The speed control system of BLDC using PID controller with PWM modulation technique

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A R T I C L E I N F O

A B S T R A C T

Brushless DC motors (BLDC) are widely applied to various applications, and controlling the speed of BLDC plays an important role in improving the quality of motion applications. So this paper presents the way to control the speed of BLDC motor using Proportional Integral (PI) Controller with the PWM technique. The output values of the (PI) controller are fed to the power switches for adjusting the duty cycle of high frequency control signal, so adjusting the motor speed. Finally, the simulation have been done using software MATLAB/SIMULINK, the simulation results show that the proposed method is simple but still effective.

1. Introduction

There are two main types of DC motors. The first one is the conventional DC motor where the flux is produced by the current through the field coil of the stationary pole structure. The disadvantage of this motor is brush and commutator segment which create sparks when motor rotating. The second type is the brushless DC motor where the permanent magnet provides the necessary air gap flux instead of the wire-wound field poles. Unlike the conventional DC motor, the commutation of a BLDC motor is controlled electronically. So BLDC motors need lower maintenance due to the elimination of the mechanical commutator and they have a high-power density which makes them ideal for high torque-to weight ratio applications (Miller, 1989).

BLDC has the inherent advantages such as high torque, high speed, simple structure, easy maintenance and small size, etc. (Parsa and Toliyat, 2005; Kan et al., 2011). So BLDC motors are becoming more and more popular for low powered vehicles such as mopeds, power assisted bicycles and mobility scooters. BLDC motors are also used in industries such as appliances, automotive, consumer, medical, industrial automation equipment and instrumentation (Bi et al., 2000). Controlling the speed of these motors is very necessary to improve the quality of all applications. So this paper presents the way to control the speed of BLDC motor with a closed-loop control using PI controller with the PWM technique.

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2. Dynamics of BLDC motor

The mathematical model of BLDC is essential to the system for designing the controllers in practical applications (Ogasawara and Akagi, 1991). Voltage equations of BLDC motor are given by (Madani et al., 2002; Kim and Ehsani, 2003):

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + p\begin{bmatrix} L_a & L_{ba} & L_{ca} \\ L_{ba} & L_a & L_{cb} \\ L_{ca} & L_{cb} & L_c \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix}$$ (1)

Where:

R is the resistance of the stator windings.

$L_a = L_b = L_c = L$, with L is the inductance of the stator winding.

$L_{ba} = L_{ab} = L_{ca} = L_{ac} = L_{bc} = L_{cb} = M$, with M is the mutual inductance.

i_a, i_b, i_c are the a, b and c phase currents.

e_a, e_b and e_c are the back emf which is a function of rotor angle which is given by:

$e = K_e.\omega_r$, with K_e is the constant, ω_r is the angular velocity of the rotor.

Because $i_a + i_b + i_c = 0$ so $M.i_b + M.i_c = - M.i_a$, so the voltage equations of BLDC motor are as follows:

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix}p\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix}$$ (2)

Mathematical model of BLDC can be represented by the following equations:

$$P\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} 1/(L-M) & 0 & 0 \\ 0 & 1/(L-M) & 0 \\ 0 & 0 & 1/(L-M) \end{bmatrix}\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} - \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} - \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix}$$ (3)

Electromagnetic torque depends on the back emf, rotor current can expressed as:

$$T_e = (e_a i_a + e_b i_b + e_c i_c) / \omega_r \qquad (4)$$

The equation of motion is as follows:

$$p\omega_r = (T_e - T_L - B\omega_r) / J \qquad (5)$$

Where:

T_L is the shaft mechanical torque.

B is the combined viscous friction of rotor and load.

J is the combined inertia of rotor and load.

3. The model of the system

The power system circuit of three phase stator windings with star connection of BLDC motor is presented in Fig. 1 (Tashakori and Ektesabi, 2012). Six power switches control the power to feed three phase stators of BLDC from 500V DC source.
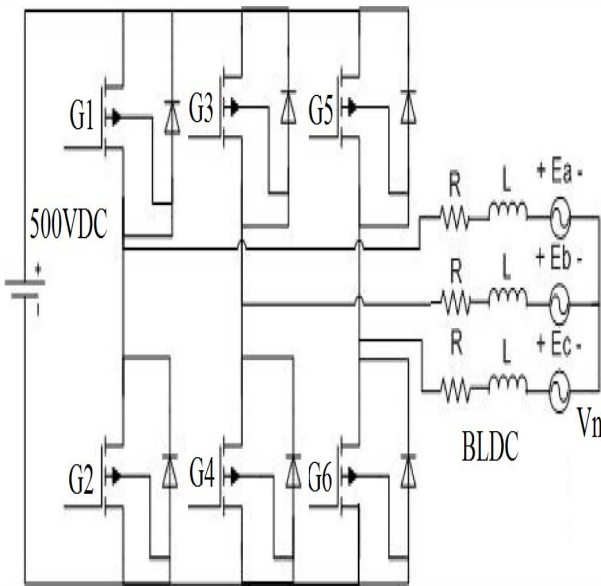

Fig. 1: The power system circuit

In Fig. 1, *Va, Vb, Vc* are referred to the terminal voltages of BLDC stators, *Vn* is the neutral point voltage and 500 VDC is the DC bus voltage fed to the inverter. G1- G6 are power switches. *R* is the resistance of stator winding and *L* is the inductance of stator winding. With assuming that three-phase are the same, the magnetic circuit saturation and losses in motor are ignored.

Based on the power system circuit, the model of the control system is built on Simulink of Matlab, which is presented in Fig. 2.

BLDC motor has three Hall effect sensors embedded into the stator of the motor to know the rotor position. Each Hall Effect sensor is on for 180 electrical degrees and off for next 180 electrical degrees according to rotor position. The output of the three Hall effect sensors are fed to the decoder block to generate the emf signals. The emf signals are *and logic* with the output signals of the pulse width modulation block, then these signal are fed to the gate block for controlling the mosfets in the inverter block. The mosfets (power switches) control the power of the DC source through the BLDC.
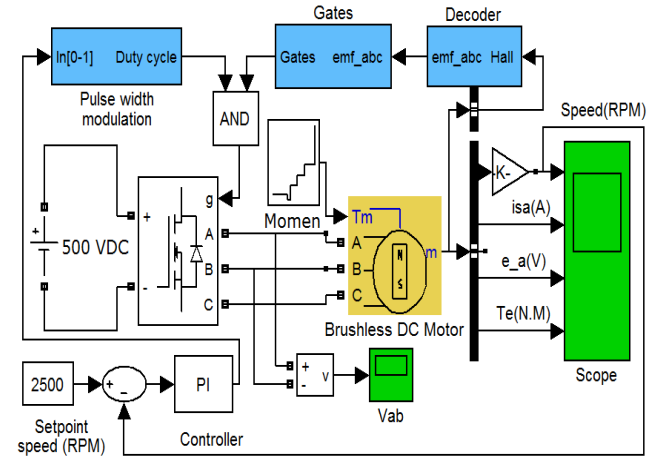

Fig. 2: The model of the BLDC system control

In the decoder block, the Hall effect signal provides a logical indication of the back EMF positioning. This signal is very useful to control directly the power switches. There is a change of state at each zero crossing of the phase to phase voltage. These signals must be decoded before being applied to the switches.

Based on the combination of these three Hall sensor signals, the exact sequence of commutation can be determined (Bi et al., 2000; Kang et al., 2001). The details of the decoder block are presented in Fig. 3 (Grenier et al., 1997), the inputs of the decoder block are the Hall signal and the output of the decoder block is the EMF signals. The true table of the relation between the input signals and output signals is presented in Fig. 4.
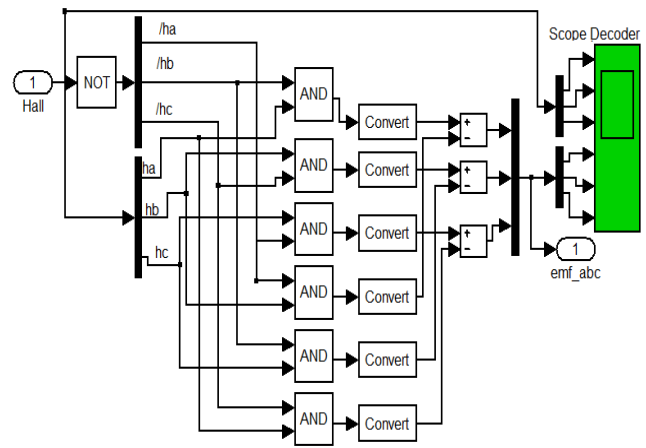

Fig. 3: The decoder block

ha	hb	hc || emf_a	emf_b	emf_c
0	0	0	0	0	0
0	0	1	0	-1	+1
0	1	0	-1	+1	0
0	1	1	-1	0	+1
1	0	0	+1	0	-1
1	0	1	+1	-1	0
1	1	0	0	+1	-1
1	1	1	0	0	0

Fig. 4: The true table of the decoder block

Running the decoder block, the signals of this block are as Fig. 5.
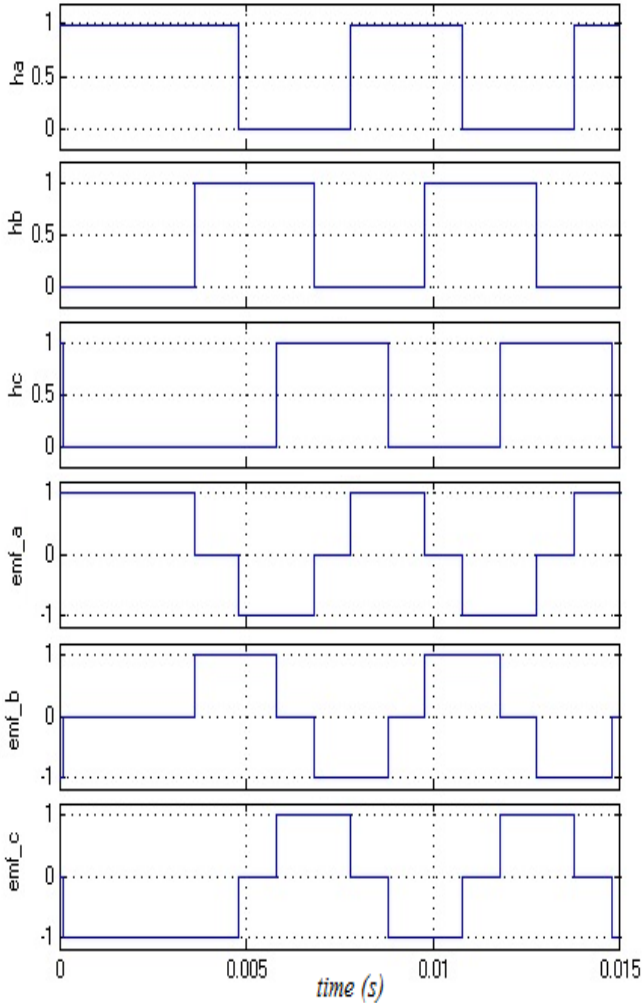
Fig. 5: The signals in the decoder block

The gate block plays a role in creating pulses to control the mosfets in the inverter; the details of this block are presented in Fig. 6.

The inputs of the gate block are the EMF signals; the outputs of the gate block are the signals which control the power switches. Running this block, the simulation signals are presented in Fig. 7.
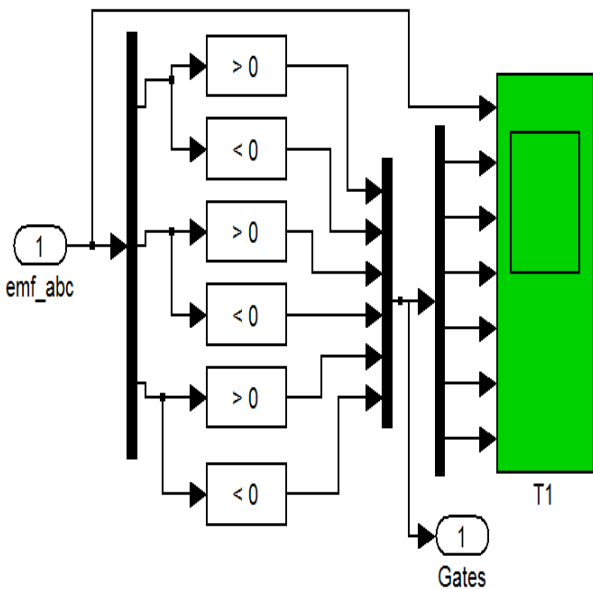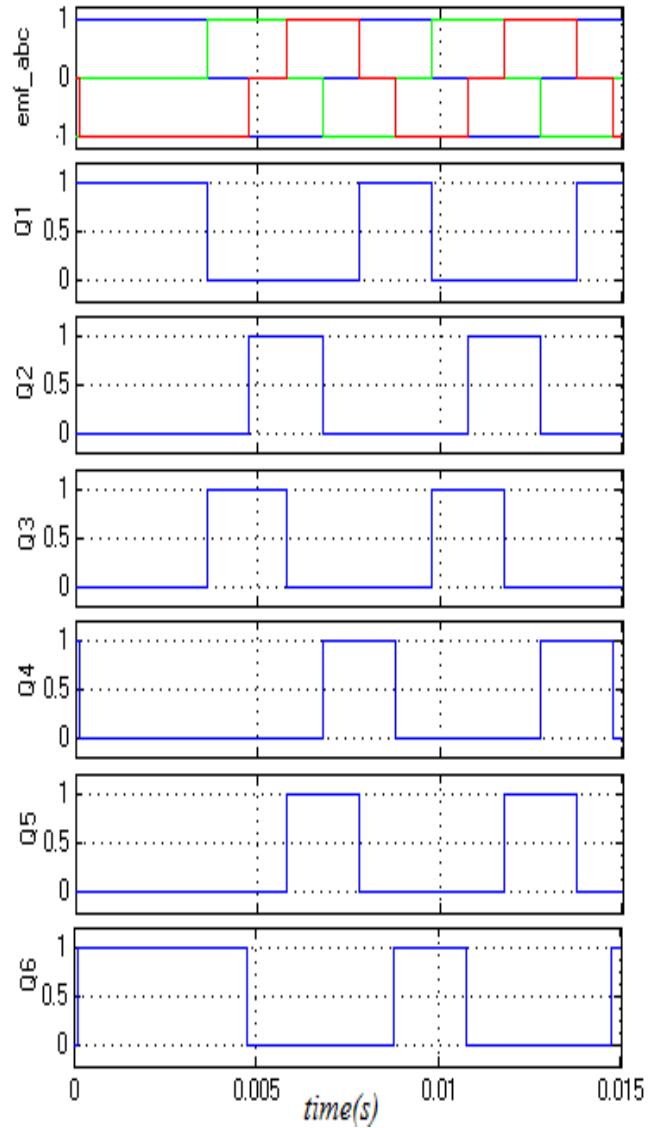

Fig. 6: The gate block

Fig. 7: The signals in the gate block

The output signals of the gate block (Q1-Q6) are and logic with the output signals of the pulse width modulation block, then these signals are fed to the gate block to control the mosfets in the inverter block.

The Proportional Integral (PI) controller is designed to adjust the duty cycle of high frequency PWM signal to minimize the speed error (Kazmierkowski and Malesani, 1998).

4. The simulation results

Set the BLDC with the stator phase resistance Rs=2.9 (ohm), the stator phase inductance Ls=0.0072 (H), the inertia J=0.00082 (kg.m^2). Set the PI controller with Kp = 0.013, Ki=0.16. Run the system, the simulation results are as follows.

4.1. When starting the system

The speed dynamic response under constant shaft mechanical torque condition and the reference speed = 2500 (rpm) is shown in the Fig. 8.
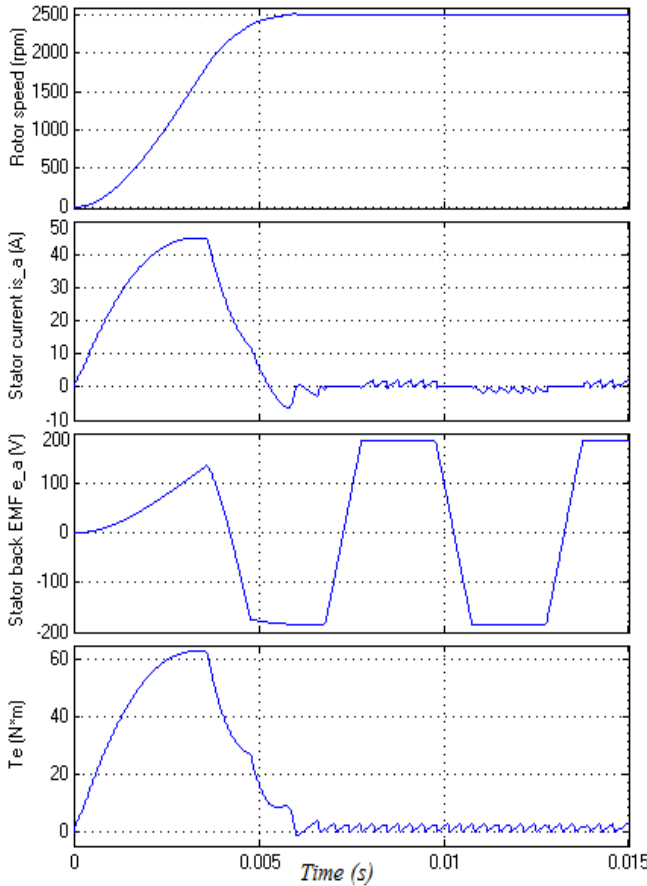
Fig. 8: The simulation results when starting the system

The simulation result shows that dynamic response of this system is fast, the settling time is very small (about 0.0055 seconds) without over shoot. So it can be assured that the control system is simple but effective.

To demonstrate the results more clearly, Fig. 8 also shows the characteristics of the stator current of A phase (is_a), the stator voltage back EMF (e_a) and the electromagnetic torque (Te). The line-line voltage Vab is also shown in the Fig. 9.
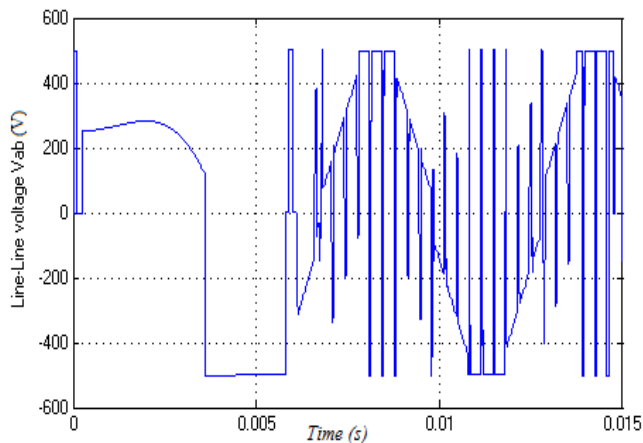

Fig. 9: The line-line voltage

4.2. When the shaft mechanical torque changes

When the shaft mechanical torque changes; the simulation results are shown in the Fig. 10.
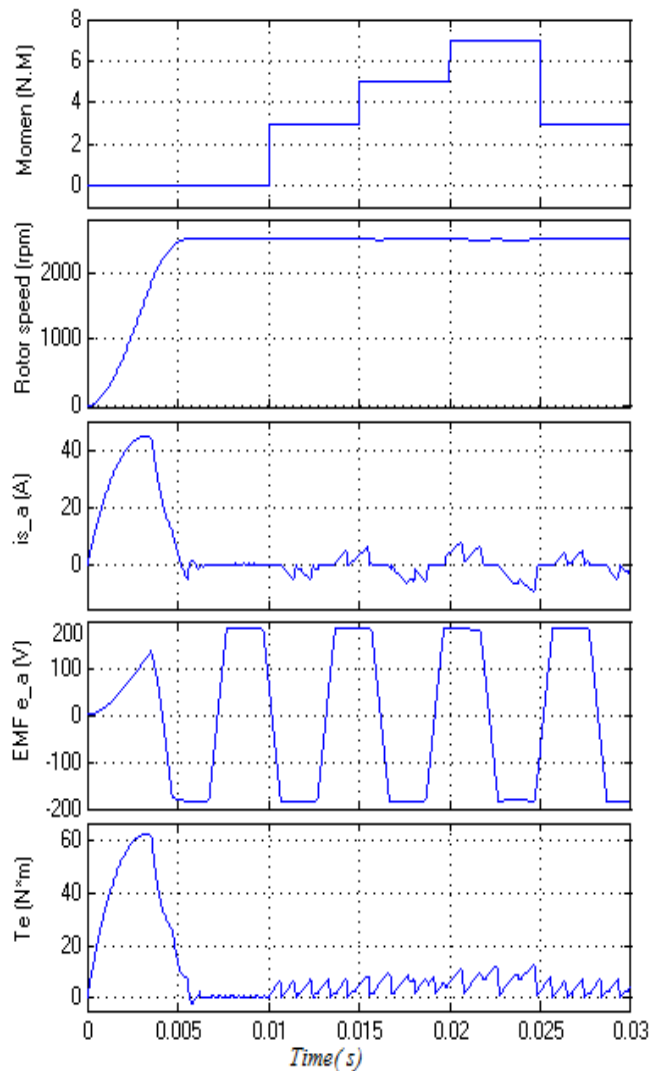

Fig. 10: The simulation results when the shaft mechanical torque changes

In the period of time from time=0 (s) to time=0.01(s), set the shaft mechanical torque=0; after every 0.005s period time, change the value of the shaft mechanical torque, these value are equal to 3, 5, 7 and 3 (N.M). The simulation results show that the speed response is still steady although the shaft mechanical torque changes. So it can be assured that the system works well when changing the load within permissible limits.

4.3. When the set point speed changes

When the set point speed changes; the simulation results are shown in the Fig. 11.

In the period of time from time=0 (s) to time=0.01(s), set the rotor setpoint speed = 2300 (rpm); after every 0.01(s) period time, change the value of the rotor setpoint speed, these value are equal to 2500, 2600, 2700 and 2500 (rpm).

Running the control system, the simulation result shows that the speed response always follows the desired value (setpoint speed) with very small transition time and response time, about 0.003 seconds. So it can be assured that the system works well when changing the setpoint speed.
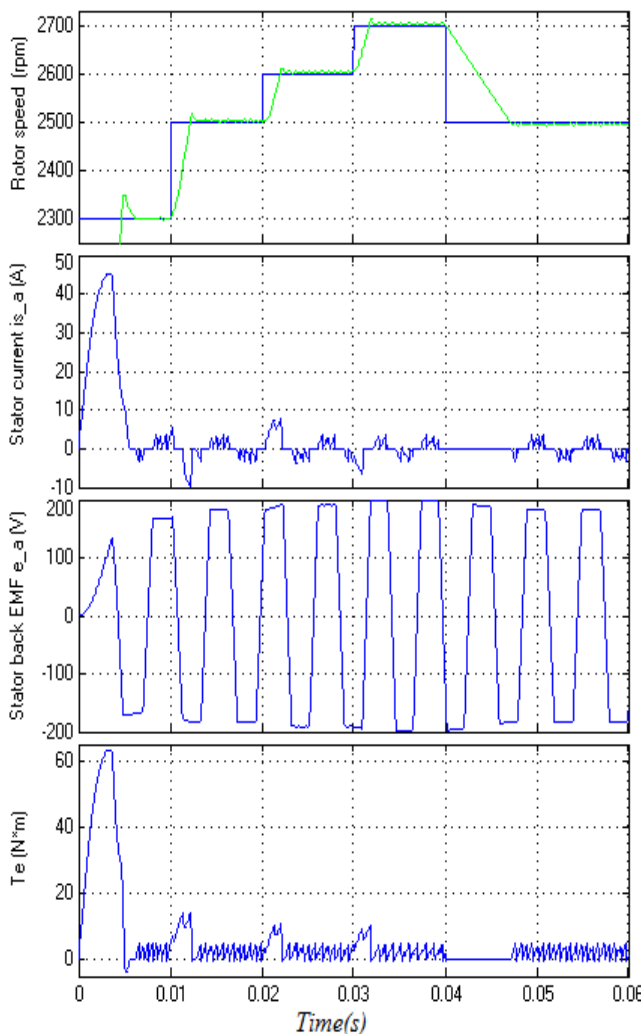
Fig. 11: The simulation results when the setpoint speed changes

5. Conclusion

In this paper, a way to control the speed of BLDC motor has been presented. A closed-loop control using PI controller with the PWM technique has been designed for driving the power of from the DC source through BLDC. In this system, the output value of PI controller plays a role in adjusting the duty cycle of high frequency PWM signals. These high frequency signals turn on or turn off the switch powers in the inverter. Finally, run the control system in case of changing the shaft mechanical torque and changing the set point speed, the simulation signal results show that the dynamic and static characteristic of the system are always good, with the transition time and the response time are very small. So it can be asserted that the proposed system has a simple control structure but operates effectively.

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