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Sensorless Speed/Torque Control of DC Machine Using Artificial Neural Network Technique

Rakan Kh. Antar1 **Ahmed A. Allu**[2]

[1] *Technical College, Mosul , Iraq*
rakanpe@yahoo.com
[2] *Technical Institute, Mosul, Iraq*
ateyahmed79@gmail.com

Abstract

In this paper, Artificial Neural Network (ANN) technique is implemented to improve speed and torque control of a separately excited DC machine drive. The speed and torque sensorless scheme based on ANN is estimated adaptively. The proposed controller is designed to estimate rotor speed and mechanical load torque as a Model Reference Adaptive System (MRAS) method for DC machine. The DC drive system consists of four quadrant DC/DC chopper with MOSFET transistors, ANN, logic gates and routing circuits. The DC drive circuit is designed, evaluated and modeled by Matlab/Simulink in the forward and reverse operation modes as a motor and generator, respectively. The DC drive system is simulated at different speed values (±1200 rpm) and mechanical torque (±7 N.m) in steady state and dynamic conditions. The simulation results illustrate the effectiveness of the proposed controller without speed or torque sensors.

Keywords: Speed/torque control, Sensorless control, DC machine, Neural Network Technique.

السيطرة على سرعة ماكنة تيار مستمر بدون متحسس للسرعة والعزم باستخدام تقنية الشبكة العصبية الاصطناعية

الخلاصة

إن البحث المقترح يتضمن استخدام تقنية الشبكة العصبية الاصطناعية لتحسين منظومة السيطرة (سرعة وعزم) لسوق ماكنة تيار مستمر منفصل التغذية. اذ ان السرعة و العزم يتم تخمينه انياً بالاعتماد على تقنية الشبكة العصبية وبشكل يتكيف ويتلائم مع ظروف تشغيل الماكنة المختلفة. إذ تقوم الشبكة العصبية بتخمين سرعة الجزء الدوار والعزم الميكانيكي المسلط على محور الدوران بشكل نموذج لمنظومة مرجعية قابلة للتكيف. يتألف منظومة السوق من دائرة مقطع قنطري باستخدام ترانستور نوع تأثير المجال مع دوائر توجيه وبوابات منطقية لتوليد اشارة السوق لتشغيل الماكنة في الانماط الاربعة. ان المنظومة المقترحة تم تصميمها ونمذجتها وتقييم ادائها باستخدام برنامج الماتلاب عند تشغيل الماكنة في اتجاه الدوران الامامي والعكسي كمحرك و مولد. تم محاكاة المنظومة عند سرع (±1200 دورة/دقيقة) وعزوم حمل ميكانيكية (±7 نيوتن.متر) مختلفة للماكنة تحت الظروف العابرة والمستقرة. نتائج التمثيل اظهرت فعالية ودقة السيطرة على المحرك من دون استخدام متحسس سرعة وعزم.

الكلمات الدالة: التحكم بالسرعة والعزم، تحكم بدون استخدام متحسسات، ماكنة تيار مستمر، شبكة عصبية.

Introduction

DC motor drive system is used in some industrial applications due to its high efficiency and flexibility control. High performance of a DC motor drive circuit is very necessary to be developed. This development can be done through tracking a good dynamic speed and load regulation responses[1]. The performance of a DC drive also depends on the static power converter's performance. The required torque-speed characteristics of the DC motor can be achieved using proper PID controllers[2]. Speed data is commonly provided using tachometer or speed transducer on the motor shaft. In addition, speed sensor characteristics changes with the mechanical wear, temperature, and humidity that affect the closed loop system stability. For this reason the speed of a DC motor is estimated from the motor induced voltage [3]. To avoid speed sensor problems, sensorless speed control of a DC motor drive is proposed in this paper.

Different techniques are used to control the speed of DC motors such as proportional–integral–derivative (PID) controller, adaptive system, artificial neural network (ANN), fuzzy logic, etc [2, 4, 5, 6]. In this paper, the sensorless speed control of a DC motor is done using ANN, which is trained to estimate the speed and load torque of the DC machine depending on instantaneous output armature voltage and current of the DC/DC chopper as shown in Figure (1).

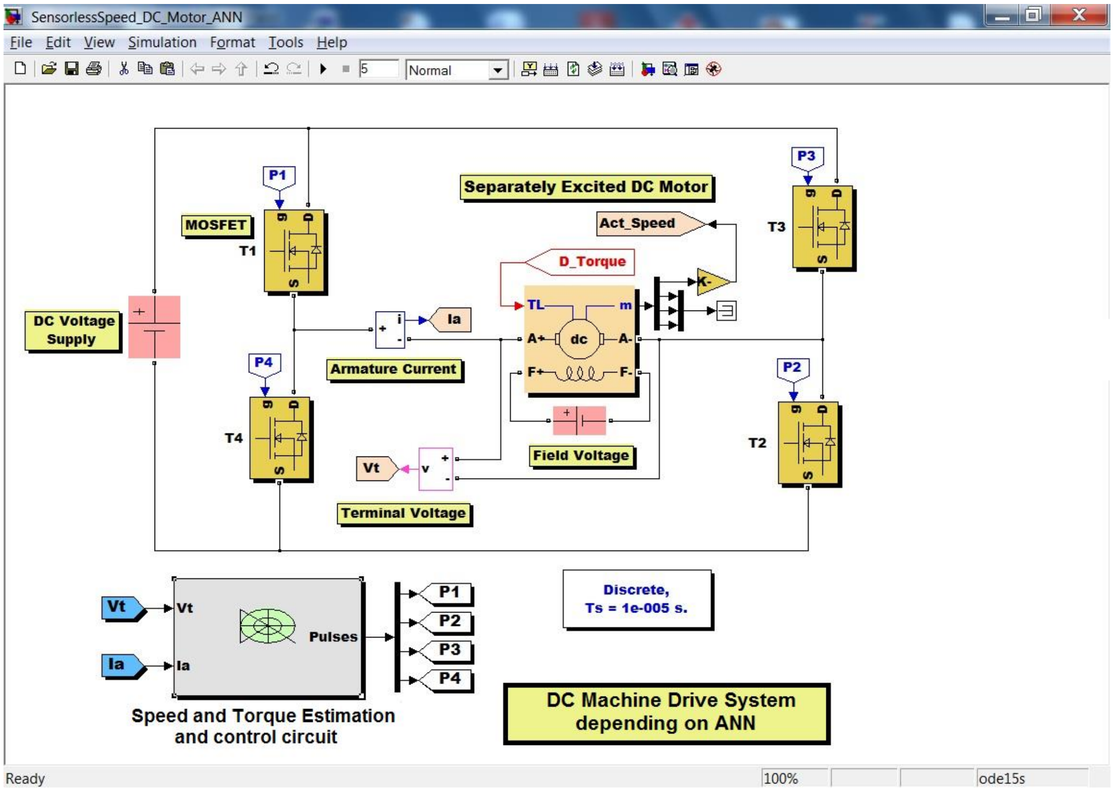


Fig. 1. The proposed DC-DC H-bridge power converter circuit

The H-bridge Chopper Fed a Separately Excited DC Machine

A separately excited DC motors are usually used as a variable speed drives. DC regenerative drives uses for applications requiring continuous regeneration for repairing changes in loads. This ability with AC drives is more complex and expensive [7]. In order to drive a separately excited DC machine in the forward and reverse modes, a four-quadrant H-bridge PWM DC/DC chopper is used as shown in Fig.(1). The converter circuit supplied from a DC source consists of four MOSFET transistors with reverse diodes. The DC motor speed is controlled by changing terminal voltage, armature resistance, and/or field current method. The former way is used in this work for controlling the terminal voltage, which is employed by switching frequency (5kHz) of Pulse Width Modulation (PWM) and adjusted with duty cycle (t_{on}/Ts), the average output voltage (V_t) is given as [5,6]:

$$V_t = \frac{t_{on}}{Ts} Vs \qquad ....(1)$$

Where (Ts=1/switching frequency).

By the Laplace Transforms, the armature current can be written as following equations [5, 6]:

$$I_a(s) = \frac{V_t(s) - K_e(s).\frac{2\pi.n}{60}}{(s.L_a + R_a)}. \qquad ....(2)$$

Where K_e is a machine constant, it can be calculated from (L_{af}*I_f), thereby the equations describing field current of separately excited machine can be determined as follow [5, 6]:

$$I_f(s) = \frac{V_f(s)}{(s.L_f + R_f)} \qquad ....(3)$$

Consequently, the estimation speed and load torque of the DC machine is evaluated depend on the instantaneous terminal voltage and current with constant field current. The analogue low pass filters (2nd order, 200Hz cut off freq.) are used to minimize harmful high frequency of voltage and current waveforms as illustrated in Figure (1).

Triggering Modes of the DC Drive Circuit

In this work, four MOSFET transistors (T_1,T_2,T_3,T_4) with freewheeling diodes (D_1, D_2, D_3, D_4) are used as a power electronics switching devices of the H-bridge DC chopper circuit. These devices are controlled according to the PWM pulse signals (P_1, P_2, P_3, P_4) as illustrated in the Table (1).

Table 1. Switching patterns of the DC drive circuit

DC Machine Modes	T_1	D_1	T_2	D_2	T_3	D_3	T_4	D_4
Forward Motoring	1	0	1	0	0	0	0	0
	0	0	1	0	0	0	0	1
Forward Regenerative Braking	0	0	0	0	0	1	0	1
	0	0	0	0	1	0	1	0
Reverse Motoring	0	0	0	1	0	0	1	0
	0	1	0	1	0	0	0	0
Reverse Regenerative Braking	1	0	1	0	0	0	0	0
	0	0	1	0	0	0	0	1

Forward (Motoring) Mode

In order to drive the DC machine in the forward motoring mode, transistors T_1 and T_2 are controlled and transistors T_3 and T_4 are switched off. So, if both T_1 and T_2 are turned on, the supply voltage appears across the motor terminals and the armature current will rise, while if T_1 is switched off and T_2 remained on, the armature current decays through D_4 [8].

Forward (Regenerative Braking) Mode

In this mode, transistors T_1, T_2, T_3 and T_4 are turned off and armature current will flow in the forward direction. The DC machines acts as a generator and returns energy to the DC supply through diodes D_3 and D_4 [8].

Reverse (Motoring) Mode

In order to run the DC machine in the reverse motoring mode, transistors T_3 and T_4 are controlled, while T_1 and T_2 are switched-off. If transistors T_3 and T_4 are turn on together, the armature current will rise and flow in reverse direction. But if transistor T_3 is switched-off and T_4 is turned-on, the armature current will fall through T_4 and D_2 [8].

Reverse (Regenerative Braking) Mode

In this mode, transistors T_1, T_2, T_3 and T_4 are turning off and armature current will flow in the reverse direction and return energy to the DC supply through D_1 and D_2 [8].

Modeling of Sensorless Speed and Torque Estimation System by ANN

A forward ANN estimator system is used to evaluate and control speed and torque of a separately excited DC motor. ANN has three neuron layers, the hidden layer neurons have log-sigmoid transfer function and the output layer neurons have a linear transfer function. It is trained based on supervised back-propagation method. The number of neurons in the hidden layer is specified as 30 neurons. The connective weights of a back-propagation ANN controller are trained off-line according to large data with error bounded equal to 1e-5.

The machine speed is controlled by controlling the DC output voltage of the DC/DC H-bridge chopper. In this paper, ANN is used to achieve sensorless speed control. The trained ANN has two inputs (terminal voltage (V_t) and armature current (I_a)) and two outputs to produce the estimated speed and load torque of the DC machine (sensorless speed and torque). The estimated speed is compared with the reference speed and the result, which is the error signal, is sent to a PI controller as shown in Fig.(2). The PI controller which is tuned by trial and error rule is given as [6]:

$$G(s) = K_p . e(s) + \frac{K_i}{s} . e(s) \quad \ldots\ldots\ldots\ldots\ldots\ldots(4)$$

Where (K_p) and (K_i) are the proportional and integral controller gains.

The designed sensorless speed control circuit has two feedback loops PI controller. The output of the first PI controller (speed controller) is an electromagnet developed torque, which is compared with the estimated torque with PI gains (K_p=1.7) and (K_i=10). The result is fed to second PI controller (torque control at K_p=0.1 and K_i=10), which regulates the developed and estimated mechanical torque, to get the modulation index value. The modulation index is compared with the carrier signal to produce the PWM patterns of the H-bridge chopper in order to drive the DC machine in the four quadrants as shown in Figure (2). The speed and torque controllers of the DC drive system are integrated together to get faster response in order to prevent excessive current to flow in the H-bridge chopper circuit. Thus, the designed controller has a fast dynamic response for any load changing to reach the steady state response for the machine as quick as possible.

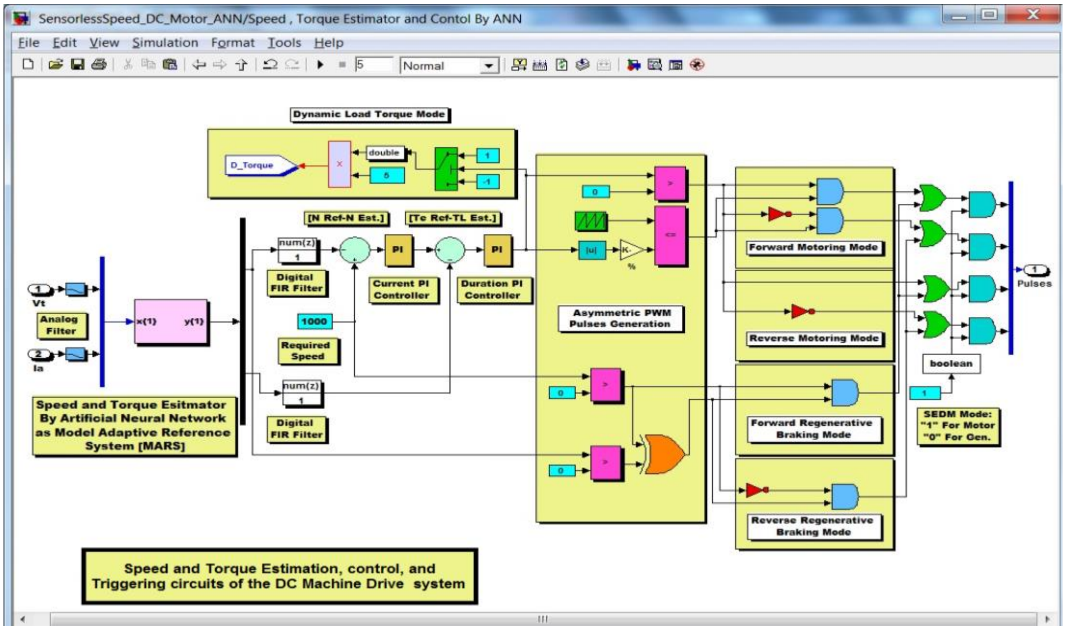


Fig. 2. Modeling of the sensorless speed controller circuit

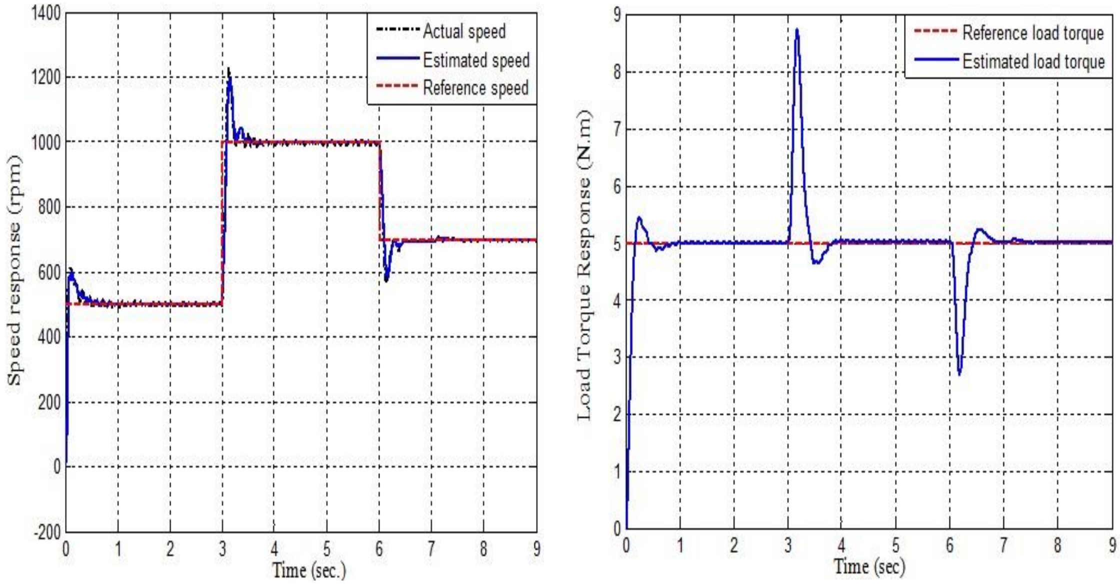
The closed loop speed and torque controllers of the DC machine is composed of ANN to estimate rotor speed and load torque values as a Model Reference Adaptive System (MRAS), and PWM signals generator with logic and routing circuits. The load torque of the DC machine is dynamically changed between (+T_L) and (-T_L) according to the required speed and power directions to run the machine in the forward and reverse modes.

Analogue and Digital Filters with ANN

In this paper, analogue and digital filters with ANN have been applied successfully to enhance the performance of the DC drive and its control circuit. Switching operation of the DC chopper device causes distortion in the voltage and current waveforms, which gives slow and oscillated response for the estimated speed DC motor. As a result, the estimation process of speed and torque by ANN will suffer from fluctuation in its values due to higher order harmonics. To overcome this problem, analogue and digital filter are used to filter inputs and outputs of the trained ANN. The analogue filters are used to minimize such aliasing effect as well as attenuate the high frequency components of V_t and I_a. The digital filter (Finite Impulse Response filter FIR-Direct form) is used to improve the numerical algorithm (pattern recognition) of the back propagation network.

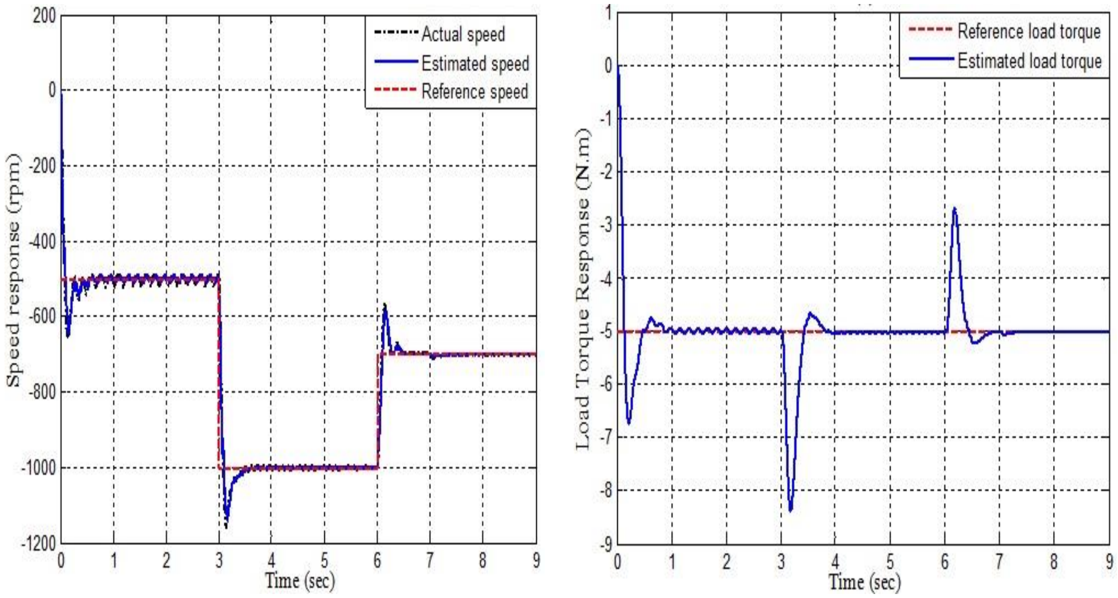
Simulation Results

To estimate the dynamic performance of the DC drive system, the simulation of DC machine has been done under different speed and load torque conditions. The dynamic speed response of the DC machine in the forward and reverse motoring modes at load torque TL equalling to (±5 N.m) is shown in Figure (3) and Figure (4). The estimated and actual speeds are compared and show that they are stable and reached the reference speed within 0.87second. The estimated (sensorless) speed has good response with low overshoot like the actual speed response. While the estimated load torque follows the reference torque and its overshoot is due to changing inputs of the ANN with speed changing.



(a) (b)

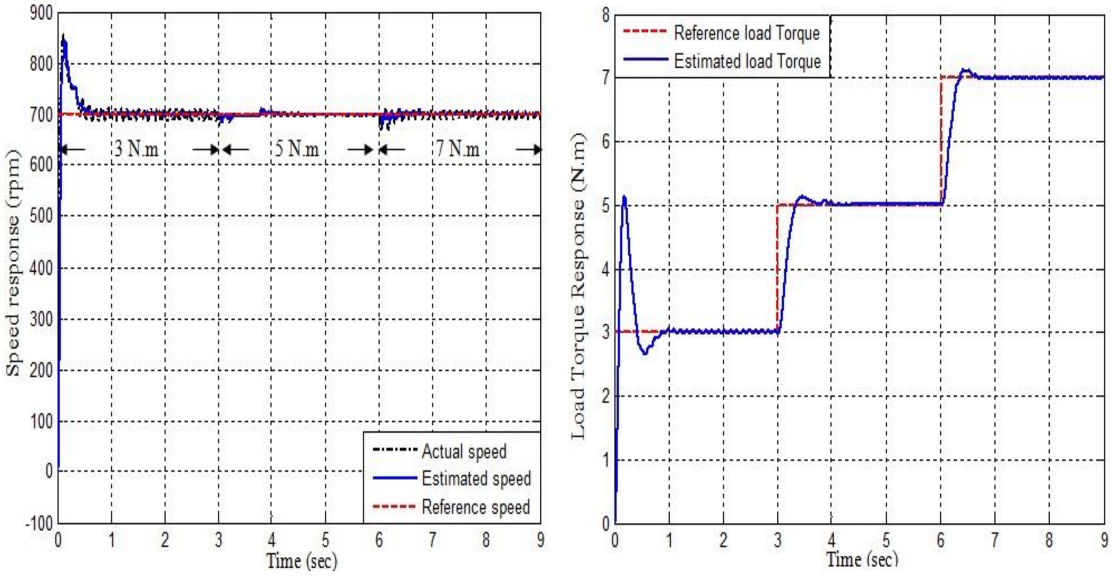
Fig. 3. (a) Speed and (b) load torque responses of the separately excited DC machine with constant load torque in the forward motoring mode



(a) (b)

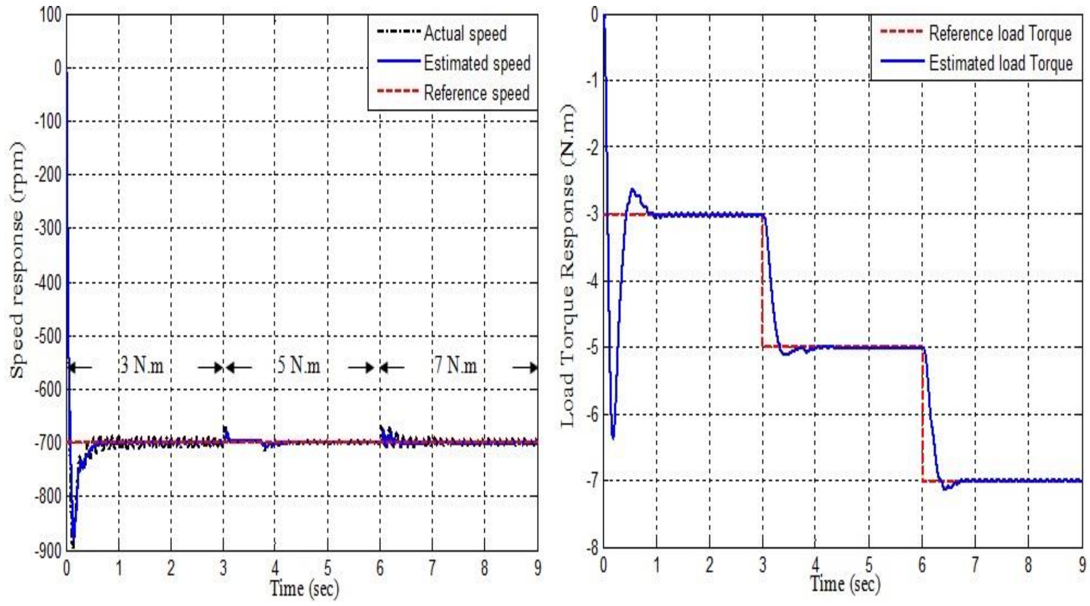
Fig. 4. (a) Speed and (b) load torque responses of the separately excited DC machine with constant load torque in the reverse motoring mode

Figure (5) and Figure (6) show the speed and load torque response of the DC machine in the forward and reverse motoring modes at different load torques. These figures illustrated that the speed response stay around the reference speed (1000rpm) with steady state error around zero. The estimated torque has good response with low overshoot and steady state error about zero. The sensorless speed and torque track the reference values and give good response as confirmed by the actual values.



(a) (b)

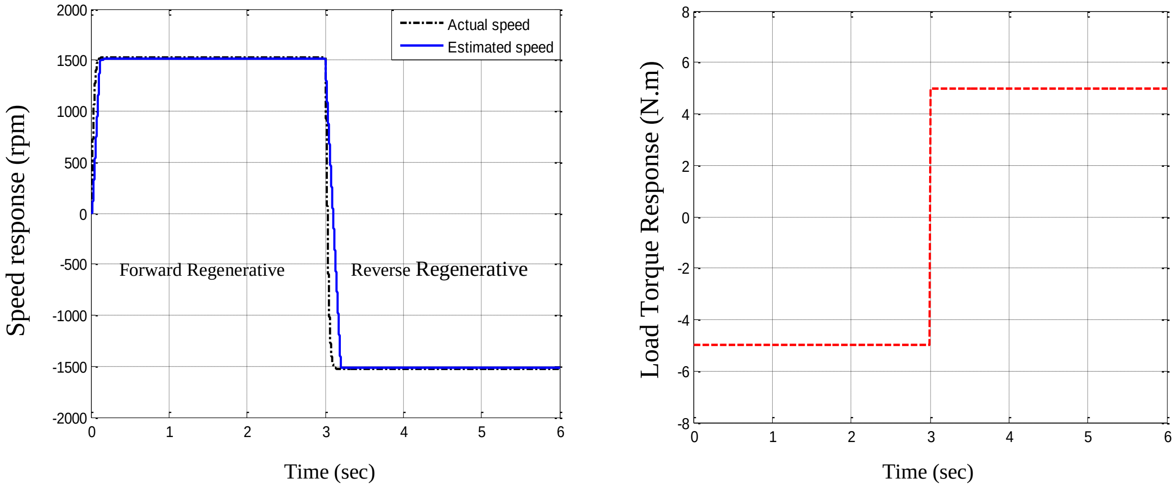
Fig. 5. (a) Speed and (b) load torque responses of the separately excited DC machine with variable load torque in the forward motoring mode



(a) (b)

Fig. 6. (a) Speed and (b) torque responses of the separately excited DC machine with variable load torque in the reverse motoring mode

Figure (7) shows the speed and torque responses of the separately excited DC machine in the forward and reverse regenerative modes. This figure explains the ability of the DC/DC H-bridge chopper to run the DC machine in the regenerative mode as a generator.



(a) (b)

Fig. 7. (a) Speed and (b) load torque responses of the separately excited DC machine in the forward and reverse regenerative modes

The overall sensorless speed and torque responses of the DC machine is good compared with the actual values which proves the effectiveness of the sensorless control system to track the required speed and load torque.

Conclusions

Sensorless speed and load torque control of a separately excited DC motor have been presented. Estimation speed and torque based on ANN has been done by measuring the chopper instantaneous average output voltage and current. Thus, there is no need for tachogenerator feedback. The estimated speed is compared with the reference speed and the result is applied to the PI controller to provide robust speed control of the DC drive. The speed of the DC machine has been controlled in forward and reverse motoring modes. The simulation results illustrate that the ANN is able to estimate the motor speed during constant and variable load torque. Also show the robustness of the sensorless speed controller to the fluctuation of the estimated speed and load torque variations.

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Appendix (A) Drive System Specifications

Separately Excited DC Machine

Voltage Sources (V_t and V_f) = 220 [V].
Armature Current (I_a) = 12 [A].
Electrical Power = 2k [w].
Mechanical Torque =13.64 [N.m].
Rate Speed (n) =1400 [rpm].
Moment of Inertia (J) = 0.012 [Kg.m^2].
Friction Coefficient (B) =0.024 (N.m.s).
Armature Resistance (R_a) = 5 [Ω].
Armature Inductance (L_a) = 60 [mH].
Field Resistance (R_f) = 250 [Ω].
Field Inductance (L_f) = 50 [H].
Mutual Inductance (L_{af}) = 1.6 [H].
Pole pairs =1.

Analogue Filters Data

Low Pass Filters, 2nd-Order, High Cut-off frequency = 200 [Hz], Damping factor Zeta = 0.707.

Digital Filter data

Finite Impulse Response FIR Type, coefficient structure: Direct form, numerator coefficients [0.5 0.5], Sampling time (Ts) =1e-5 sec.