CONTINUOUS AND DISCONTINUOUS OPERATION OF D.C MOTOR FED FROM THYRISTOR CHOPPER +

Bilal A. Nasir * **Zaki M. Abdullah** ** **Obaid M. Ali** ***

Abstract:

Keywords: D.C. motor, thyristor chopper, Discontinuous operation, speed control.

التشغيل المستمر والمتقطع لمحرك التيار المستمر المغذى من المقطع الثايرستوري

بلال عبدالله ناصر زكي مجيد عبدالله عبيد مجيد علي

المستخلص:

محرك التيار المستمر اله مفضلة في مجال السيطرة على سرعة المحركات الكهربائية, وذلـــك لخصائـــصه المتميزة في التحميل. هدف البحث لتشخيص العوامل الرئيسة التي تتحكم بالتشغيل المستمر والتشغيل المتقطع لهـــذا النوع من المحركات عندما تتغذى من المقطع الثايرستوري. تم اعتماد علاقة رياضية لتحديد العوامل التي تؤدي الى التشغيل المتقطع للمنظومة.التشغيل المتقطع يؤدي الى اهتزاز المحرك خلال الدوران وبالتالي تكون الـــسرعة غيـــر مستقرة, وهذا يجب تجنبه خلال التشغيل. نتائج التحليل الرياضي تم مقارنتها مع نتائج الماتلاب لأثبات صحة الموديل الرياضي.

Introduction:

The thyristor choppers can be classified in terms of operation range as first quadrant (90^o range), two-quadrant (180^o range) and four quadrant (360^o range). When the regenerative process is not required in motor operation, then the first quadrant is suitable for motor speed control.

Adjustable speed D.C. motors may be operated over a wide speed range by controlling the armature voltage [1-2]. The chopper-driver fed from D.C. supply has the following advantages over thyristor-bridge rectifier D.C. motor controlling method [3-4]:

1. High energy efficiency.
2. Flexibility in control.
3. Less ripple in the armature current.
4. Ability to control down to very low speed.

The aim of this work was to indicate the factors governing the discontinuous operation of the D.C. motor fed from thyristor chopper. The discontinuous operation leads to speed variation

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*Assist. Prof /Technical Institute/Kirkuk.
** Lecturer /Technical Institute/Kirkuk
***Assist Lecturer/Technical Institute/Kirkuk

during the operation, which leads to a bad performance of the whole system and it must be avoided the motor operation [].

The basic chopper circuit is called step-down converter because the output voltage cannot exceed the input voltage level. The action of the D.C. chopper is to apply a train of voltage pulses to the armature winding of the D.C. motor [6].

<u>The Basic System Equations:</u>

A schematic diagram of a chopper controlled D.C. motor is shown in figure (1). The idealized motor input voltage and current are given in figure (2). It is assumed that both continuous and discontinuous conduction occurs in the motor operation, which is generally the case because of small armature inductance (L_a), variable duty ratio (γ), variable chopping frequency (F_c) and the motor may be rotate at light loads.

The machine equations during the ON and OFF periods of chopper operation are given as [4]:

During ON-period $\{MT_c<t\leq(M+\gamma)T_c\}$

$$\frac{di_a}{dt}=\frac{1}{L_a}\left(V_s-i_a*R_a-K_m*w\right) \quad (1)$$

During OFF-period $\{(M+\gamma)\,T_c<t\leq(M+1)T_c\}$

$$\frac{di_a}{dt}=\frac{1}{L_a}\left(-i_a*R_a-K_m*w\right) \quad (2)$$

While the motor speed during ON and OFF Periods is given as:

$$\frac{dw}{dt}=\frac{1}{J}\left(K_m*i_a-B*w-T_L\right) \quad (3)$$

The analytical or closed form solution of equations (1) and (2) are given as [3]:

$$i_{a(ON)}=I_d\left[1-e^{-(t-MT_c)/\tau_{ON}}\right]+I_{\min}*e^{-(t-MT_c)/\tau_{ON}} \quad (4)$$

And

$$i_{a(OFF)}=\frac{K_m*w}{R_a}\left[e^{-\{t-(M+\gamma)T_c\}/\tau_{OFF}}-1\right]+I_{\max}*e^{-\{t-(M+\gamma)T_c\}/\tau_{OFF}} \quad (\square)$$

Where:

- R_a=armature resistance (Ω).
- R_{sm}=smoothing inductor-resistance (Ω).
- L_a=armature inductance (H).
- L_{sm}= smoothing inductor-inductance (H).
- M=Dummy variable=1, 2, 3, ------.
- γ=duty ratio= T_{ON}/T_c.
- T_{ON}= ON-period in every cycle (second).
- T_c=period of one chopping cycle (second).
- B=torque constant [(N.M)/ (rad. /sec.)].
- K_m=motor constant (N.m/A).
- w=motor speed (radian/second).
- T_L=load torque (N.m).
- V_s=the net motor supply voltage across the chopper (V).
- V_d=the average rectifier output voltage (V).

- I_d=the average rectifier output current (A).
- i_a=instantaneous armature current (A).
- $\tau_{ON}=(L_a+L_{sm})/R_a$ motor time constant during ON-period.
- $\tau_{OFF}=(L_a/R_a)$ motor time constant during OFF-period.
- I_{min}=initial motor current during ON-period.
- I_{max}=initial motor current during OFF-period.

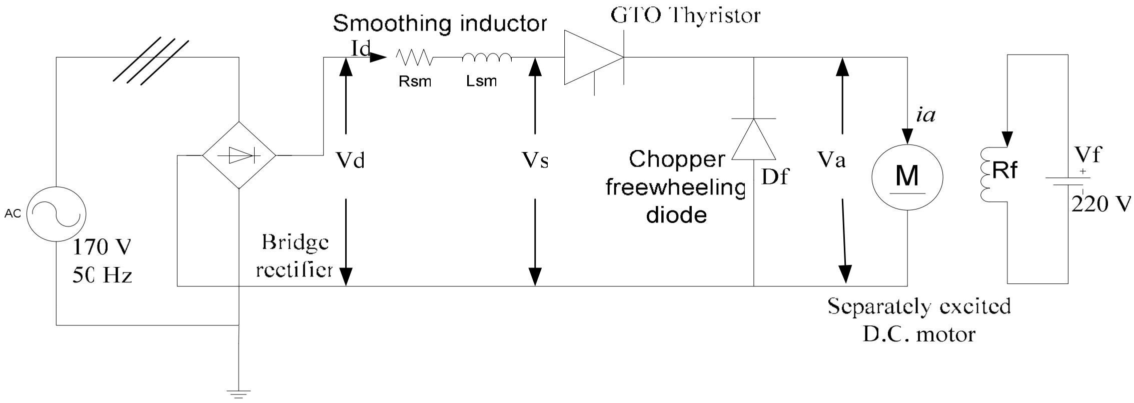
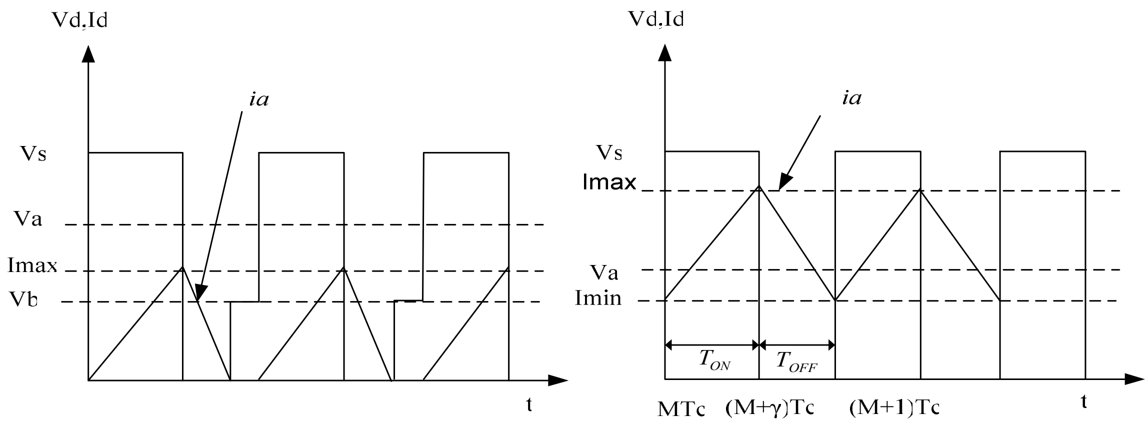


Figure (1) Schematic Diagram of the system



(a) Discontinuous conduction

(b) Continuous conduction

Figure (2) The ideal motor input voltage and current for continuous and discontinuous operation

Continuous Conduction Case:

In the steady-state, from figure (2.b) the following equations must be satisfied:

$$i_a(ON)\Big|_{t=MT_c} = i_a(OFF)\Big|_{t=(M+1)T_c} \quad \text{.....} \quad (6)$$

$$i_a(ON)\Big|_{t=(M+\gamma)T_c} = i_a(OFF)\Big|_{t=(M+\gamma)T_c} \quad \text{.....} \quad (7)$$

Since (γ) and (T_c) are known from the chopper operation, then substitute equations (6) and (7) into equation (4) and (□) to obtain I_{min} and I_{max} as:

$$I_{\min} = \frac{I_d(1-\lambda)\mu - (K_m * w / R_a)(1-\mu)}{(1-\mu * \lambda)} \quad \text{......} (8)$$

And:

$$I_{\max} = \frac{I_d(1-\lambda) - (K_m * w / R_a)(1-\mu)\lambda}{(1-\mu * \lambda)} \quad \text{......} (9)$$

Where:

$$\lambda = e^{-(\gamma T_c / \tau_{ON})} \quad \text{......} (10)$$

$$\mu = e^{-\{(1-\gamma)T_c / \tau_{OFF}\}} \quad \text{......} (11)$$

The average motor current (I_a) can be calculated as:

$$I_a = \frac{1}{T_c}\left[\int_{MT_c}^{(M+\gamma)T_c} i_{a(ON)}dt + \int_{(M+\gamma)T_c}^{(M+1)T_c} i_{a(OFF)}dt\right]$$

$$I_a = \frac{1}{T_c}\left[(I_{\min} - I_d)(1-\lambda)\tau_{ON} + (I_{\max} + \frac{K_m * w}{R_a})(1-\mu)\tau_{OFF}\right] + \gamma I_d - (1-\gamma)(K_m * w)/R_a \text{..} (12)$$

The average motor voltage (V_a) is:

$$V_a = I_a R_a + K_m w \quad \text{......} (13)$$

The average motor torque (T_m) is:

$$T_m = K_m I_a \quad \text{......} (14)$$

The mechanical power developed by the motor (P_m) is:

$$P_m = K_m w I_a \quad \text{......} (1\square)$$

Discontinuous Conduction:

This case of operation occurs when the minimum motor current (I_{min}) cease to zero in every cycle before the gate pulse of the thyristor chopper reach to the chopper to turn it on in the next operation cycle. The condition or criterion of the discontinuous conduction can be derived from equation (8), when I_{min} is substituted be zero, as:

$$\frac{K_m * w}{R_a} \geq \frac{(V_d - K * w)}{(R_a + R_{sm})}\frac{(1-\lambda)\mu}{(1-\lambda)} \quad \text{......} (16)$$

From this criterion, the discontinuous conduction depends on the duty ratio (γ), chopping frequency (F_c) and the motor speed (w).

The motor speed (w) can be calculated in closed-form by solving equation (3) as:

$$w = \frac{(K_m * i_a - T_L)}{B}\left(1 - e^{-\frac{B}{J}t}\right) + w_o e^{-\frac{B}{J}t} \quad \text{......} (17)$$

Where w_o is the initial speed of the motor. When (i_a) becomes zero in case of discontinuous conduction the motor speed (w) become negative, while it is positive when (i_a) greater than zero. This means that the speed vibrates during the discontinuous conduction

Results:

The equations developed in the previous section have been used to determine the steady-state and transient behavior of a separately excited D.C. motor whose particulars are given in the appendix.

The validity of the equations and effectiveness of the method are verified by comparing the results obtained by the present equations with those obtained using MATLAB Simulink analysis [7] as showing in figure (3).

1- The MATLAB/Simulink results for starting-up and steady-state conditions of D.C. motor were shown in figures (4-9). Figure (4) shows the starting-up condition without load at (□0 Hz) chopping frequency and (0.□) duty ratio, while figure (□) shows the steady-state condition at the same chopper parameters. The discontinuity in motor operation is very clear due to low duty ratio, low chopping frequency and without load. Figure (6) shows the steady-state motor performance at high duty ratio (0.99) and without load. The discontinuity operation is disappear at high duty ratio although the motor running without load. Figure (7) shows the performance at high chopping frequency (200 Hz) and the operation is continuous due to high chopping frequency and high duty ratio. Figure (8) shows the motor operation at rated load (□ N.M.). The motor operation is continuous at rated load, high chopping frequency and high duty ratio. Figure (9) shows the continuous operation of the motor at rated load although the chopping frequency is low.

2- The numerical results using Runge-Kutta technique to solve the system differential equations, for starting-up and steady-state conditions of the motor performance were shown in figures (10-1□). These results were compared with those corresponding results which are obtained from MATLAB/Simulink model, to prove the validity of the analysis. Figure (10) shows the starting-up condition without load at the same parameters given in figure (4). The main difference between the two results that spikes appear in the armature voltage in the numerical result while these spikes are not appear in the MATLAB results due to the snubber circuit is considered in the Simulink model, while the thyristor chopper is replaced by an ideal switch in the numerical model. Figures (11-1□) show the motor performance at the same parameters which are corresponding to figures (□-9), for comparison purposes. From the comparison with those of MATLAB results, there is a close agreement between the two results.

The possibility of discontinuous conduction is reduced with increasing (γ) and chopping frequency (F_c) and load, but it is increased with reducing the motor duty ratio at light load as shown in table (1).

Table (1) effect of chopper parameters and load condition on the motor parameter

Chopper Parameters		Load condition	Motor performance		
Chopping frequency F_c(Hz)	Duty ratio γ	T_L (N.m)	Armature current (A)	Armature voltage (V)	Speed (rad./sec.)
□0	0.□	0.0	discontinuous	discontinuous	oscillate
□0	0.99	0.0	continuous	discontinuous	oscillate
□0	0.99	□0	continuous	discontinuous	constant
200	0.99	0.0	continuous	discontinuous	oscillate
200	0.99	□0	continuous	continuous	constant

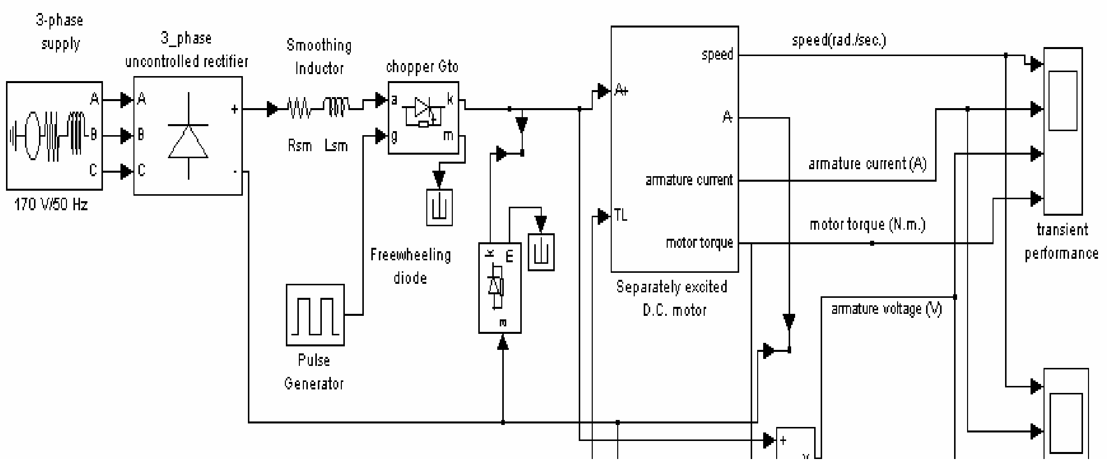


Figure (3) complete system block diagram

Conclusion:

A closed-form solution for the motor performance in both continuous and discontinuous conduction operation has been developed analytically. The equations can also be used to obtain the transient behavior of the system. The duty ratio, the chopping frequency and the motor speed are the main factors governing the discontinuous operation of the motor system. From the results, the discontinuous operation of D.C. motor can be occurred at low duty ratio, low chopping frequency and light load.

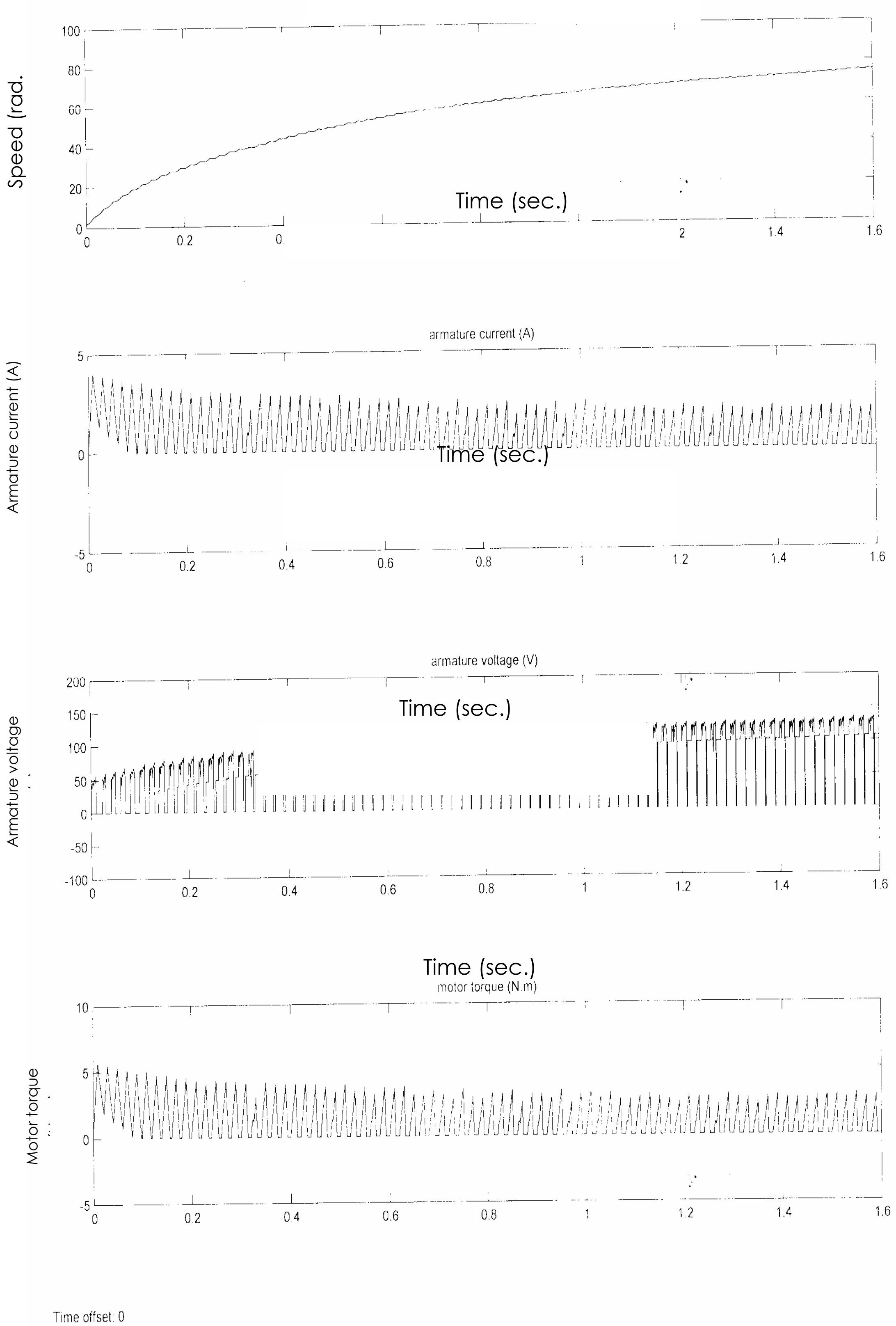


Figure (4) MATLAB results for starting-up condition (F_c=50 Hz, T_L=0, γ=0.5)

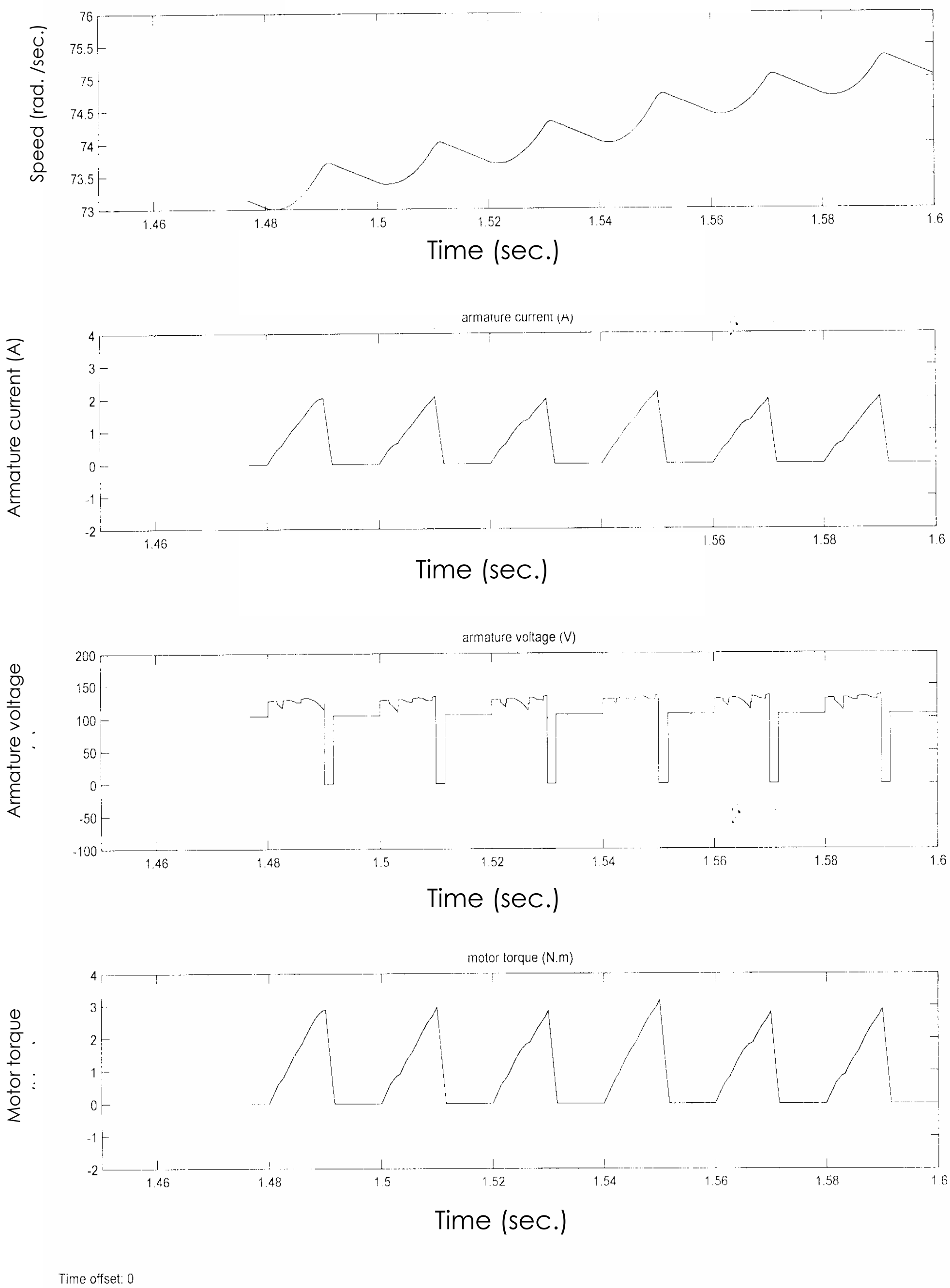


Figure (5) MATLAB results for steady-state condition (F_c=50 Hz, T_L=0 N.m., γ=0.5)

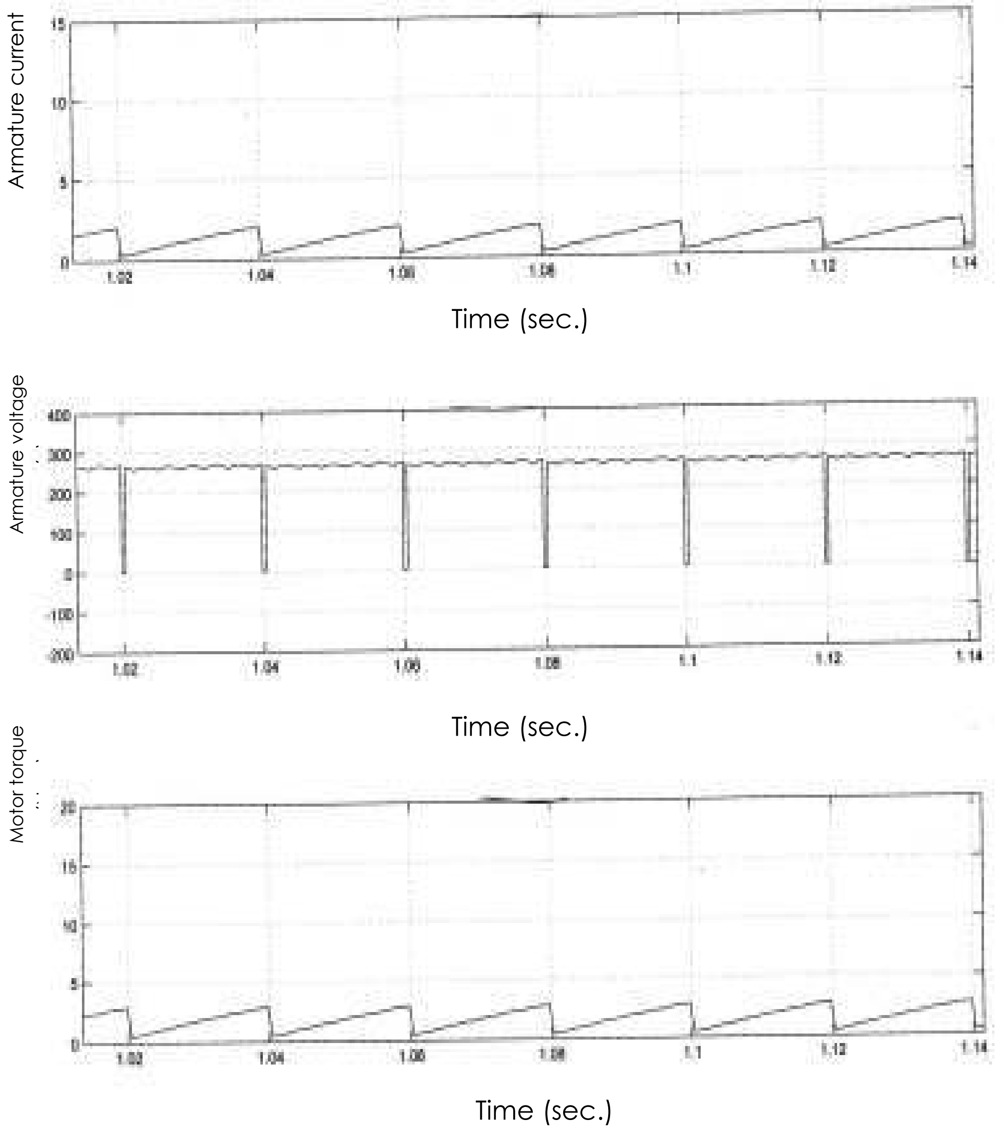


Figure (6) MATLAB results for steady-state condition (Fc=50 Hz, T_L= 0 N. m., γ=0.99)

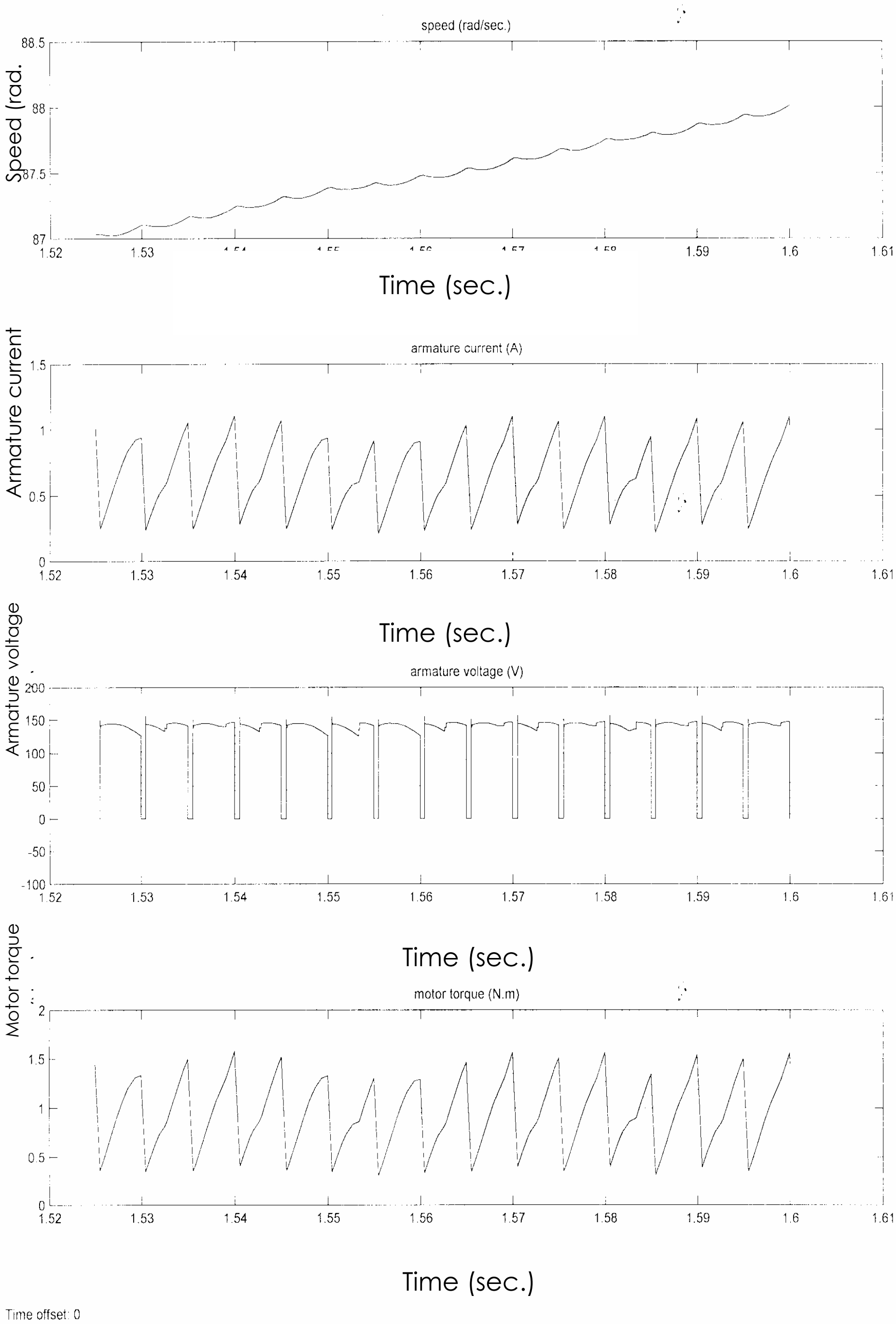


Figure (7) MATLAB results for steady-state condition (F_c=200 Hz, T_L=0 N.m., γ=0.99)

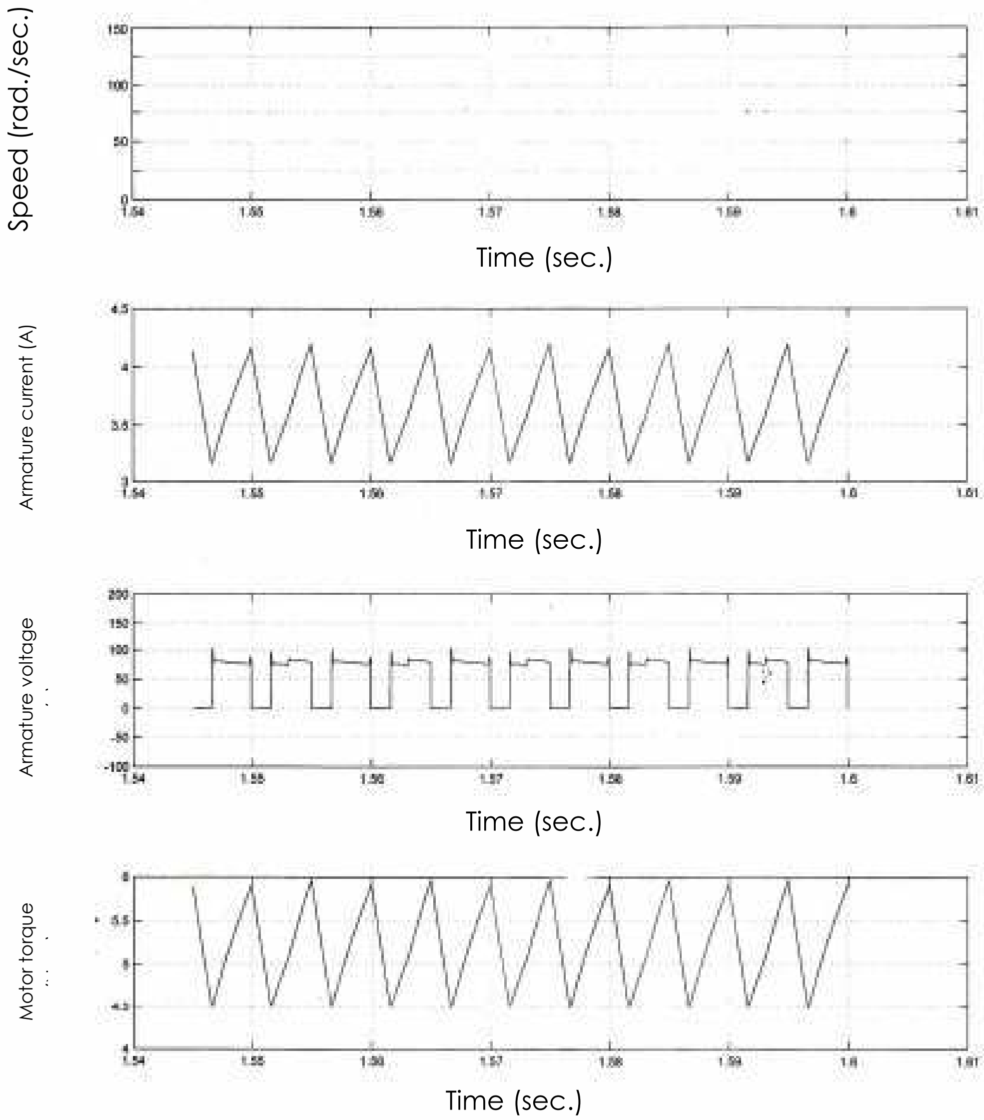


Figure (8) MATLAB results for steady-state condition (Fc=200 Hz, T_L= 5.0 N. m., γ=0.99)

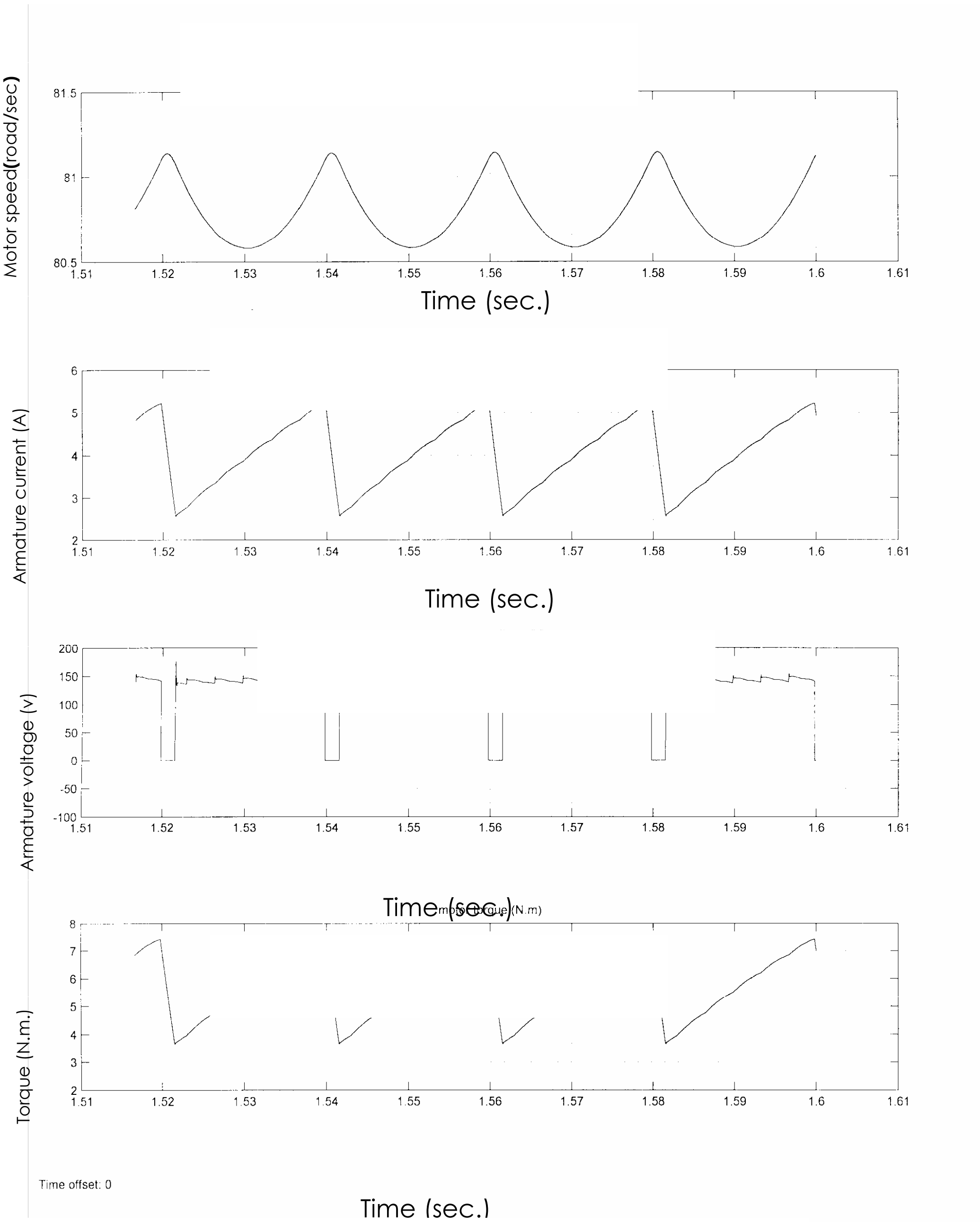


Figure (9) MATLAB results for steady-state condition (F_c=50 Hz, T_L=5.0 N.m., γ=0.99)

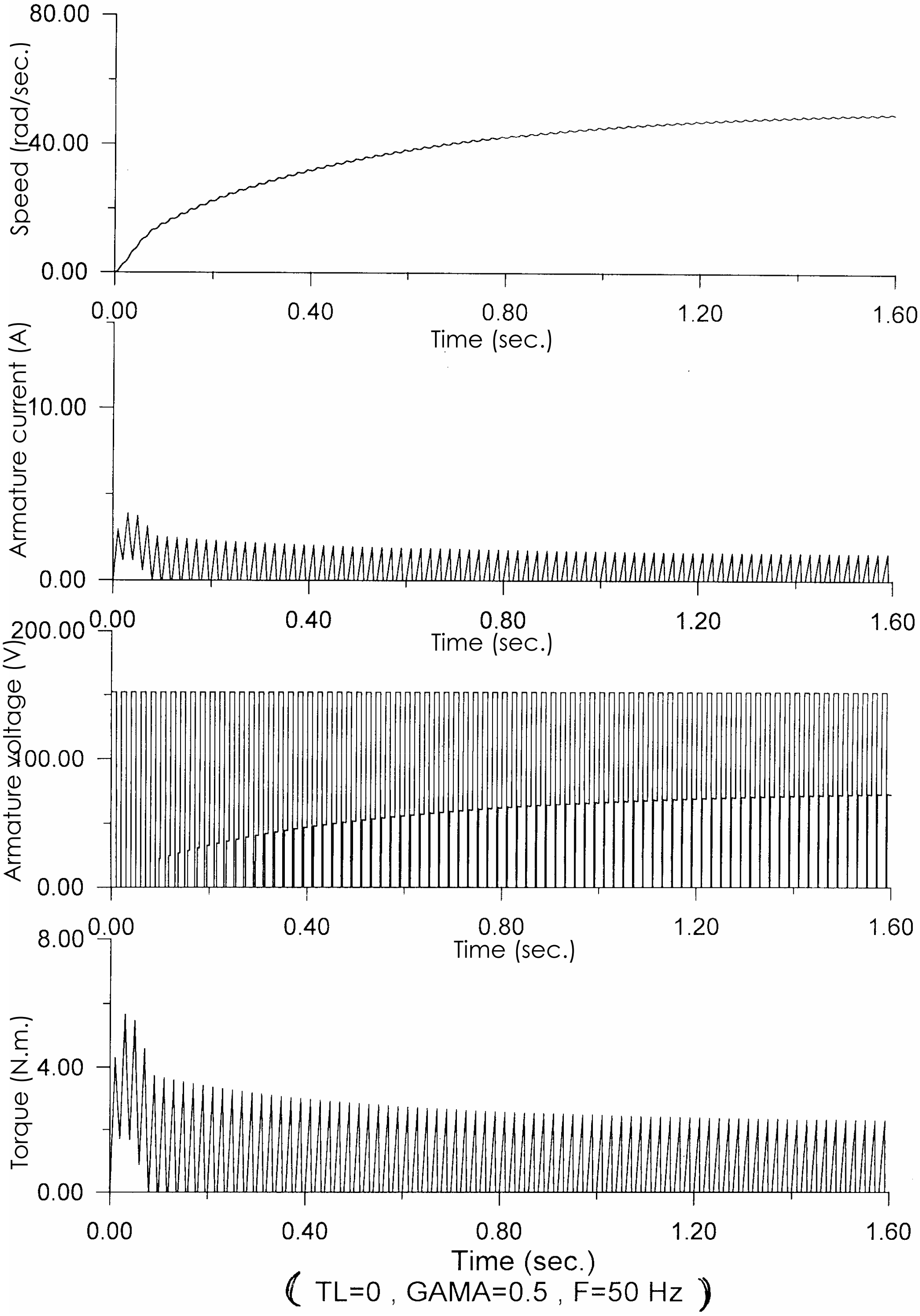


Figure (10) Numerical results for starting-up condition (F_c=50 Hz, T_L=0 N.m., γ=0.5)

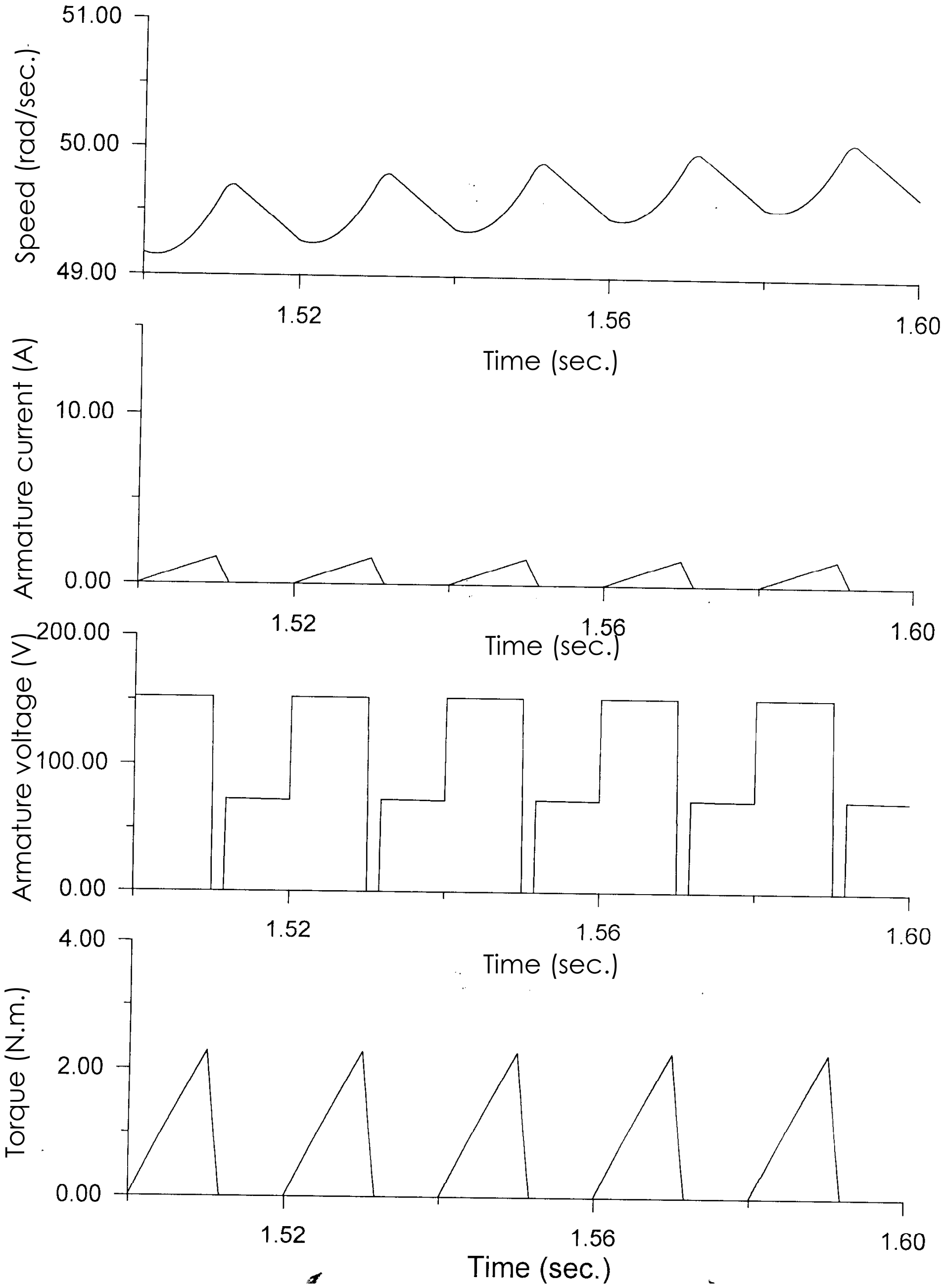


Figure (11) Numerical results for steady-state condition (F_c=50 Hz, T_L=0 N.m., γ=0.5)

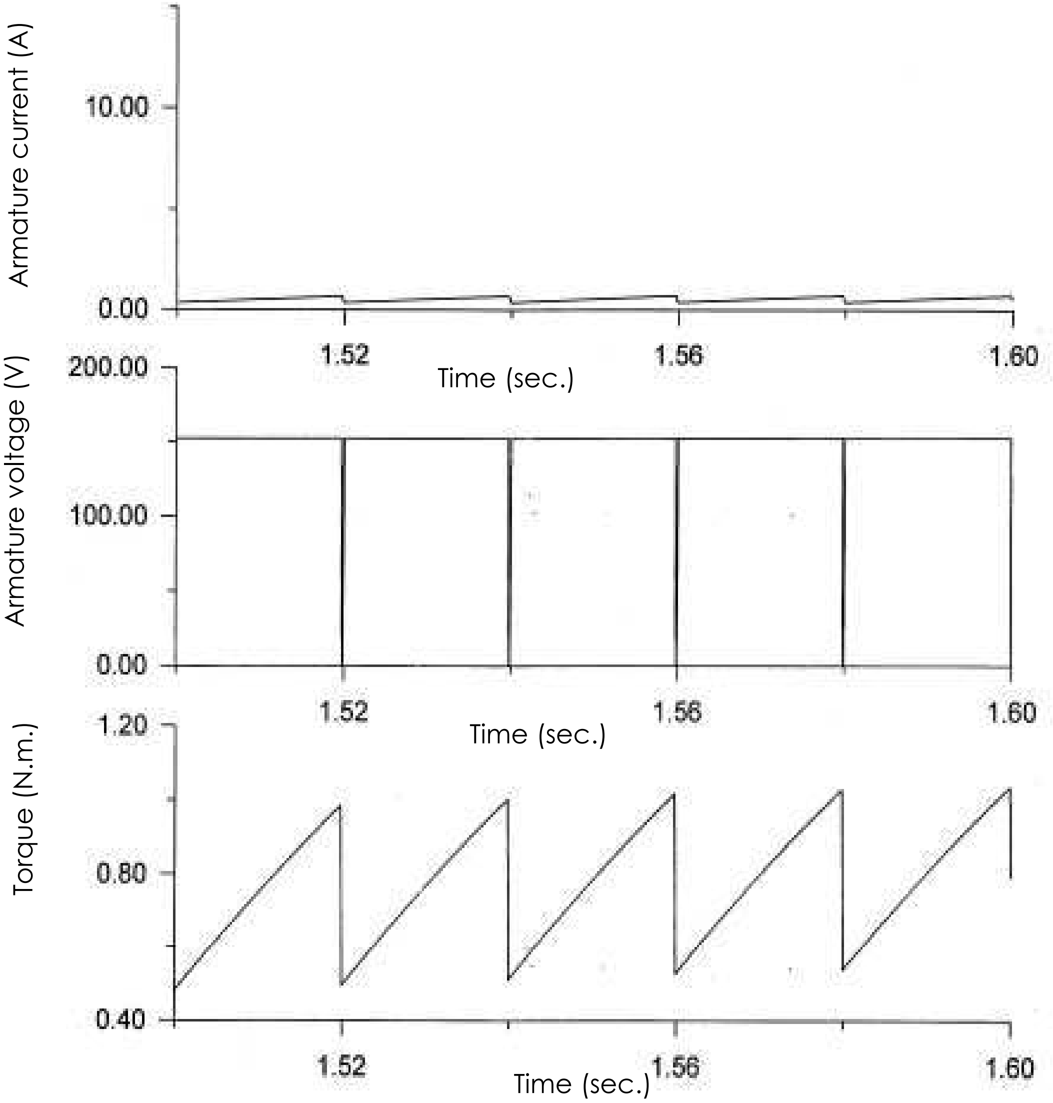


Figure (12) Numerical results for steady-state condition (F_c=50 Hz, T_L=0 N.m., γ=0.99)

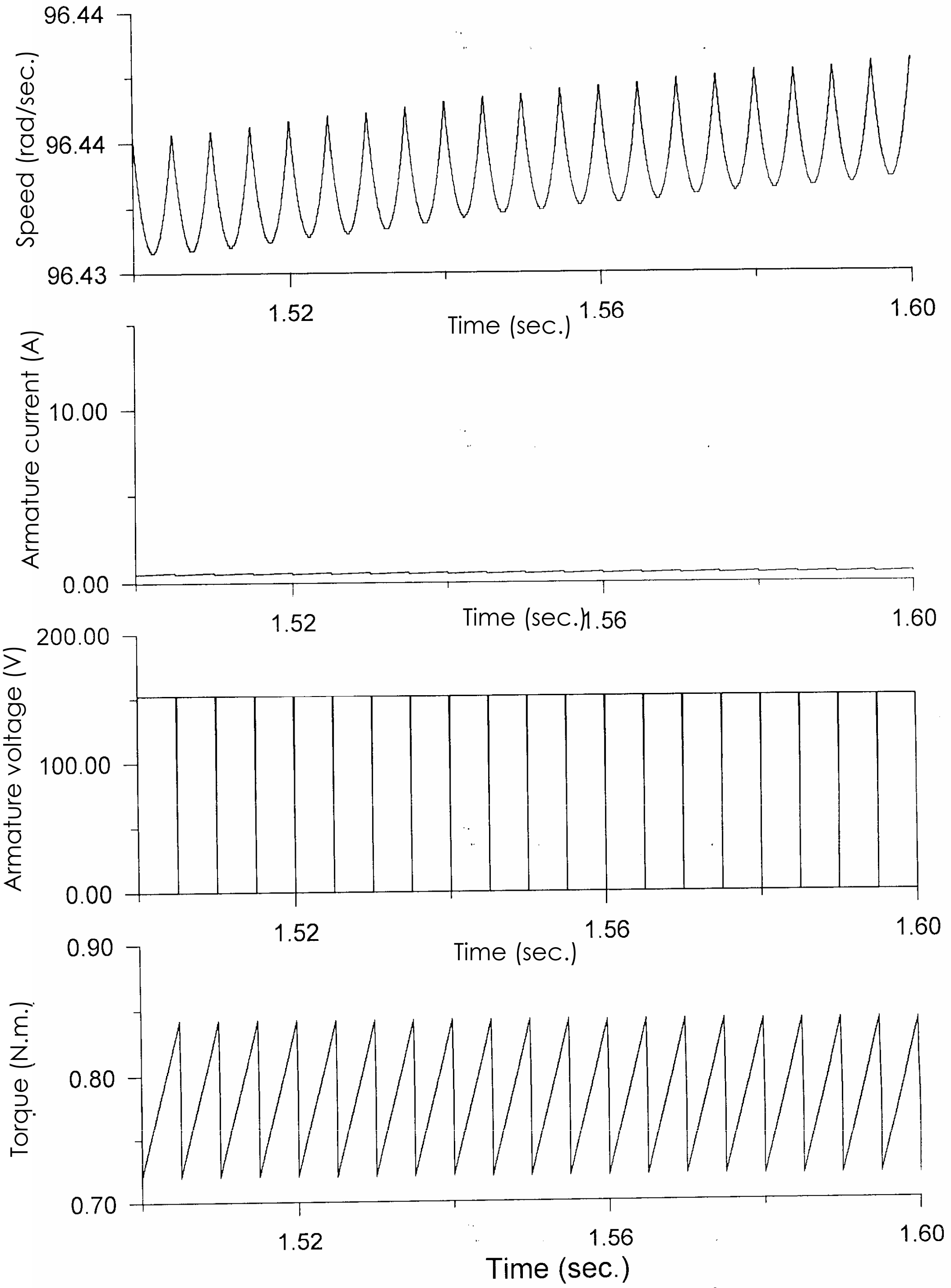


Figure (13) Numerical results for steady-state condition (F_c=200 Hz, T_L=0 N.m., γ=0.99)

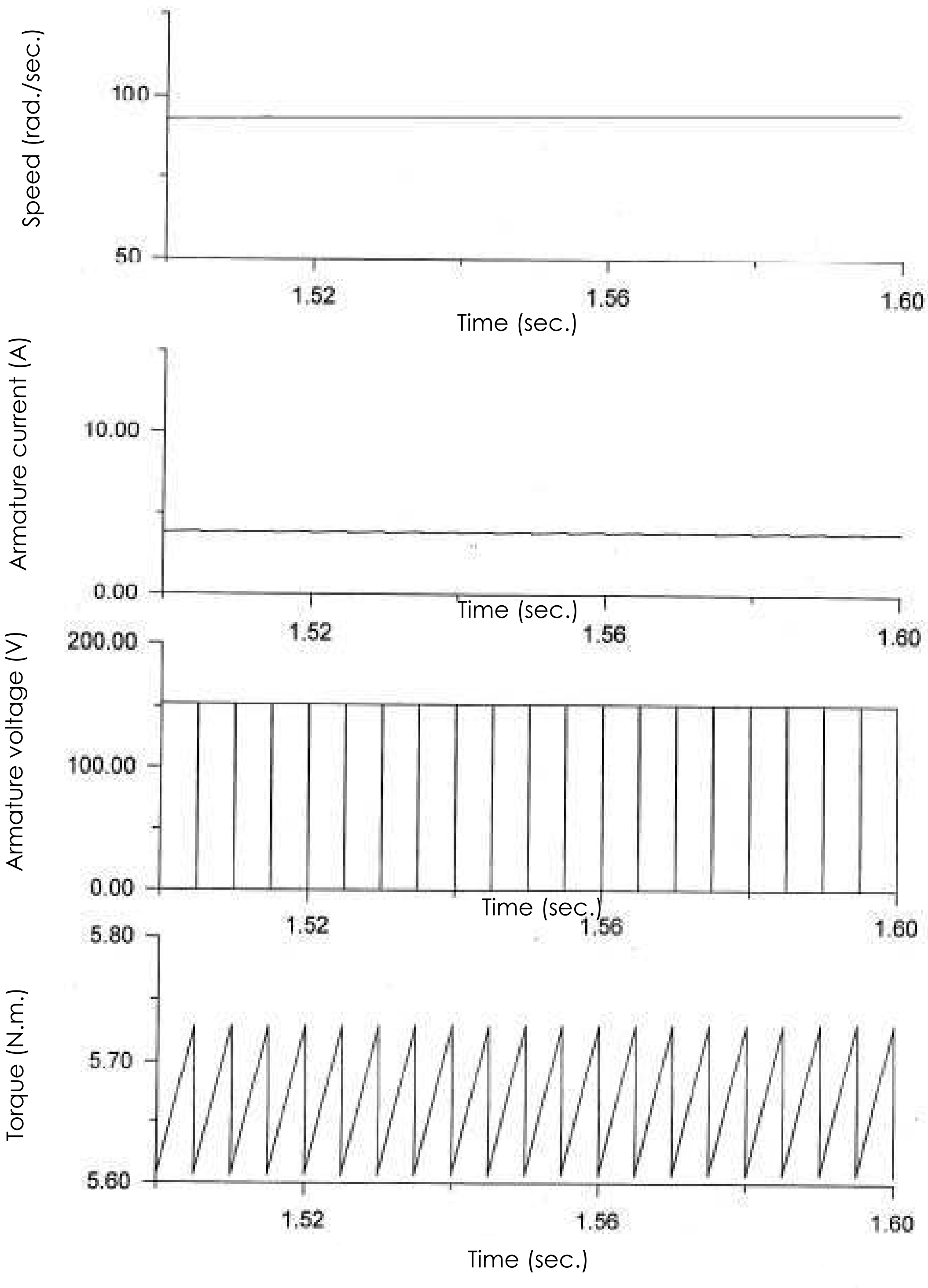


Figure (14) Numerical results for steady-state condition (F_c=200 Hz, T_L=5 N.m., γ=0.99)

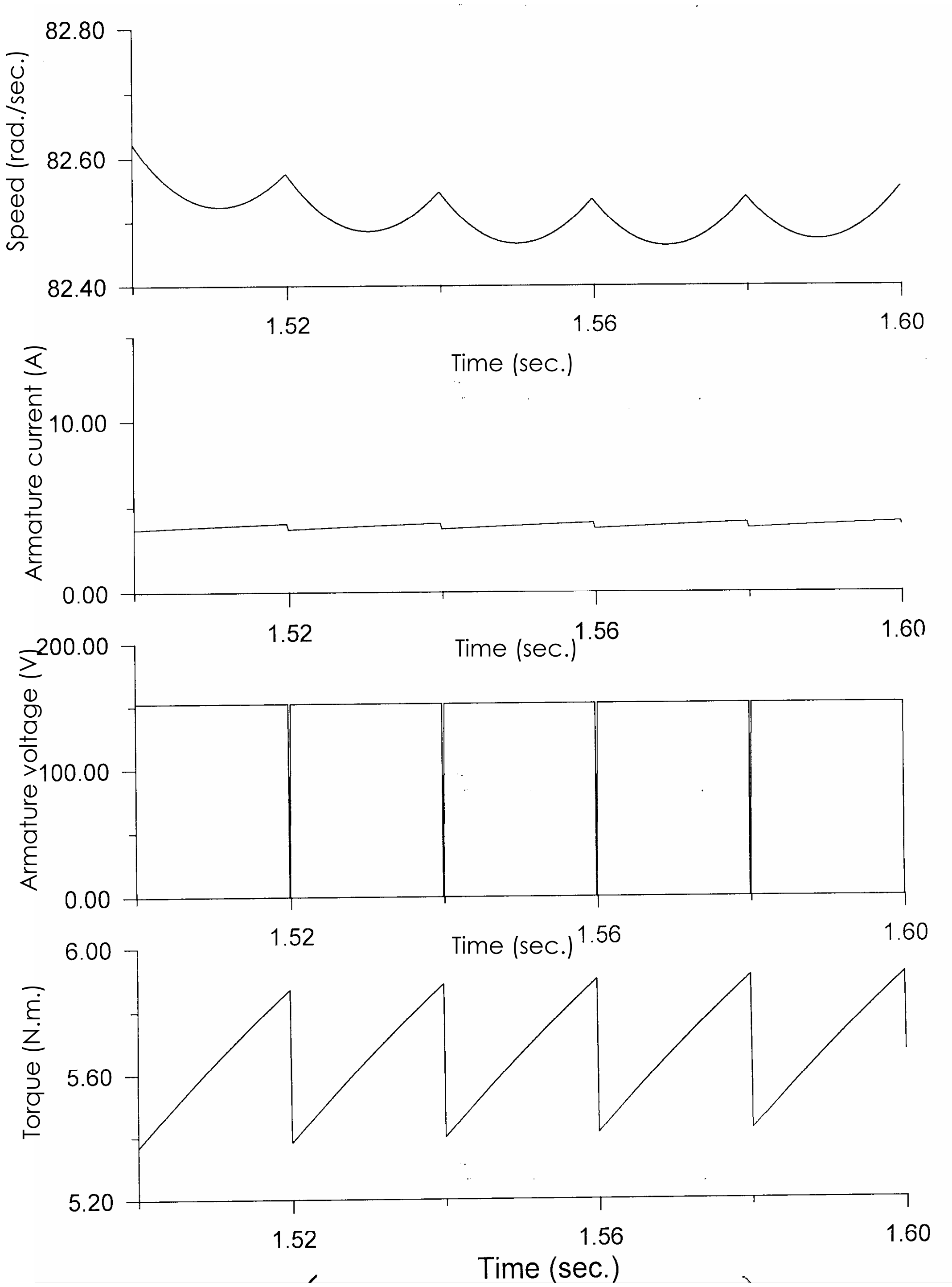


Figure (15) Numerical results for steady-state condition (F_c=50 Hz, T_L=5.0 N.m., γ=0.99)

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Appendix:

A) D.C. Motor Specifications
The D.C. Machine has the following parameters:
Armature input voltage = 220V. Motor rated power =1.2 KW. Field voltage =220 V.
Field resistance =370 Ω. Field inductance =6.7 H. Armature resistance =4 Ω.
Armature inductance=0.086 H. Moment of inertia=0.017 $Kg.m^2$.
Friction torque constant =0.0081 (N.m)/ (rad. /sec.).
B) The uncontrolled, 3-phase bridge, diode rectifier has the following properties:
Forward resistance =0.2 Ω. Forward voltage drop=0.6 V. Reverse voltage =400 V.
Snubber resistance =3*10□Ω. Snubber capacitance $=0.01*10^{-6}$ Farad.
C) Thyristor chopper specifications:
Forward resistance =0.001Ω. Forward voltage drop =0.8 V. Snubber resistance $= 10^3$ Ω.
Snubber capacitance $=4.7 *10^{-6}$ F. Turn-off time $=100*10^{-6}$ second.
D) Smoothing inductor specifications:
Smoothing resistance = 2Ω. Smoothing inductance=0.3 H.