Transient Analysis of Commutatorless DC Shunt Motor

Mohammad Abdul Mannan and Md. Aminul Islam

Abstract − This paper presents a transient analysis of a line commutated inverter (LCI) fed synchronous motor (the equivalent of commutatorless d.c. shunt motor) 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 transient analytical model of the system was developed using steady state equivalent circuit and vector diagram. The performance characteristic of LCI fed synchronous motor in shunt mode was computed from the mathematical model. The transient characteristics of step changes load (either load applied or load removed) are identified.

Keywords − Rotor Position Sensor, LCI, FORTRAN Power Station, Model of Commutatorless DC Shunt Motor

1 INTRODUCTION

RECENTLY, variable speed drives have been widely used in modern industrial fields. From the outset, the conventional DC motor was used as variable speed drives in many industrial applications [1]. However for a reliable system operation, DC motor drives are not recommended in many cases. DC motor drives have several drawbacks, such as brush and commutator wear, which occurs as a result of 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; and the mica insulation limits the voltage between commutator segments.

A DC motor can be considered 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. Similarly, a synchronous motor may be operated as a DC motor. In a synchronous machine, the field rotates, whereas the armature is stationary. However it should be supplied by an inverter controlled by rotor position sensing signals. The line commutated inverter with rotor position sensitive controller can well be regarded as an electronic commutator, serving the same function as the mechanical commutator. A line commutated inverter (LCI) fed synchronous motor is the most economical, as variable speed drives substitute conventional DC motor drives for a wide range of speeds [2-4]. A synchronous motor supplied by a line commutated inverter acts as a commutatorless DC motors. The drives have several advantages. Synchronous machines are strong, reliable and trouble free. A large volume of research has been undertaken on the series type commutatorless DC motors [6]. However the literature review finds that no steady state and transient analysis have been reported in the field of commutatorless DC shunt motor.

- *Mohammad Abdul Mannan, Department of Electrical and Electronic Engineering at Dhaka University, Gazipur. E-mail mannan489@yahoo.com*
- *Md. Aminul Islam, Department of Electrical and Electronic Engineering at Dhaka University, Gazipur. E-mail aminkeari@yahoo.com*

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2 SYSTEM DESCRIPTION

The block diagram of the commutatorless DC shunt motor is shown in Fig.1. It is comprised 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 a 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 to shunt with extra resistance (r_i) to the input of inverter. Therefore the excitation winding is suitable for standard excitation voltages (i.e. 50 volts).To better understand the system operation, the major components are briefly discussed below:

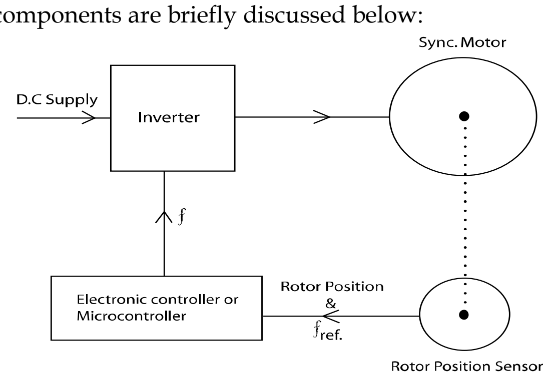

Figure 1: Block Diagram of Commutatorless D.C. Shunt Motor

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(i) Uncontrolled diode bridge

The diode bridge's function is to rectify the fixed frequency AC supply to DC voltage (V_D) and to 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 smooths the DC link and suppress the harmonics contained in the output of the bridge rectifier. The DC link inductor acts as a current source.

(iii) Line commutated inverter (LCI)

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

(v) Rotor Position Sensor

Rotor position sensor measures the value of the displacement angle between stator pole axis and rotor pole axis of a synchronous machine. It produces an analog signal in respect to displacement angle, in between stator and rotor. The output signal is sent 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 changes in proportion to rotor speed changes, so that the armature field always moves at the same speed as the rotor. Self-control ensures that in all operating points, the armature and rotor fields move at exactly the same speed. This prevents the motor from pulling out of step, hunting oscillations, and the instability which results from a step change in torque or frequency. Accurately tracking speed is usually obtained using 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

In this paper, the steady state performance equation of a commutatorless DC motor is developed. Simple and effective equivalent circuits are presented for commutatorless DC shunt motor system during the conduction and commutation intervals. The performance equation of the commutatorless DC shunt motor was derived using the 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. The three phase uncontrolled bridge rectifier and DC link inductor act as a DC current source for the line commutated inverter. The equivalent circuit diagram of commutatorless shunt motor shown in fig 2 finds the inverter input voltage.

Part−1 (Steady State Analysis)

$$V_{DC} = V_D - I_{DC}\, r_d \quad (1)$$

General equation of synchronous motor

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

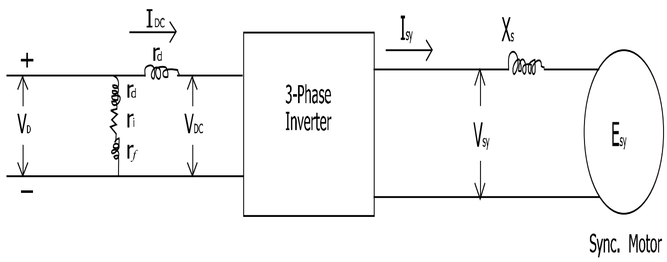

Figure 2: Equivalent Circuit Diagram of Commutatorless Motor

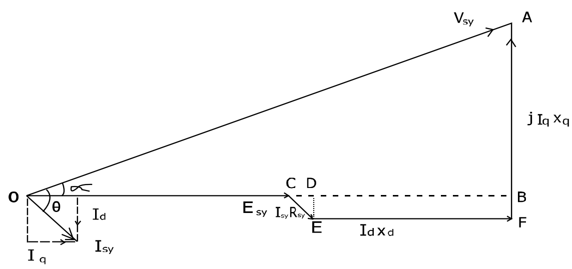

Figure 3 Vector Diagram of Commutatorless D.C Motor

From the 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]:

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

(Commutation reactance is neglected here)

$\beta = 180 - \alpha' \qquad \frac{\pi}{2} \leqslant \alpha' \leqslant \pi$ (for LCI)

Where, V_{DC} = Inverter input voltage
β= Inverter lead angle in electrical degree.
α/ = Inverter firing angle in electrical degree.

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

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

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

Now we get:

$(V_{SY})^2 = (E_{SY} + I_{SY} R_{SY} \cos\gamma + I_dX_d)^2 + (I_qX_q - I_{SY} R_{SY} \sin\gamma)^2$
$(V_{SY})^2 = (E_{SY} + I_{SY} R_{SY} \cos\gamma + I_{SY} X_d \sin\gamma)^2 + (I_{SY} X_q \cos\gamma - I_{SY} R_{SY} \sin\gamma)^2$

Here:

Motor capacity is 6 KW (400V, pf 0.8)
No load current of motor, I_{SY}=1.09 A
No Load Inverter input current, I_{DC}=1.40 A [From Eq. 5]
And full load current of motor I_{SY}=10.8253 A
Full load inverter input current I_{DC}=13.8840 A [From Eq. 5]

The speed or frequency of the commutatorless motor is dependent on the rotor position angle. The maximum displacement of the load angle is 20 degrees (elect) [13],[14]. The electronic controller controller circuit requires the calibration of inverter frequency in accordance with the 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 finds that the relation between inverter frequency (f) and load angle (α) is:

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

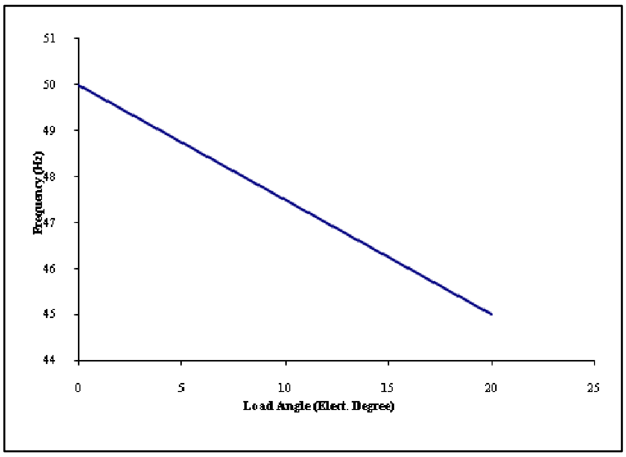

Figure 4.A: Relation between load angle and Frequency

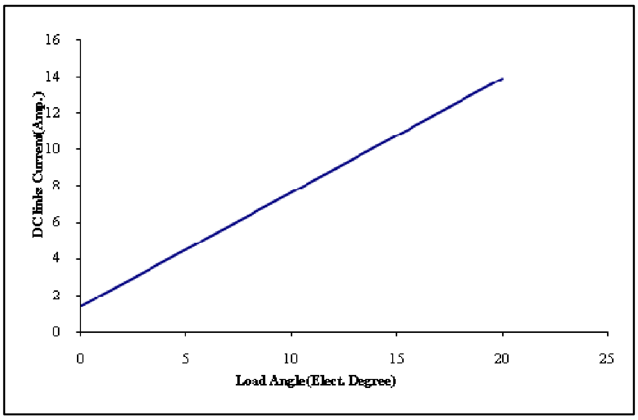

Figure 4.B: Relation between α and IDC

$X_q = 2\pi f L_q = 2\pi(50 - 0.25\,\alpha) L_q \quad (7)$
$X_d = 2\pi f L_d = 2\pi(50 - 0.25\,\alpha) L_d \quad (8)$

Where:
X_d = Direct axis reactance of synchronous machine.
X_q = Quadrature axis reactance of synchronous machine.

Fig.4-B finds that the relationship between current (I_{DC}) and load angle (α) is:

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

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

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

I_{DC} and V_{SY} are inserted in equation 3. We get:

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

The inverter frequency (Equation 6) and the value of E_{SY} (Equation 9) varies with the load angle from 0 to 20 degrees. The results are presented in table-1.

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

TABLE-1

Load Angle in Degrees (α)	Inverter Output Frequency(Hz) (f)	E_{SY} (Volts)
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 relationship between the frequency value (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)

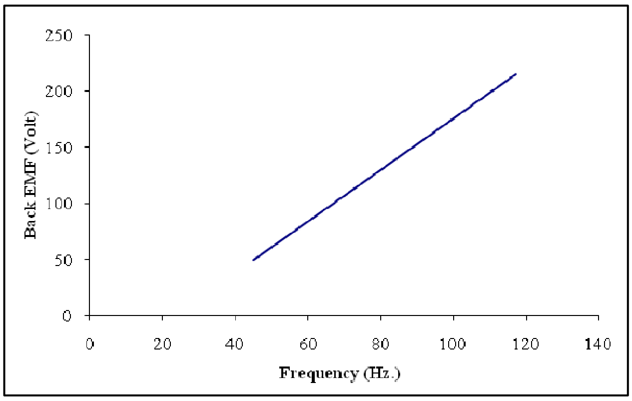

Fig.5: Relationship between f and E_{SY}

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]

Motor speed, N = 120 f / P

$$N = 1350 + 1.53\left[\sqrt{\frac{\pi^2(V_D - I_{DC}r_d)^2}{(3\sqrt{6}Cos\beta)^2} - 6\left(\frac{I_{DC}}{\pi}\right)^2(X_qCos\gamma - R_{SY}Sin\gamma)^2} - \sqrt{6}\left(\frac{I_{DC}}{\pi}\right)(R_{SY}Cos\gamma - X_dSin\gamma) - 117\right] \quad (12)$$

Torque developed by the motor,

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

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

$$Tm = \frac{3x60xE_{sy}\sqrt{6}I_{DC}Cos(\theta-\alpha)}{2\pi N\ \pi}$$

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

[If, K=22.34]

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

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

Part−2 (Transient Analysis)

Here we derive the transient analysis as performance equations from steady state equation, where the transient time is one second [13]. The total transient consists of two parts: sub-transient (20% of total transient time) and transient (80% of total transient time).

Sub-transient time (time duration 0.20 Sec.) [13]:

$\alpha_{ST} = [\alpha + 0.1875\ \alpha\ Sin(\omega t)e^{-1.63t}]$ (14)
When the load is applied on the motor
Where, α_{ST} = Sub transient load angle in electrical degree.
$\alpha_{ST} = [\{(\alpha - \alpha_r) - (0.1875\ \alpha_r)\}\ Sin(\omega t)e^{-1.63t}]$ (15)
When the load is removed from the motor
Where, α_r = removed load angle
I_{DC}=1.40 + 0.6242 α_{ST} (16)
f=50−0.25 α_{ST} (17)

Transient time (time duration 0.8 Sec.) [13]:
$\alpha_{ST} = [\alpha + 0.125\ \alpha\ Sin(\omega t)e^{-2.14t}]$ (18)
When the load is applied on the motor

Where, α_T = Transient load angle in electrical degree.

$$\alpha_{ST} = [\{(\alpha - \alpha_r) - (0.125\ \alpha_r)\}\mathrm{Sin}(\omega t)e^{-2.14\,t}] \quad (19)$$

When the load is removed from the motor

Where, α_r = removed load angle

$$I_{DC}=1.40 + 0.6242\ \alpha_{ST} \quad (20)$$

$$f=50-0.25\ \alpha_{ST} \quad (21)$$

If I_{DC} of sub-transient and transient are applied in the general equation (12) & (13) of the steady state, the transient equations during load applied or load removed moment are derived.

4 Results and Discussion

The following transient characteristics of the drive are derived from the computed results during load applied or load removed moments. Firstly, the analytical transient characteristics of the commutatorless DC motor are shown in Fig.6 to 8 for an applied load.

i) Speed Vs time.
ii) DC Current Vs time.
iii) Torque Vs time.

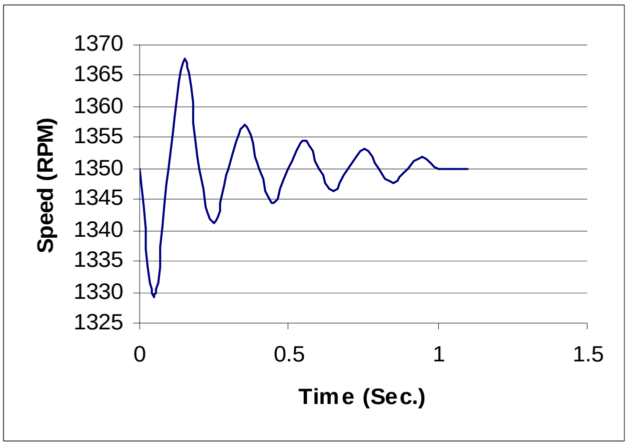

Figure 6: Speed Verses Time Characteristics

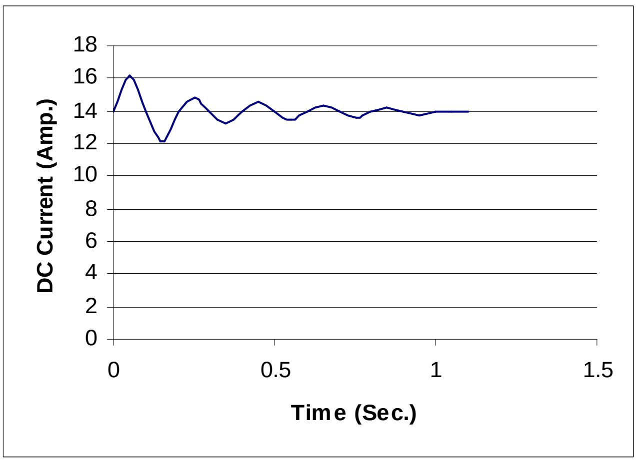

Figure 7: DC Current Verses Time Characteristics

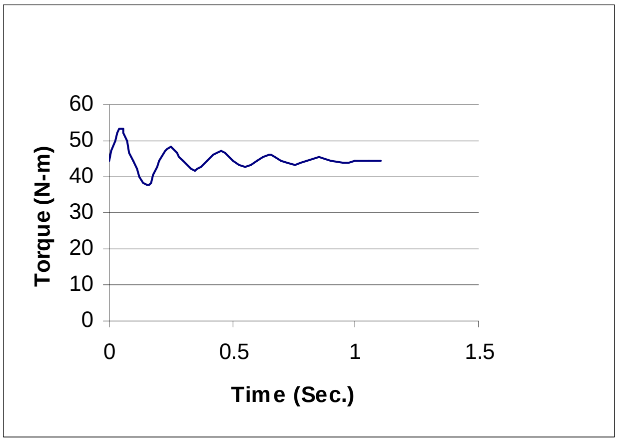

Figure 8: Torque Verses Time Characteristics

Secondly the analytical transient characteristics of the commutatorless DC motor are shown in Fig.9 to 11 for a removed load.

i) Speed Vs time.
ii) DC Current Vs time.
iii) Torque Vs time.

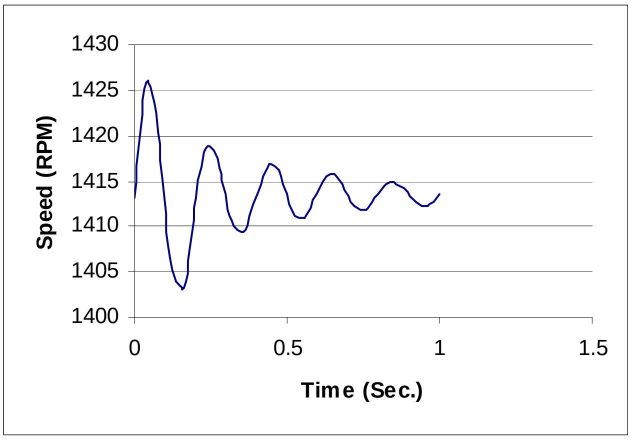

Figure 9: Speed Verses Time Characteristics

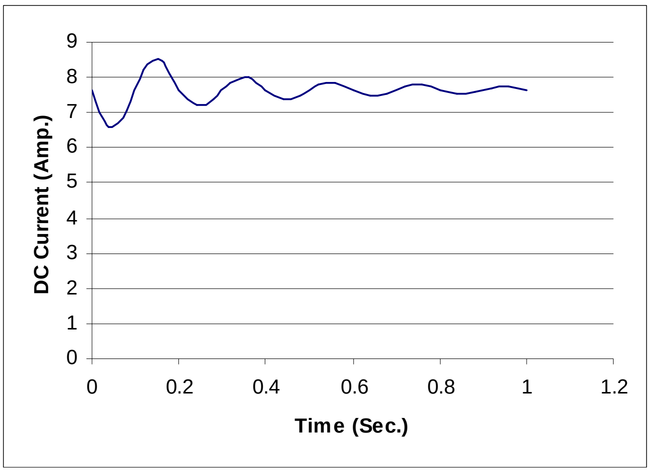

Figure 10: DC Current Verses Time Characteristics

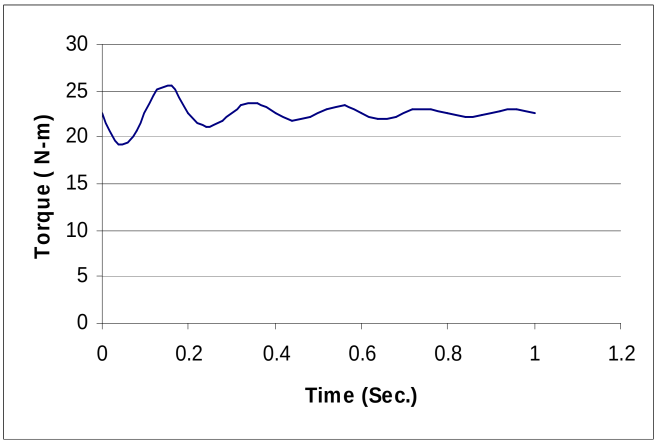

Figure 11: Torque Verses Time Characteristics

The salient feature regarding the performance of commutatorless DC shunt motor may be observed from the computed results during step changes or variation in load. The transient results are provided in Figs 6-11. Figs 6 and 9 represent the deviation (oscillation with time) of the speed of the commutatorless DC shunt motor. Figs 7 and 10 represent the deviation (oscillation with time) of the inverter input DC link current of the commutatorless DC shunt motor. Figs 8 and 11 represent the deviation (oscillation with time) of the torque of the commutatorless DC shunt motor.

5 Conclusions

The transient performance of the commutatorless DC shunt motor was computed using Fortran Power Station programming. The performance characteristic (its speed verses time, d.c. link inverter current verses time and torque verses time) of LCI fed synchronous motor in shunt mode is computed from the mathematical model and the transient characteristics of step changes load (either load applied or load removed). It is evident that transient performance of commutatorless D.C shunt motor is superior to the conventional D.C shunt motor.

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Engr.Mohammad Abdul Mannan received B.Sc. Engg. (EE) from Ctg.Engg. College (Now CUET) in 1984 and M.Sc. Engg (CSE) from BUET in 1993. He is a Professor of EEE Dept, Dean of EEE faculty and Syndicate Member of DUET, Gazipur. He has published more than ten publications and five Professional System Design works. His reaserch interests include Renewable Energy Systems, High Tech Security Systems and Control and Automation Systems.

Md. Aminul Islam received B.Sc. Engg. (EEE) from BIT Dhaka (now DUET) in 1995 and M.Sc. Engg. (EEE) from DUET in 2005. He is presently undertaking a Ph.D in Electrical and Electronic Engineering, Dhaka University of Engineering & Technology (DUET). He is also the Deputy Chief Engineer (Electrical) in a private organization. His resarch interests include Energy Systems, Smart Grid and PLC Systems.