Elimination of Output Voltage Oscillations in DC-DC Converter Using PWM with PI Controller

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Abstract: In this paper the SIMULINK model of a PWM controlled DC-DC converter is modeled using switching function concept to control the speed of the DC motor. The presence of the voltage oscillation cycles due to higher switching frequency in the DC-DC converter is identified. The effect of these oscillations on the output voltage of the converter, Armature current, Developed torque and Speed of the DC motor is analyzed. In order to minimize the oscillation cycles the PI controller is proposed in the PWM controller.

Keywords: PWM Controller, DC-DC Converter, DC Motor, PI Controller.

1 Introduction

One of the challenges in controlling the speed of the DC motor through DC-DC converter is compensation for the converter's non-linear damped dynamics which are a function of load parameters [1]. This paper proposes the modeling and simulation of PWM controlled DC-DC converter with PI controller to eliminate damped dynamics and output voltage oscillations of the converter.

Computer simulation plays a vital role in the design and analysis of power electronics converters and their controllers. Designing power electronic systems without computer simulation is extremely laborious, time consuming, error-prone and expensive [2]. With the help of powerful computer simulation tools such as MATLAB/SIMULINK, one can model and analyze the static power converter systems effectively with the system equations. In power electronic systems, the simulation is mainly performed to analyze and design circuit configuration and the applied control strategy. The organization of this paper is as follows. In Section 2 the modeling of the DC motor and DC-DC converter are discussed. In Section 3 the proposed PWM technique with PI controller is discussed. The results are discussed in Section 4.

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2 Modeling of DC Motor and DC-DC Converter

Consider a DC motor, whose electric equivalent circuit of armature, field and the free body diagram of the rotor are shown in Fig. 1, where:

V_{dc} - Armature voltage (V);

E_b - Back emf (V);

R_a - Armature resistance (Ω);

L_a - Armature inductance (H);

L_f - Field inductance (H);

I_f - Field current (A);

T_e - Torque developed by the motor (Nm);

T_L - Load torque (Nm);
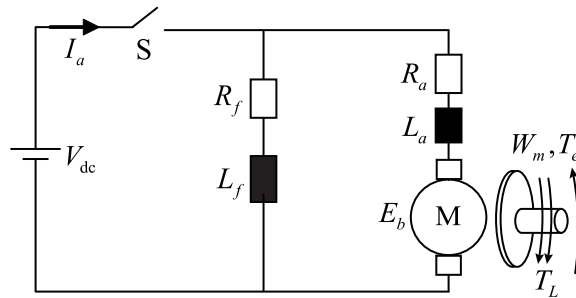
I_a - Armature current (A);

W_m - Rotor speed (rad/s), $W_m = \dfrac{2\pi N}{60}$;

N - Speed of rotation (revolutions/min);

R_f - Field resistance (Ω);

J - Moment of inertia of the rotor (kgm^2);

B - Damping coefficient (Nms).

Fig. 1 – *Equivalent circuit of* DC *motor*.

The torque developed by the motor, T_e, is related to the armature current, I_a, and Torque constant (K_m):

$$T_e = K_m I_a = K_f I_f I_a. \tag{1}$$

The back emf, E_b, is related to angular velocity, W_m by:

$$E_b = K_m W_m = K_f I_f W_m. \tag{2}$$

Torque constant, K_m is related by:

$$K_m = E_b / W_m. \tag{3}$$

For armature side when switch S is closed at $t = 0$, by Kirchhoff's voltage law:

$$V_{dc} = I_a R_a + L_a \frac{dI_a}{dt} + E_b. \tag{4}$$

Substituting Equation (2) in (4), taking Laplace transform and solving for $I_a(s)$, we get

$$I_a(s) = \frac{V_{dc}(s) - K_m W_m(s)}{R_a + sL_a}. \tag{5}$$

The dynamic Equation for the mechanical system is:

$$T_e = K_m I_a = J \frac{dW_m}{dt} + BW_m + T_L, \tag{6}$$

where BW_m term represents the rotational loss torque of system.

Taking Laplace transform to Equation (6) and solving for $W_m(s)$, we get:

$$W_m(s) = \frac{K_m I_a(s) - T_L(s)}{B + sJ}. \tag{7}$$

For field side, by Kirchhoff's voltage law:

$$V_{dc} = R_f I_f + L_f \frac{dI_f}{dt}. \tag{8}$$

Taking Laplace transform to Equation (8) and solving for $I_f(s)$, we get:

$$I_f(s) = \frac{V_{dc}(s)}{R_f + sL_f}. \tag{9}$$

With field current $I_f(s)$, the Torque constant, K_m is related by:

$$K_m = K_f I_f(s). \tag{10}$$

The SIMULINK model of a DC motor is shown in Fig. 2.

Now consider DC-DC converter, whose equivalent circuit is shown in Fig. 3. Under ideal assumptions: ideal switch, ideal capacitor and ideal inductor the converter can be described using ordinary differential equations as:

$$C\frac{\mathrm{d}V_C}{\mathrm{d}t} = i_L - \frac{V_C}{R} - i_o, \tag{11}$$

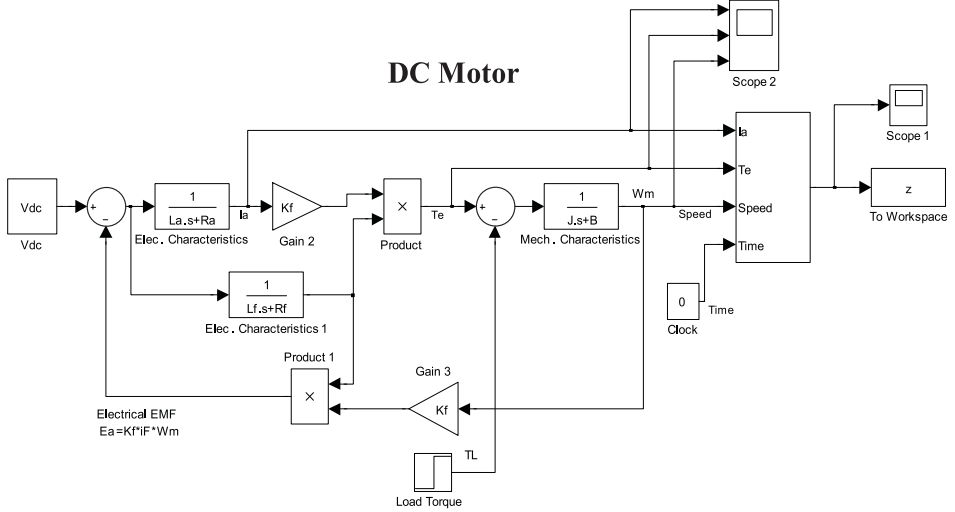$$L\frac{\mathrm{d}i_L}{\mathrm{d}t} = SV_{\mathrm{dc}} - V_o. \tag{12}$$

Fig. 2 – *Model of a* DC *motor*.

In more general cases, consider a body resistor of the inductor, R_L and a series resistor of the capacitor, R_C, then equations (11) and (12) become:

$$C\frac{\mathrm{d}V_C}{\mathrm{d}t} = \frac{R}{R+R_C}\left(i_L - \frac{V_C}{R}\right), \tag{13}$$

$$L\frac{\mathrm{d}i_L}{\mathrm{d}t} = \left[SV_{\mathrm{dc}} - \frac{R}{R+R_C}V_C - \left(\frac{RR_C}{R+R_C} + R_L\right)i_L\right], \tag{14}$$

where $S = 1$ for $0 \le t \le DT_S$, $S = 0$ for $DT_S \le t \le T_S$.

The output voltage V_o of the converter is given by:

$$V_o = V_C\frac{R}{R+R_C} + \frac{RR_C}{R+R_C}i_L. \tag{15}$$

The SIMULINK model of the DC-DC converter is shown in Fig. 4 based on equations (13), (14) and (15). Due to the instantaneous switching action caused by *S*, the initial inductor current in *L* is automatically taken care of. The PWM generator generates switching pulses S defined in equation (14). To obtain i_L during the ON and OFF periods equation (14) is integrated.
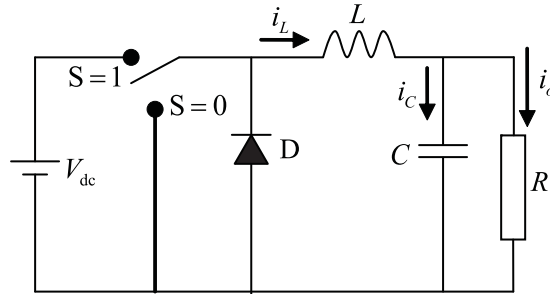
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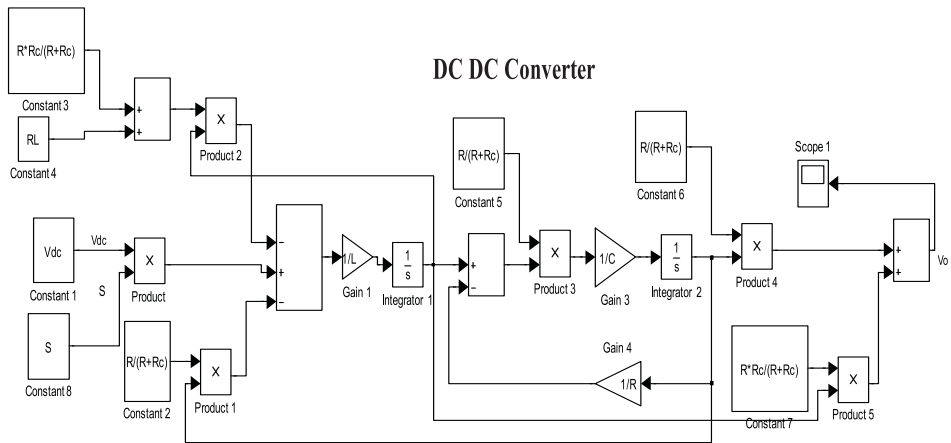**Fig. 3** – *Switching-mode* DC-DC *converter*.

Fig. 4 – *Model of a* DC-DC *converter.*

3   Proposed PWM with PI Controller

The proposed block diagram of the PWM controller with and without PI controller is shown in Fig. 5.
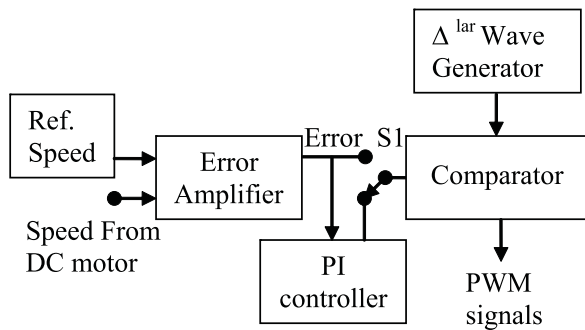

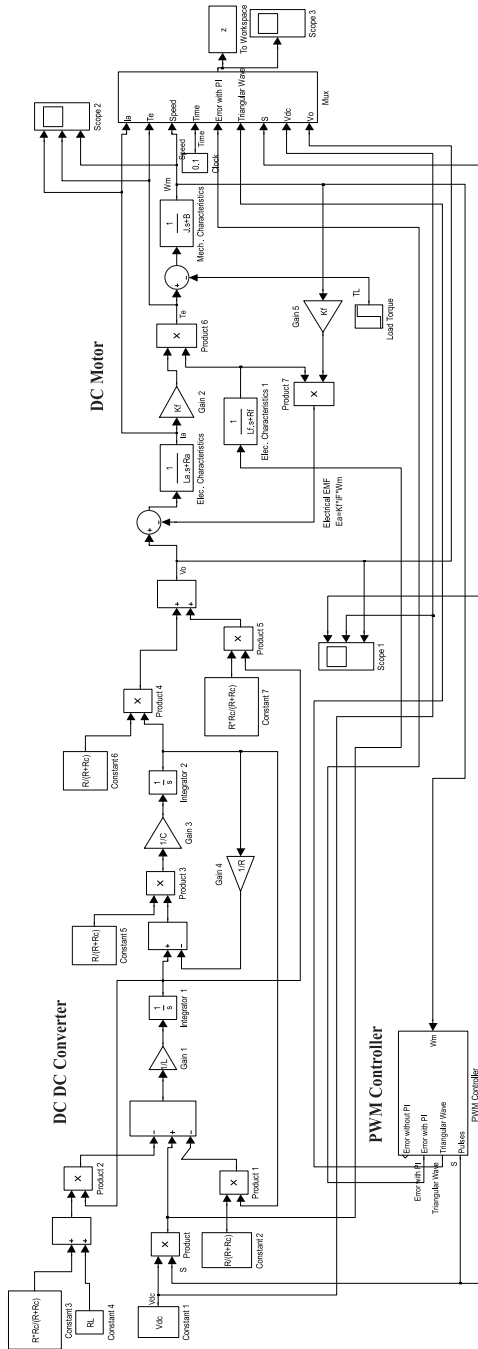**Fig. 5** – *Proposed block diagram of* PWM *controller*.

Fig. 6 – *Model of the overall system*.

The speed obtained from the DC motor is subtracted from reference speed using error amplifier. The selector switch S1 either connect or disconnect the PI controller. The output of S1 is compared with the output of triangular wave generator using comparator. The PWM signal obtained from the comparator is used to turn-ON and turn-OFF the switch S in the converter.

The SIMULINK model of the overall system is shown in Fig. 6 where converter, DC motor and PWM controller are interconnected.

4   Results and Discussion

The specifications of the DC motor, DC-DC converter and PWM controller are listed below.

4.1 Specifications of DC motor

Armature voltage	24 V	Field inductance	0.5 H
Armature current	1.35 A	Moment of inertia (J)	0.0236 Kg m^2
Armature resistance	4 Ω	Armature inductance	0.0567H
Field resistance	5 Ω	Damping coefficient (B)	0.0075 Nms

4.2 Specifications of DC-DC converter

| Normal input voltage (V_{dc})	24V
Load Resistance (R)	20 Ω
Filter Inductance (L)	4.4mH
Filter Capacitance (C)	200μF

4.3 Specifications of PWM controller

| Switching frequency (F_S)	150 kHz
PI controller	$K_P = 0.1$ and $K_I = 10$

The simulation was carried out using MATLAB/SIMULINK version 7.4 [4]. The Variable step method type, ode23 [Bogacki-Shampine] solver, maximum step size of 0.0001 s, stop time of 0.1 s with a tolerance of 1e-3 was used. Simulated results of error, triangular wave, switching pulses, input voltage, output voltage, armature current, torque developed and speed of the DC motor without and with PI controller are shown below for various set speeds.

4.4 With out PI controller

In Fig. 7a for the speed of 40rpm the non-sinusoidal voltage oscillations are appeared in the error (–2 to 2.5 V peak-to-peak) and in the output voltage (15 V peak-to-peak) of the converter. As a result, the oscillations are also appeared in the armature current, electrical torque and speed of the DC motor as shown in Fig. 7b.
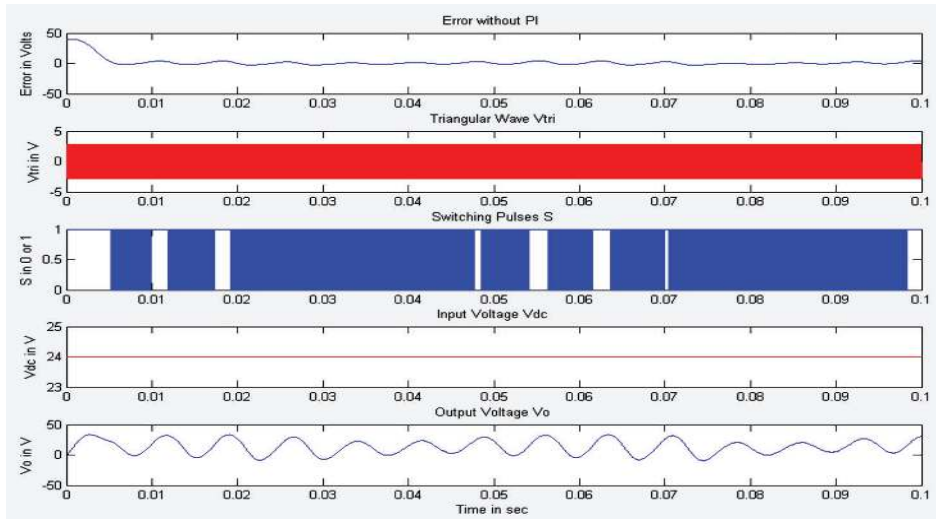
Fig. 7a – *Waveforms of Error, Triangular wave, Switching pulse, Input and Output voltage for Set* Speed = 40 rpm.
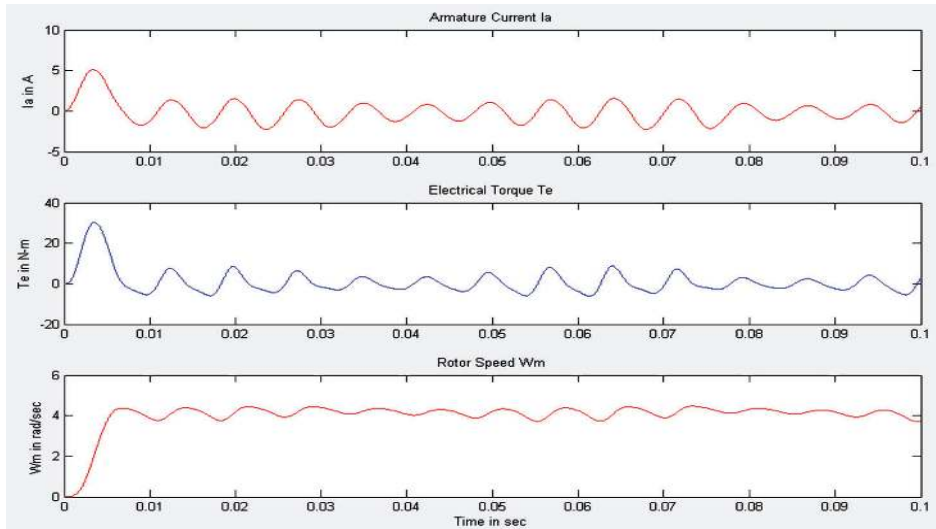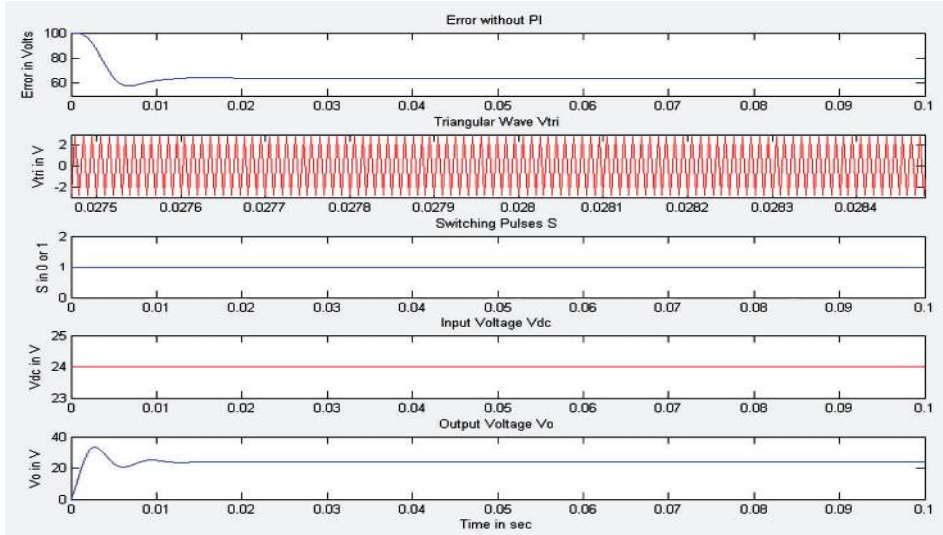

Fig. 7b – *Waveforms of Armature current, Electrical torque and Speed for* Set Speed = 40 rpm.

These oscillations can cause vibrations in the motor and motor may generate Electro Magnetic Interference (EMI) signals which are responsible for the malfunctioning of the neighboring circuits. So PWM with PI controller is necessary to eliminate these oscillations for the proper functioning of the motor

and preventing from generating EMI signals. The results of PI controller are discussed in subsection E.

It is also been observed from Figs. 8a and 8b that for the set speed of 100rpm large variation in the error and switch in the converter is ON all the time as switching pulse is high. As a result no oscillations in the output voltage but speed remains fixed and cannot be varied because of fixed voltage which is undesired for speed control applications.

Fig. 8a – *Waveforms of Error, Triangular wave, Switching pulse, Input and Output voltage for* Set Speed = 100 rpm.
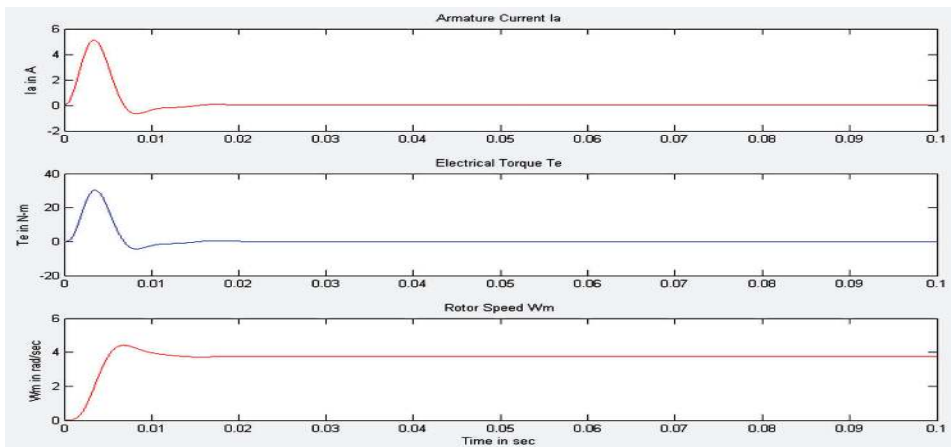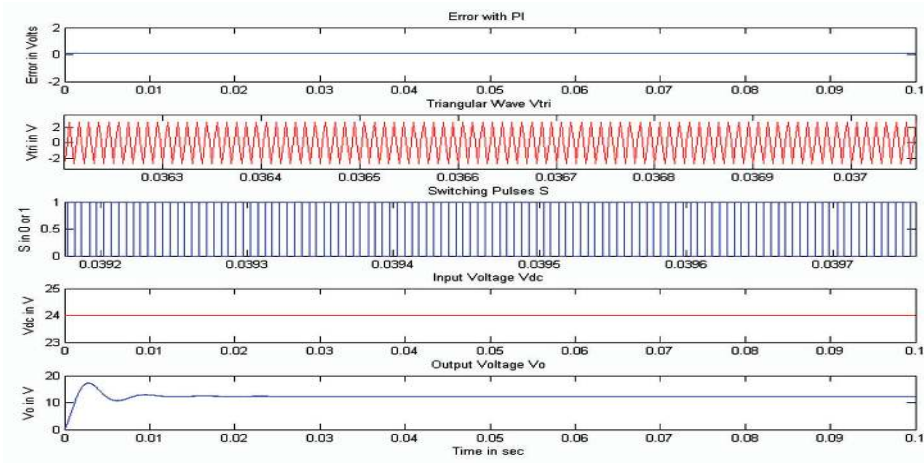

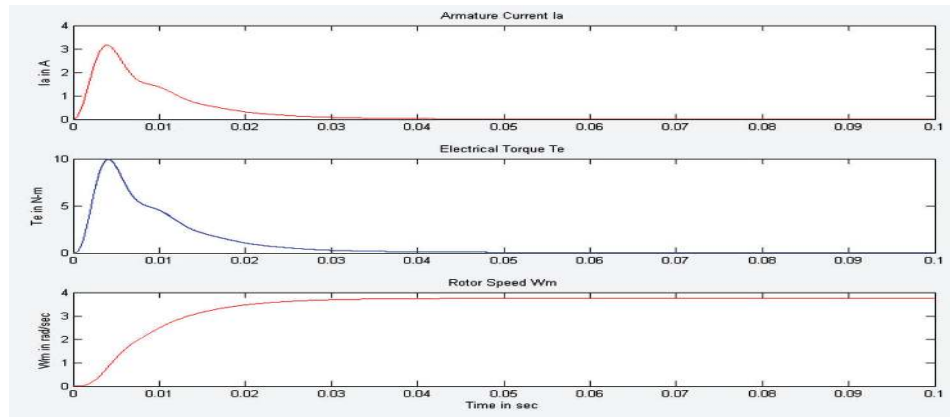**Fig. 8b** – *Waveforms of Armature current, Electrical torque and Speed for* Set Speed = 100 RPM.

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4.5 With PI controller

In Fig. 9a for the speed of 40 rpm no oscillations in the error (0.1 V) and in the output voltage (12.5 V dc).

Because of the effect of PI controller oscillations are eliminated in the output voltage of the converter and in the error as well. As a result no oscillations in the armature current, torque and speed of the DC motor under steady state condition as shown in Fig. 9b. The switching pulses and other waveforms are also shown in the Fig. 9b For the speed of 100 rpm the waveforms are shown in Figs. 10a and 10b where the output voltage is 22.5 V, armature peak current is 6.5 A, peak electrical torque is 3.2 Nm. The switching pulses and other waveforms are also shown in the Fig. 10b.
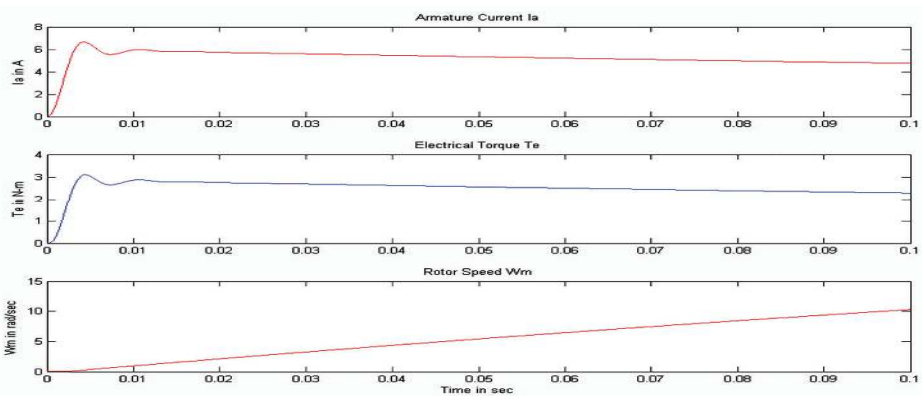

Fig. 9a – *Waveforms of Error, Triangular wave, Switching pulse, Input and Output voltage for* Set Speed = 40 rpm.

Fig. 9b – *Waveforms of Armature current, Electrical torque and Speed for* Set Speed = 40 rpm.
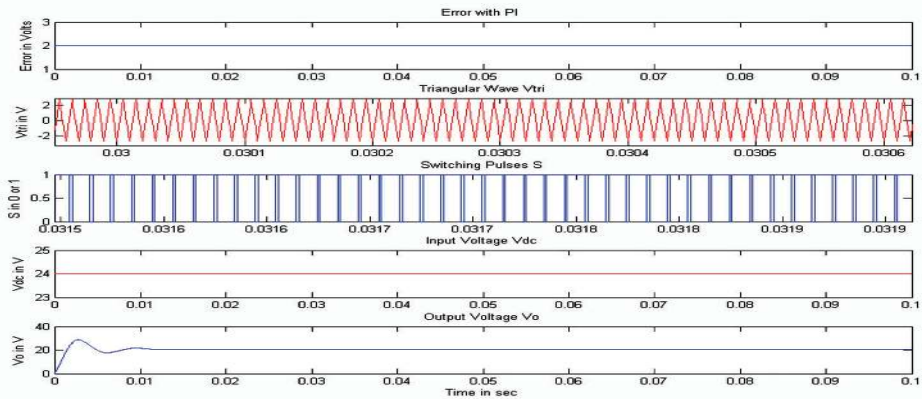
Fig. 10a – *Waveforms of Error, Triangular wave, Switching pulse, Input and Output voltage for* Set Speed = 100 rpm.

Fig. 10b – *Waveforms of Armature current, Electrical torque and Speed for* Set Speed = 100 rpm.

5 Conclusion

In this paper, PWM with PI controller have been proposed to control the speed of the DC motor and to eliminate the output voltage oscillations of the converter due to high frequency. The entire system is modeled and simulated using SIMULINK tool. The output voltage of the converter, armature current, developed torque and speed of the DC motor are compared with and without PI controller.

6 Acknowledgment

7   References

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