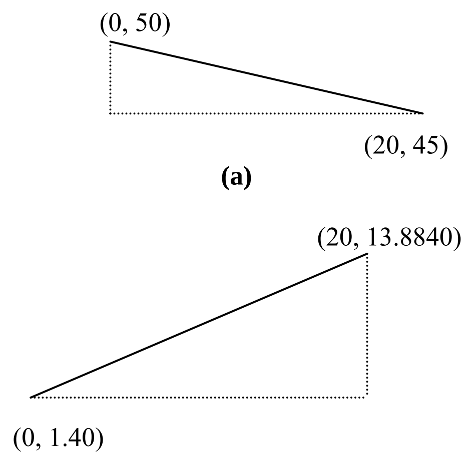

Fig. 4: (a) Relation between α and *f* and (b) Relation between α and I_{DC}.

From Fig. 4(a), we have found that the relation between inverter frequency (*f*) and load angle (α) is:

$$f=50 - 0.25 \, \alpha \quad (6)$$

$$X_q = 2\pi f L_q = 2\pi(50 - 0.25 \, \alpha) L_q \quad (7)$$

$$X_d = 2\pi f L_d = 2\pi(50 - 0.25 \, \alpha) L_d \quad (8)$$

Where,

X_d = Direct axis reactance of synchronous machine.

X_q = Quadrature axis reactance of synchronous machine.

From Fig. 4(b), we have found that the relation between current (I_{DC}) and load angle (α) is:

$$I_{DC}=1.40 + 0.6242 \, \alpha \quad (9)$$

From equations 1 and 4 and we get the new equation,

$$V_{SY} = \frac{\pi V_{DC}}{3\sqrt{6}Cos\beta}$$

$$V_{SY} = \frac{\pi(V_D - I_{DC} r_d)}{3\sqrt{6}Cos\beta} \quad (10)$$

I_{DC} and V_{SY} are put in Eqn. 3 we get,

$$E_{SY} = \sqrt{\frac{\pi^2 (V_D - I_{DC} r_d)^2}{(3\sqrt{6}Cos\,\beta)^2} - 6\left(\frac{I_{DC}}{\pi}\right)^2 (X_q Cos\,\gamma - R_{SY} Sin\,\gamma)^2} - \sqrt{6}\left(\frac{I_{DC}}{\pi}\right)(R_{SY} Cos\,\gamma - X_d Sin\,\gamma) \quad (11)$$

It is found that the inverter frequency (by Eqn. 6) and the value of E_{SY} (by Eqn. 9) varies with the load angle from 0 to 20 degree and the results shown in table-1.

Table 1: Values of f & E_{SY} for different values of α

Load angle in Degree (α)	Inverter output Frequency(Hz) (*f*)	E_{SY} (Volt)
0	50	215.0195
1	49.75	208.53
2	49.5	202.22
3	49.25	196.10
4	49	190.16
5	48.75	184.40
6	48.5	178.82
7	48.25	173.42
8	48	168.1835
9	47.75	163.1218
10	47.5	158.2250
11	47.25	153.49
12	47	148.9090
13	46.75	144.4802
14	46.5	140.1971
15	46.25	136.06
16	46	132.0434
17	45.75	128.16
18	45.5	124.40
19	45.25	120.7395
20	45	117.18

The relation between the value of frequency (f) and the value of induced e.m.f. (E_{SY}) with the help of Table-1 is as follows.

(45,117.18), (50, 215.0195)

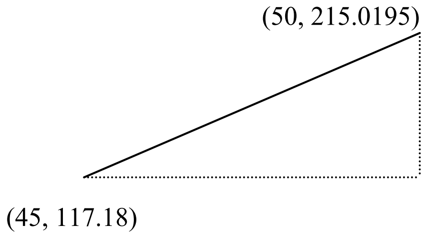

Fig. 5: Relation between f and E_{SY}.

From Fig. 5

$$f = 45 + \frac{5}{97.8395}(E_{SY} - 117.18)$$

We know that,

Motor speed, N = 120 f / P [where, no. of pole = 4]

N = 1350 +1.53 x

$$\left[\sqrt{\frac{\pi^2 (V_D - I_{DC} r_d)^2}{(3\sqrt{6}Cos\,\beta)^2} - 6\left(\frac{I_{DC}}{\pi}\right)^2 (X_q Cos\,\gamma - R_{SY} Sin\,\gamma)^2} - \sqrt{6}\left(\frac{I_{DC}}{\pi}\right)(R_{SY} Cos\,\gamma - X_d Sin\,\gamma) - 117\right] \quad (12)$$

Torque developed by the motor,

$$Tm = \frac{3E_{sy} I_{sy} Cos(\theta - \alpha)}{\omega}$$

$$Tm = \frac{3E_{sy} I_{sy} Cos(\theta - \alpha)}{2\pi N_{rps}} \quad \text{[where, } N_{rps} = \frac{N}{60}\text{]}$$

$$Tm = \frac{3 \times 60 \times E_{sy} \sqrt{6} I_{DC} Cos(\theta - \alpha)}{2\pi N\,\pi}$$

$$Tm = \frac{22.34 E_{sy}(1.40 + 0.6242\alpha)Cos(\theta - \alpha)}{N} \quad (13)$$

Eqn. 12 is the steady state general equation of commutatorless DC shunt motor. The load angle leads the all parameter of X_q (Eqn. 7), X_d (Eqn. 8) and I_{DC} (Eqn. 9). Here the speed of commutatorless DC shunt motor is dependent on the value of load angle, D.C link voltage and firing angle of inverter. Such as the machine torque depends on load angle (α).

4. RESULTS AND DISCUSSION

The steady state performance of the commutatorless DC motor is computed using the mathematical Eqns. 12 and 13 derived in article 1. FOTRAN power station program has been used for the computation of the characteristics of the

drive. The following steady-state characteristics of the drive are derived from the computed results:
i) Speed Vs DC link current i.e. N / I_{DC} characteristic.
ii) Torque Vs DC link current i.e. Tm / I_{DC} characteristic.
iii) Speed Vs Torque i.e. N / Tm characteristic.

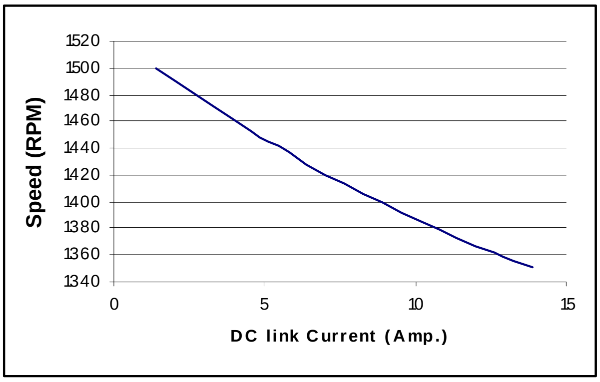

Fig. 6: Speed versus DC link current characteristics.

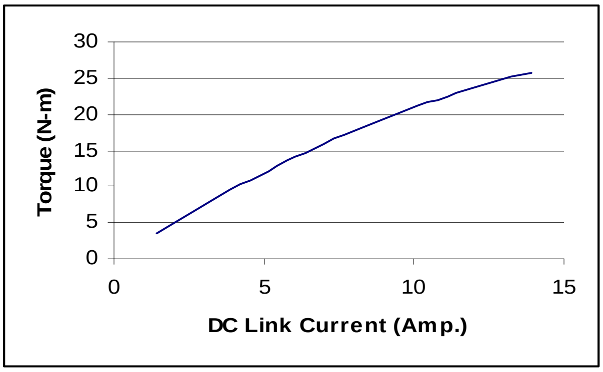

Fig. 7: Torque versus DC link current characteristics.

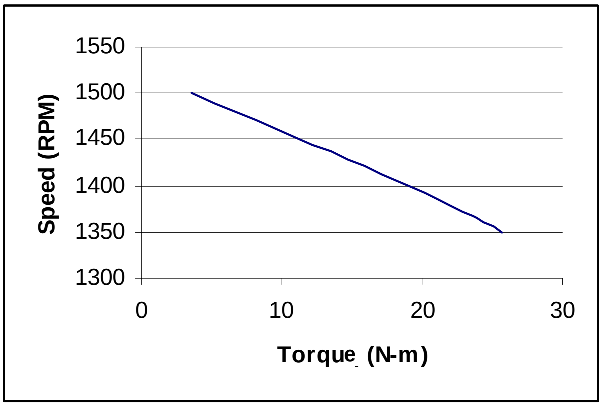

Fig. 8: Speed versus torque characteristics.

The analytical characteristics of the commutatorless DC motor are shown in Figs. 6 to 8.

The following salient features on the performance of commutatorless DC motor may be observed from the computed results.

i) The variation of speed with the DC inverter input current is shown in fig.6. It is observed from fig.6.that the speed of synchronous machine slightly decreases with the increase of DC link current. In equation 12. It is found that; the speed of the synchronous motor mainly depends on the DC link current. This characteristic exactly correlates with that of conventional DC shunt motor.

ii) The variation of machine torque with DC link current are shown in fig.7 It is observed from equation 11 that the torque of the machine is proportional to the DC link current. Therefore the torque increases with input current, like a conventional DC shunt motor.

iii) The variation of machine speed with increase in machine torque is shown in fig.8. It can be observed from fig.8 that the speed of synchronous machine decreases with torque like a conventional DC shunt motor.

5. CONCLUSIONS

The steady state performance analysis of the commutatorless DC shunt motor has been computed by using Fortran Power Station programming. The study of steady state analysis shows that a synchronous motor with the excitation winding connected in parallel with the inverter input is equivalent to a conventional DC shunt motor. Hence, Synchronous motors can be used as variable speed drives in modern industrial applications as commutatorless DC shunt motor.

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