MODELING AND SIMULATION OF A BUCK CONVERTER CONTROLLED A SENSORLESS DC SERIES MOTOR

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ABSTRACT

This paper presents modeling and simulation of a speed sensorless control for dc series motor driven by a buck converter through computation of the motor speed from converter output voltage and current. The system model considers the nonlinearity of the series motor magnetization characteristics including the variation of the field inductance with the motor current.

الخلاصه:

يقدم البحث نمذجة ومحاكا ة محرك تيار مستمر متوالي الاثاره مغذى من محول تيار مستمر خافض للفولتيه ومسيطر على سرعته بدون استخدام متحسس سرعه. نمذجة المحرك تاخذ بنظر الاعتبار اللا خطيات للخواص المغناطيسيه للمحرك متضمنة تغير معامل الحث الذاتي لملفات الاثاره المتواليه مع تغير التيار.

KEY WORDS: DC series motor, speed control, sensorless.

List of Symbols:

e_g : Motor generated voltage (or back emf).
f_s : Converter switching frequency.
i_a : Motor armature current.
i_L : Converter inductor current.
i_o : Converter output current.
K_p : Controller proportional constant.
n : Motor speed.
n_o : Motor speed corresponding to that of E_g versus I_a curve.
n_{ref} : Motor reference speed.
T_d : Developed torque.
v_a : Motor armature voltage.
v_c : Converter capacitor voltage.

v_o :Converter output voltage.
B :Friction coefficient.
C :Converter capacitance.
D :Duty ratio.
E_g :Average motor generated voltage.
I_a :Average armature current.
J :Moment of inertia.
$Ka.\Phi$:Back emf and torque constant.
L :Converter inductance.
L_a :Motor armature circuit inductance.
L_f :Series field inductance
R_a :Motor armature circuit resistance.
R_f :Series field resistance
R_{esr} :Capacitor equivalent series resistance.
R_l :Converter inductor internal resistance.
T_d : Motor developed torque.
T_i :Controller integral constant.
T_l :Load torque.
T_s : Switching time period
V_a :Average motor armature voltage.
V_c :Average capacitor voltage.
V_o :Average converter output voltage.
V_s :Converter input voltage.
Δi_L :Converter inductor current ripple.
ψ : Flux linkage in the field in Wb-turn.
Φ : Flux in Wb.

INTRODUCTION

DC series motor are extensively used in traction and application which required high starting torque[Seen].Its speed can be controlled by varying the armature voltage using dc-dc converter operated in high switching frequency to supply continuous armature current without significant torque and speed ripple. There are many articles study the modeling of the dc series motor, some of them like [Okoro 08] and [Soliman 95] ignores all the nonlinearity of the magnetization characteristics while [Samir 98] take its effect on the back emf and the developed torque, but consider the inductance of the series field is constant.

In much application the use of speed sensors like tachogenerator or shaft encoder will add a significant cost and weight to the drive system. In this work, these adverse effects can be avoided using a sensorless speed control. The first section of this work demonstrates the design, modeling and simulation of the buck converter, while section two explains the dc series motor modeling and simulatin.The speed computing unit , the PI controller will explained in section four and five respectively. The system performance is evaluated using Matlab Simulink toolbox through demonstrating the transient response of the motor speed and current due to step change in the desired speed, load torque, and the input voltage. The block diagram of the proposed system is shown in **Fig.1,** where the output voltage of the buck converter is applied to the dc series motor. The motor armature voltage and hence its speed is controlled by using a pulse width technique to control the power MOSFET. The reference speed signal which represents the required motor speed is compared with the actual speed which is computed from the measurement of the armature voltage and current. Any disturbance in the motor load torque or converter input voltage or change in the reference speed causes the PI controller to produce an adequate control signal which is then compared with a constant frequency sawtooth waveform to adjust the duty ratio of the gate control pulses to maintain the motor actual speed equal to the reference speed.

-The buck converter design, modeling and simulation:

The buck converter steady state output voltage depends linearly on the duty ratio D which is defined as the ratio of the on duration to the switching time period. The converter output voltage is given by:

$$V_a = D.V_s \qquad 0 \leq D \leq 1 \qquad (1)$$

The buck converter modes of operation are explained in details by [Mohan 03].
The converter switching frequency is 20 KHz, and the input voltage is 240V.

Inductor design:

The inductor value depends on the admissible current ripple ΔiL which is given by the following relation [Mohan 03]:

$$\Delta i_L \equiv \frac{1}{L}(V_s - V_a).\frac{D}{f_s} \qquad (2)$$

The continuous conduction mode of the converter is ensured by making the minimum output current equal to the minimum permissible motor current which is taken to be 1A according to the specifications of the used motor in this work. Therefore $\Delta i_L = 2A$ is the maximum admissible value. Solving eq. (2) for L yields:

$$L = \frac{(V_s - V_a).D.T_s}{\Delta i_L} \qquad (3)$$

Where: $T_s = \dfrac{1}{f_s}$

Substitute eq.(1) in eq.(3), gives:

$$L = \frac{V_s(1-D)D.T_s}{\Delta i_L} \qquad (4)$$

Clearly the maximum value of the right hand side of eq. (4) occurs at $D = 0.5$, thus the value of the inductor becomes:

$$L = \frac{V_s .T_s}{4\Delta i_L} \tag{5}$$

Taking $\Delta i_L = 2A$, the value of the inductor will be $1.5\, mH$.

Capacitor Design:

The output voltage ripple can be minimized by making the corner frequency f_c of the output LC filter such that $f_c << f_s$, also a rule of thumb of $300\mu f / A$ minimum at $20KHz$ is more realistic when electrolytic capacitors are used[Chyrysis 89]; accordingly for the 8.2A rated armature current, the capacitor selected to be $3300\, \mu f$.

Converter Model:

The averaged state space equations for the buck converter are [Chrip 07]:

$$\frac{\partial i_L}{\partial t} = \frac{1}{L}(d.v_s - i_L R_l - v_o) \tag{6}$$

$$\frac{\partial v_c}{\partial t} = \frac{1}{C}(i_L - i_o) \tag{7}$$

$$v_o = v_c + R_{esr}(i_L - i_o) \tag{8}$$

Where:

$d = 1$ When the switch is on.
$d = 0$ When the switch is off.

The converter matlab-simulink is shown in **Fig.2** where the converter is controlled using pulse width modulation technique which its matlab-simulink is simply shown in **Fig.3.**

III-DC motor Modeling and Simulation:

The dc series motor is modeled by the equations below:

$$v_a = e_g + (R_a + R_f).i_a + L_a.\frac{\partial i_a}{\partial t} + L_f.\frac{\partial i_a}{\partial t} \tag{10}$$

Where:

$$e_g = Ka.\Phi(i_a)..n$$

$$L_f = \frac{\partial \Psi}{\partial i_a} \approx \frac{\Psi(i_a + \Delta i_a) - \Psi(i_a)}{\Delta i_a} \text{ Where } \Delta i_a \approx 0$$

The torque balance equation is:

$$T_d = T_l + B.n + J.\frac{\partial n}{\partial t} \qquad (11)$$

Where:

$$T_d = Ka.\Phi(i_a).i_a$$

E_g Versus I_a and Ψ_f versus I_a for the used motor are shown in **table (1)** [Sailendra 87].These curves are interpolated with piecewise linear interpolation using the one dimension lookup tables of the matlab simulink library. These curves and motor parameters shown in the appendix are used in the matlab- simulink of the dc series motor as in **Fig.4.**

Table 1. Flux linkage (Ψ_f) and emf (E_g) as a function of armature current

I_a in A	Ψ_f in $Wb-turn$	E_g in V at n_o=1600 rpm
0.0	0.0	5.0
1.0	0.115	22.25
2.0	0.28	35.0
3.0	0.415	52.5
4.0	0.54	67.0
5.0	0.665	79.0
6.0	0.76	88.5
7.0	0.82	95.5
8.0	0.88	102.0
9.0	0.94	106.5
10.0	0.99	108.5

IV- Speed Computing Unit, PI controller, and Current Limiter:

Using eq.(10) in terms of the average values, the motor speed can be computed as:

$$n = \frac{V_a - (R_a + R_f)I_a}{Ka.\Phi(I_a)} \qquad (12)$$

$Ka.\Phi(I_a)$ is found from the one dimension lookup table (E_g versus I_a) after division the back emf by the motor speed (n_o) at which the motor back emf is measured. The output of this unit is passed through a low pass filter to remove or reduce the noise. The simulink of this unit is built as shown in **Fig.5.**

Using transient performance specification [Basilio 02], P-I controller is designed and tuned such that its transfer function is given by:

$$K(S) = K_p(1 + \frac{1}{T_i.S}) \tag{13}$$

Where: $K_p = 1.1$ and $T_i = 0.4 Sec.$

A current limiter is used to protect the system from the large starting and transient currents, which can be damage the converter and possibly the motor**. Fig.6** and **Fig.7** represent the simulink of the controller and the current limiter respectively.

V-Simulation Results:

Based on the system model, the motor parameters, and the converter parameters shown in appendix, Simulink is used to simulate the system under consideration as shown in **Fig.8.** The dynamic performance of the drive system is evaluated through step disturbances in the desired speed, load torque, and converter input voltage.**Fig.9** shows the transient response of the motor speed and current due to step increase and decrease in the desired speed (from 100 rad/sec to 200 rad/sec at t = 5 sec and from 200 rad/sec to 100 rad/sec at t =10sec), when the load torque is 2.5N.m at rated converter input voltage. The motor attained its reference speed in about 2.5 sec. **Fig.10** demonstrates the response due to step increase and decrease in the load torque (from 1.5 N.m to 3 N.m at t = 6sec and from 3 N.m to 1.5 N.m at t = 10sec), when the desired speed is 200 rad/sec at rated converter input voltage. The speed is restored to the reference value within 1.5 sec. Furthermore the system is tested by step decrease and increase in the converter input voltage as shown in **Fig.11** (from 240V to 180V at t = 5sec and from 180V to 240V at t= 10 sec, when the load torque is 2.5N.m and motor speed is 200 rad/ Sec.).The motor retained its reference speed within 2 sec. The three figures clarify the soft start of the motor and the operation of the current limiter.

VI-Conclusion:

A dc series motor fed from buck converter with sensorless speed control is simulated taking the nonlinearity of the dc series motor in consideration and this will lead, to expected good coherency between the simulation and practical results if the system is implemented. Speed computation unit is used based on the measurement of the converter output voltage and current. The system simulation shows the effectiveness of this speed unit with satisfactory operation of the PI controller since the speed response has small overshoot, accepted rise time with nearly zero steady state error.

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APPENDIX:

The dc series motor used has the following specifications:
DC series motor, 110V, 8.2-A, 2300 rpm, 0.9 Kw
$R_a + R_f = 2.32\Omega,\ L_a = 25mH,\ J = 0.025Kg - m^2,\ B = 0.001N.m.\sec/rad.$
The buck converter specifications are:
Input voltage $V_s = 240V$.
Output voltage $V_o = V_a$ is adjustable according to required speed and load.
Output current $I_o = I_a = 8.2\,A$.
$L = 1.5mH$, with internal resistance $R_l = 0.017\,\Omega$, $C = 3300\,\mu f$. with $R_{esr} = 0.05\,\Omega$, switching frequency $f_s = 20KHz.$

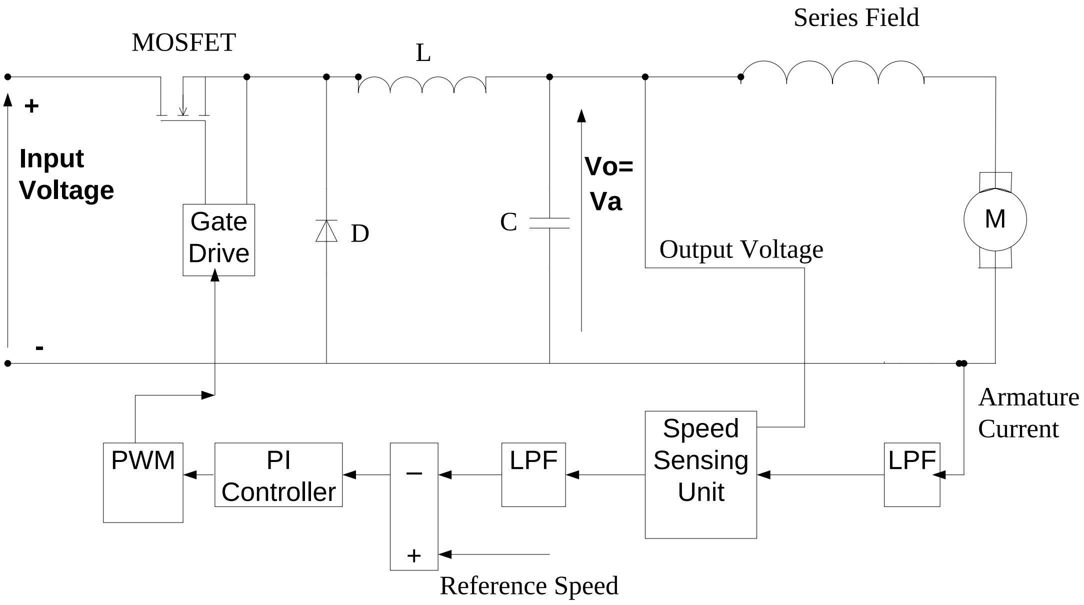


Fig.1 Sensorless dc series drive system

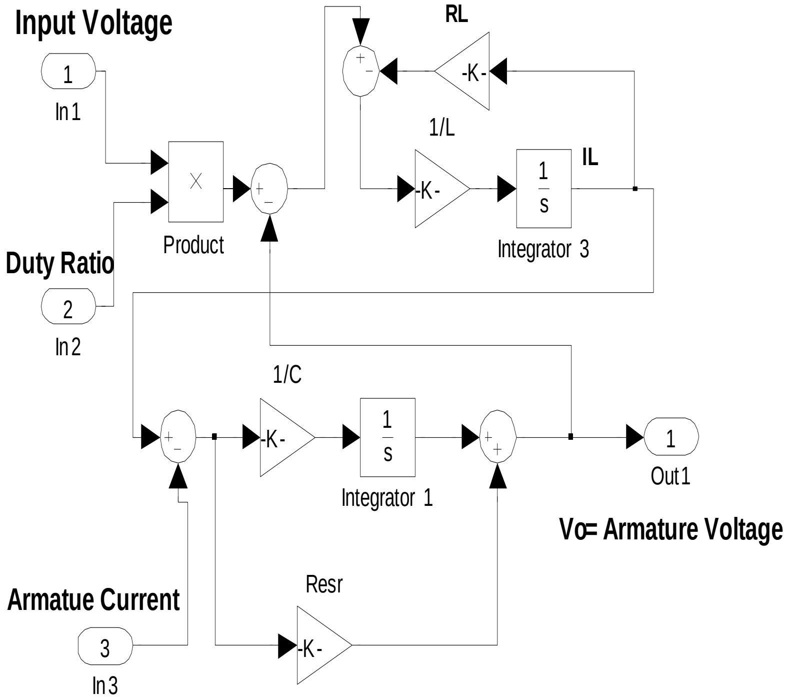


Fig.2 Simulink of a buck converter

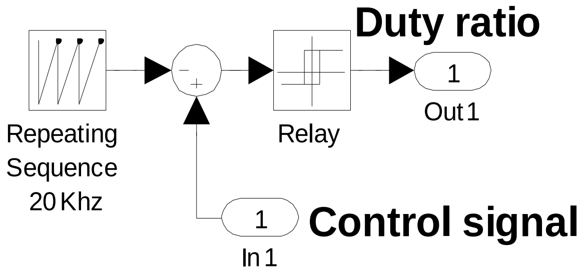


Fig.3 Simulink of PWM

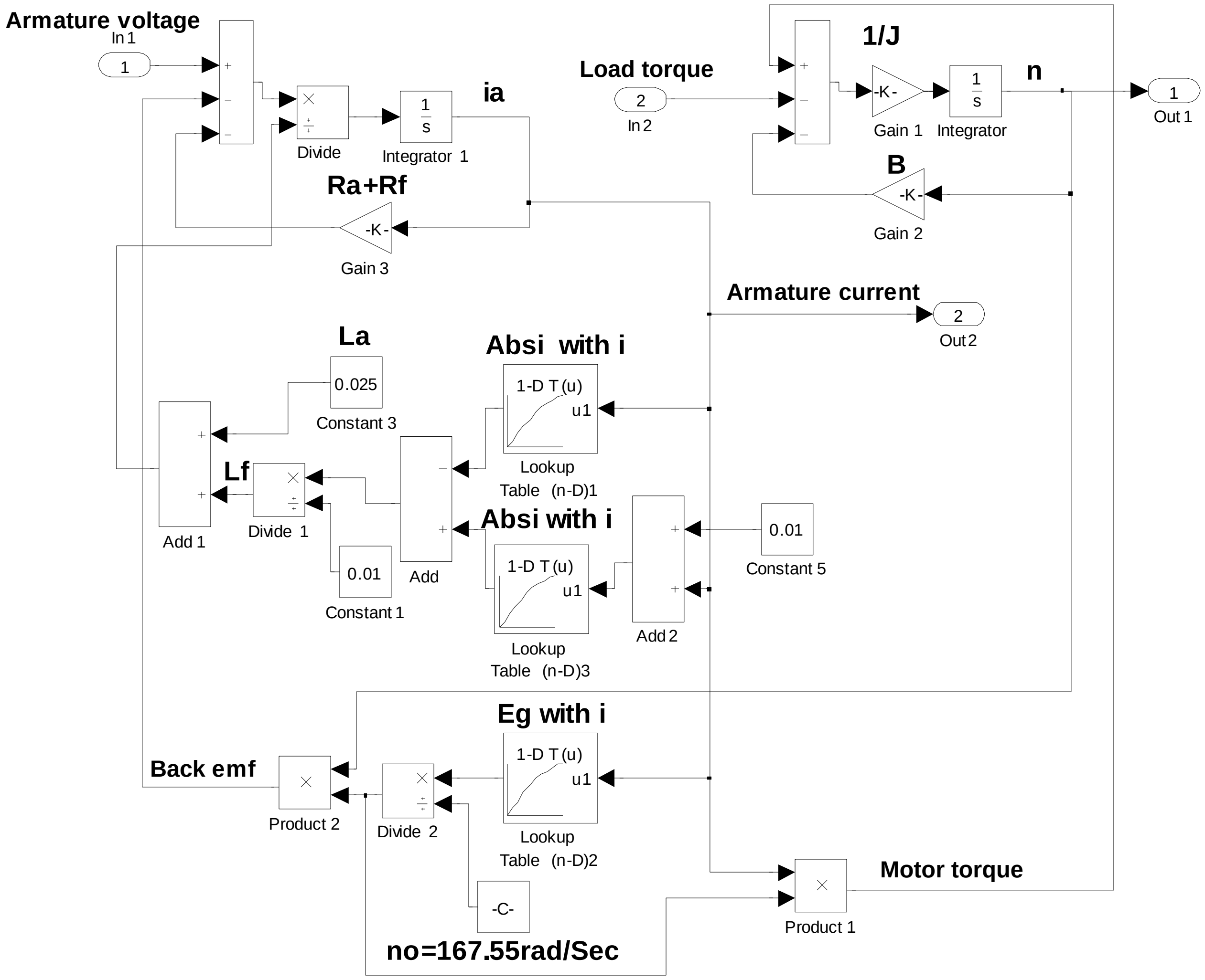


Fig.4 Simulink of dc series motor

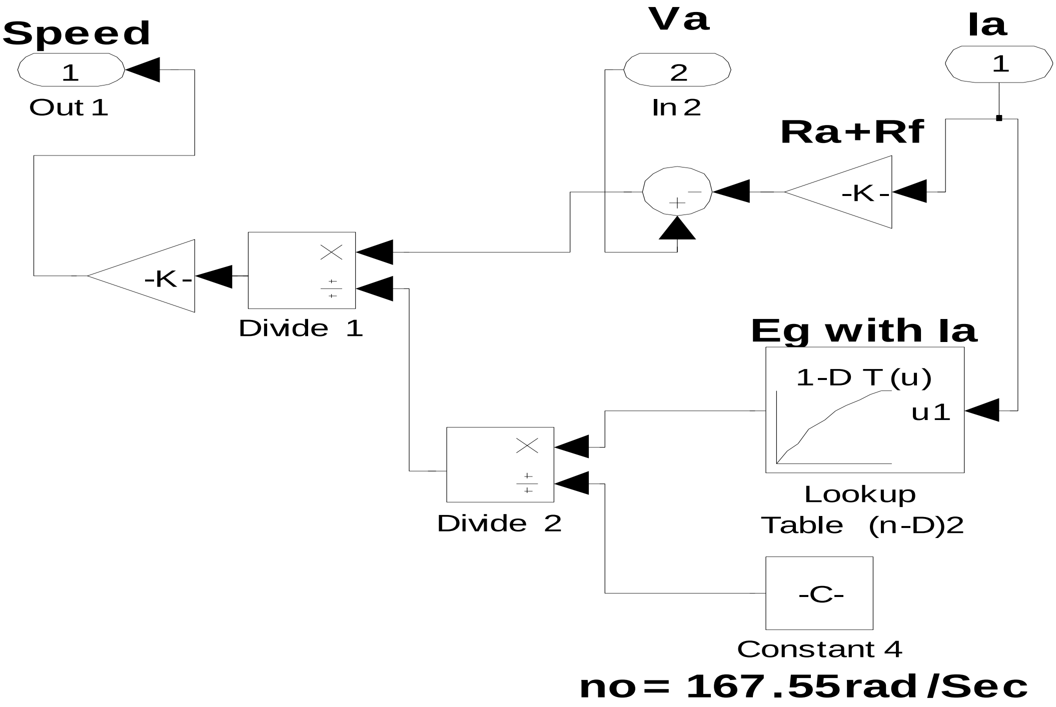


Fig.5 Simulink of speed sensing unit

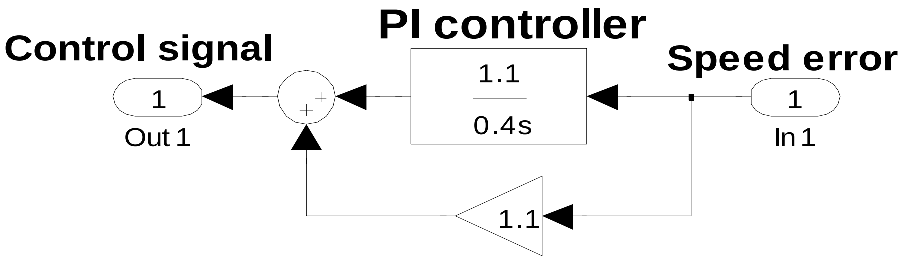


Fig.6 Simulink of PI controller

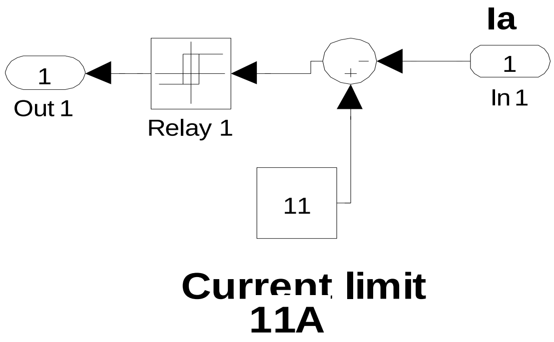


Fig.7 Simulink of current limiter.

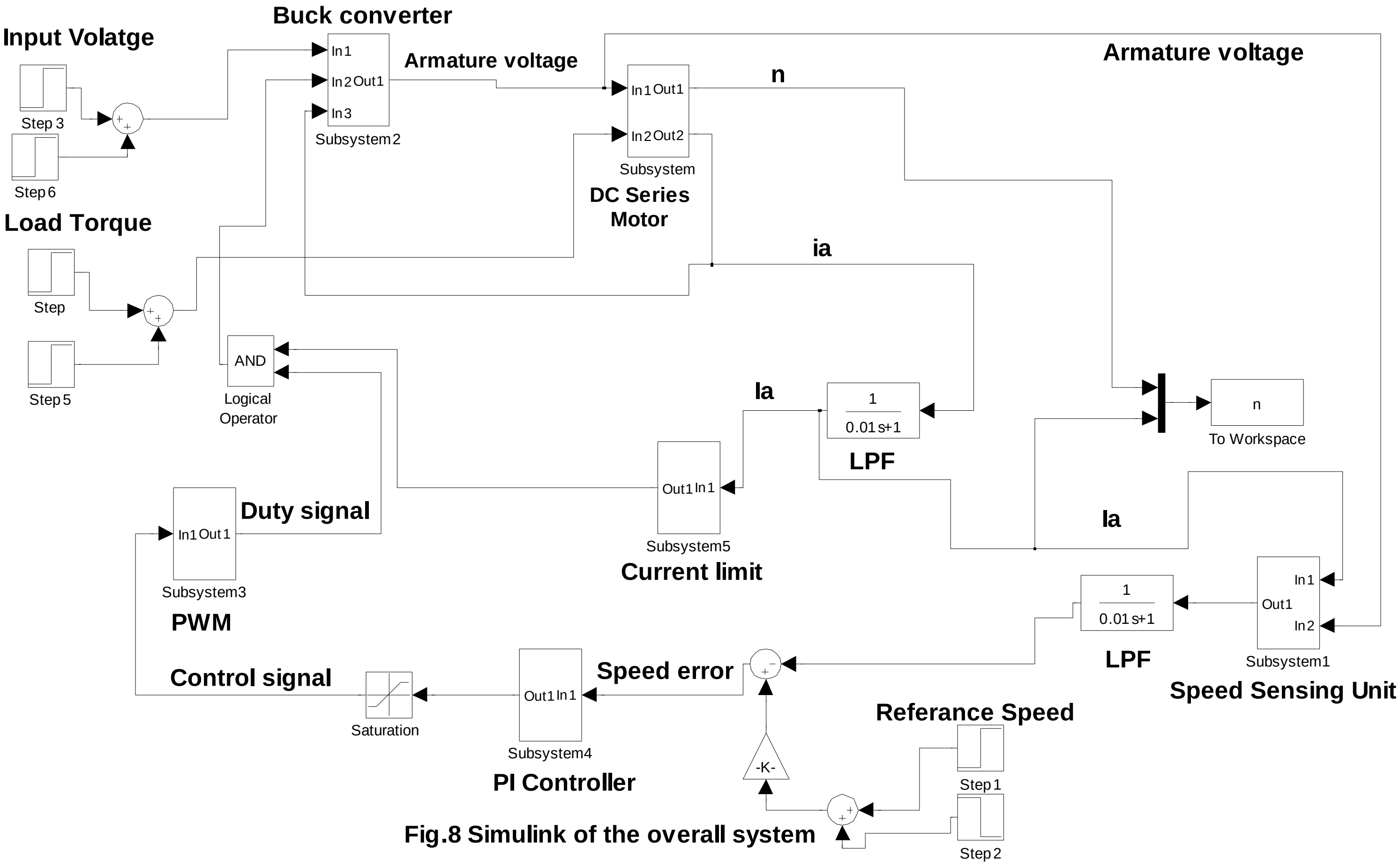
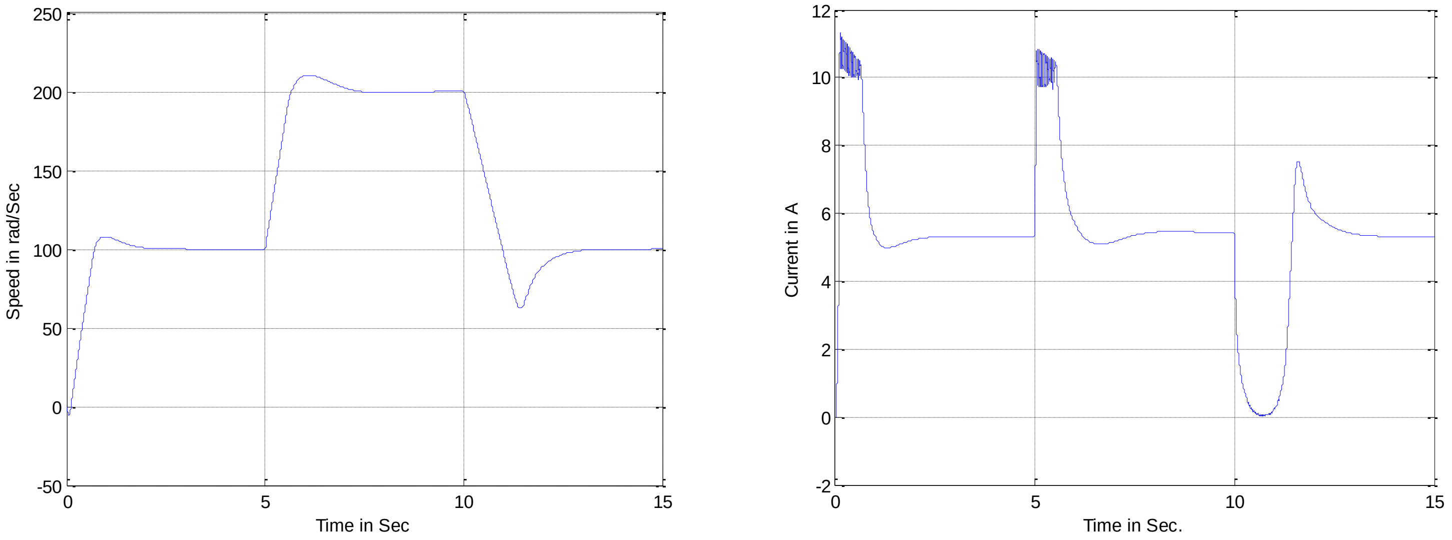
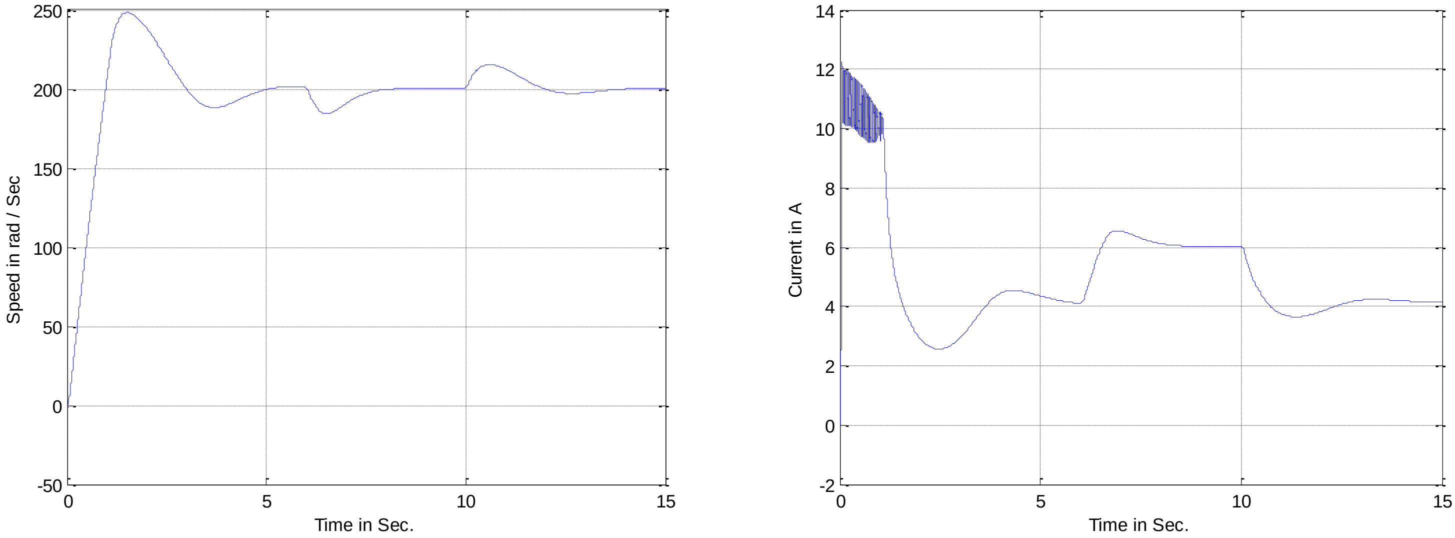


Fig.8 Simulink of the overall system



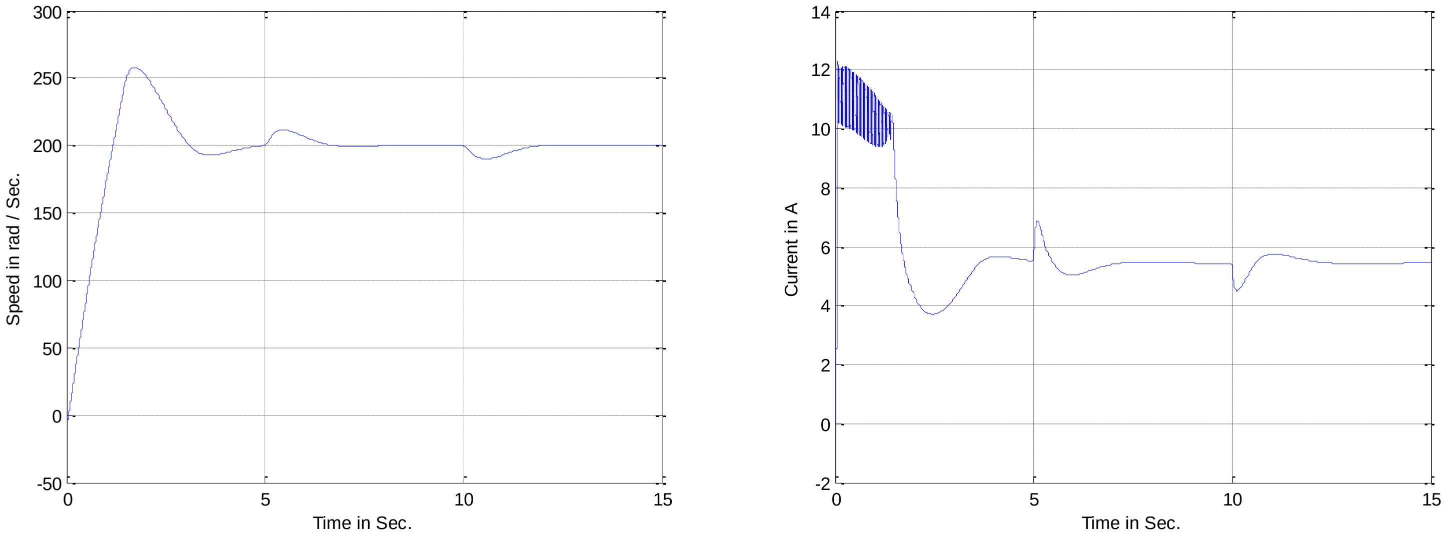
(a)- Speed **(b)- Current**

Fig.9 Transient response due to step increase and decrease in speed



(a)- Speed **(b)- Current**

Fig.10 Transient response due to step increase and decrease in load torque



(a)- Speed **(b)- Current**

Fig.11 Transient response due to step increase and decrease in the input voltage