Speed Control of DC Motor Using Artificial Neural Network

Mohammed Alhanjouri

Islamic University of Gaza, Computer Engineering Department, Al-Rimal, Gaza, Palestine

Abstract: ***This paper uses Artificial Neural Networks (ANNs) in estimating speed and controlling it for a separately excited DC motor which is one of the most important modern techniques that using in control applications and to improve efficiency speed control of separately excited DC motor (SEDM). The rotor speed of the DC motor can be made to follow an arbitrarily selected trajectory. The purpose is to achieve accurate trajectory control of the speed, especially when the motor and load parameters are unknown. Such a neural control scheme consists of two parts. One is the neural identifier which is used to estimate the motor speed. The other is the neural controller which is used to generate a control signal for a converter. These two neural networks are trained by Levenberg-Marquardt back-propagation algorithm. In this paper, the intelligent model is developed to speed control of SEDM which operated at two stages:-the first, NARMA-L2 controller used to control the speed under different external loads conditions. The second, the controller is performance at different reference speed. Simulation results indicates to the advantages, effectiveness, good performance of the artificial neural network controller which is illustrated through the comparison obtain by the system when using conventional controller (Proportional-Integral (PI)). So the results show ANN techniques provide accurate control and ideal performance at real time***

Keywords: Artificial Neural Networks, separately excited DC motor, NARMA-L2, conventional controller

1. Introduction

The development of high performance motor drives is very important in industrial applications. Generally, a high performance motor drive system must have good dynamic speed command tracking and load regulating response. Direct current motor drives have been widely used where accurate speed control is required. The direct current DC motors have been widely utilized in many industrial applications [1,2] such as electric vehicles, steel rolling mills, electric crank, and robotic manipulators due to precise, wide ,simple and continuous control characteristics.

D.C motors have long been the primary means of electric traction. D.C motor is considered a SISO system having torque/speed characteristics compatible with most mechanical loads.

This makes a D.C motor controllable over a wide range of speeds by proper adjustment of its terminal voltage. Recently, brushless D.C motors, induction motors, and synchronous motors have gained widespread use in electric traction. However, there is a persistent effort towards making them behave like dc motors through innovative design and control strategies. Hence dc motors are always a good proving ground for advanced control algorithm because the theory is extendable to other types of motors.

Many practical control issues (motor control problems):
- Variable and unpredictable inputs
- Noise propagation along a series of unit processes
- Unknown parameters
- Changes in load dynamics

Under these conditions, the conventional constant gain feedback controller fails to maintain the performance of the system at acceptable levels.

The proportional Integral (PI) controller is one of the conventional controllers and it has been widely used for speed control of dc motor drives .The major features of the PI controller are its ability to maintain a zero steady-state error to a step change in reference [3].

The last decade has seen an increasing interest in computational intelligence (CI) applications in control of various dynamic systems, including electric motor drives. Most frequently used CI methods, Artificial Neural Networks (ANN) and Fuzzy logic (FL), are widely utilized in area of modeling, identification, diagnostics and control [4].

With the emerging development in artificial intelligence applications, Neural Network has been used in identification and control of linear and non-linear system. The main advantage of ANN based techniques over conventional techniques is the non-algorithmic parallel-distributed architecture for information processing that allows it to learn any complex input-output mapping[5] .So, ANN are rapidly gaining popularity among power system researches. ANN are extremely useful in the area of learning control. Consequently, the traditional adaptive control designed has taken a new turn with advent of ANN.

The incorporation of feed forward in artificial neural networks is important for several reasons the dynamical properties of the system, and in practice it may improve the performance. They are generally present in most non-linear dynamical system and can be used to implement specific structures.

Advantages of using ANNs:
- Learning ability
- Massive parallelism
- Fast adaptation
- Inherent approximation capability
- High degree of tolerance

Speed control techniques in separately excited dc motor:

- Varying the armature voltage in the constant torque region.
- In the constant power region, field flux should be reduced to achieve speed above the rated speed.

Methods of speed control:

- Traditionally rheostat armature control method was used for low power dc motors.
- Use of conventional PID controllers.
- Neural network controllers (NNC).
- Constant power field weakening controller based on load-adaptive multi-input multi-output linearization technique (in high speed regimes).
- A single phase uniform PWM ac-dc buck-boost converter with only one switching
- Device used for armature voltage control.
- Use of NARMA-L2 (Non-linear Auto-regressive Moving Average) controller in the constant torque region.

Through experience gained in designing trajectory controllers based on self-tuning and PID control, it is seen that the neural network controller gives comparable performance in speed tracking. In addition to those mentioned above, a unique advantage of the neural network controller is its ability to cope with bad measurement data that occur during training and testing.

The traditional means adapted by the motion control industry with motor drives has been the approach of linearizing the system dynamics and designing a linear feedback controller. However, in high-performance motor drives such an approach is seldom satisfactory, as it results in poor speed and position tracking when sudden changes in load result in continuous acceleration or deceleration of the motor/load system. Adaptation is necessary to ensure optimal performance.

2. Separately Excited DC Motor

- When a separately excited motor is excited by a field current of if and an armature current of ia flows in the circuit, the motor develops a back emf and a torque to balance the load torque at a particular speed.
- The if is independent of the ia .Each windings are supplied separately. Any change in the armature current has no effect on the field current.
- The if is normally much less than the ia.

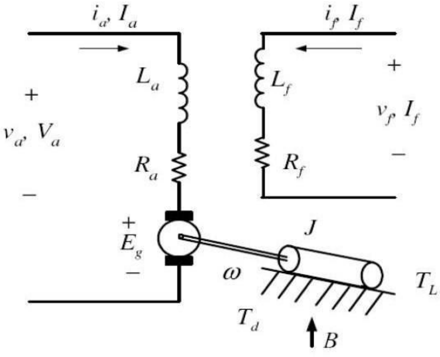


Figure 1: Separately Excited DC Motor

The field windings are used to excite the field flux.

- Armature current is supplied to the rotor via brush and commutator for the mechanical work.
- Interaction of field flux and armature current in the rotor produces torque.

Instantaneous field current:

$$vf= Rfif+Lf*dif/dt$$

Where Rf and Lf are the field resistance and inductor, respectively.

And we can calculate Instantaneous armature current as:

$$Va= Raia+La*dia/dt+eg$$

Where Ra and La are the armature resistance and inductor, respectively.

While the motor back emf, which is also known as speed voltage, is expressed as:

$$eb= Kv\ \omega\ if$$

Where Kv is the motor voltage constant (in V/A-rad/s) and ω is the motor speed (in rad/sec)

2.1 Basic torque equation

For normal operation, the developed torque must be equal to the load torque plus the friction and inertia,i.e.:

$$Td = J*d\omega/dt+B\omega+TL$$

The torque developed by the motor is:

$Td=Ktifia$

Where (Kt=Kv) is torque constant in V/A-rad/sec.

Sometimes it is written as:

$Td=Kt\varphi ia$

For normal operation, the developed torque must be equal to the load torque plus the friction and inertia, i.e.:

where

B : viscous friction constant,(N.m/rad/s)

TL :load torque (N.m)

J : inertia of the motor (Kg.m2)

2.2 Steady State Operation

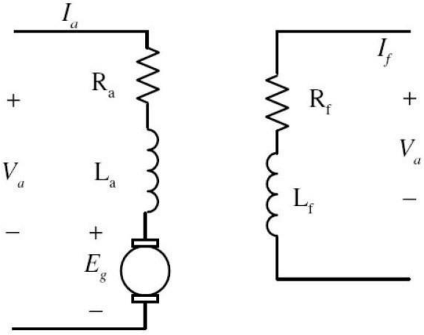


Figure 2: Separately Excited DC Motor in Steady State

Under study state operation, a time derivative is zero. Assuming the motor is not saturated.

For field circuit,

$Vf=IfRf$

The back emf is given by:

$Eg=Kv\omega If$

The armature circuit,

$Va = IaRa+Eg = IaRa+Kv\omega If$

2.3 Steady-state torque and speed

The motor speed can be easily derived: if Ra is a small value (which is usual), or when the motor is lightly loaded, i.e. Ia is small, that is if the field current is kept constant, the motor speed depends only on the supply voltage.

The developed torque is:
Td=KtIfIa=Bω+TL
The required power is:
Pd = Tdω

2.4 torque and speed control

From the derivation, several important facts can be deduced for steady-state operation of DC motor.

a) For a fixed field current, or flux (If), the torque demand can be satisfied by varying the armature current (Ia).
b) The motor speed can be varied by:
   - Controlling Va (voltage control)
   - Controlling Vf (field control)
c) These observations lead to the application of variable DC voltage for controlling the speed and torque of DC motor.

2.5 Variable Speed Operation

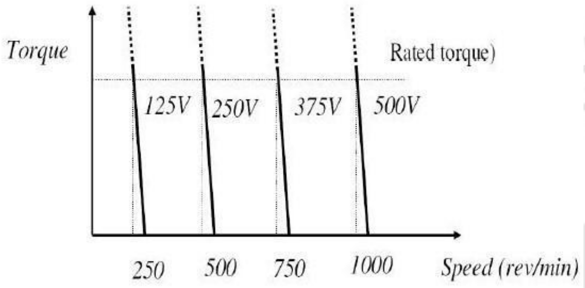


Figure 3: Torque Vs Speed Characteristic For Different Armature Voltages

Family of steady-state torque speed curves for a range of armature voltage can be drawn as above.

- The speed of DC motor can simply be set by applying the correct voltage.
- Note that speed variation from no-load to full load (rated) can be quite small. It depends on the armature resistance.

2.6 base speed and field-weakening:

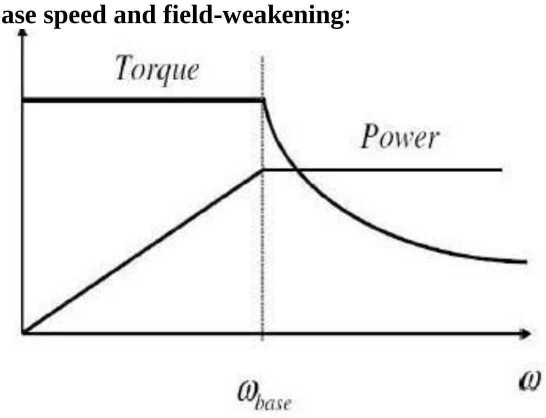


Figure 4: Torque Vs Speed and Power Vs Speed Characteristic Of Separately Excited DC Motor

Base speed: (ωbase)
– the speed which correspond to the rated Va, rated Ia and rated If.
• Constant Torque region (ω > wbase)
– Ia and If are maintained constant to met torque demand. Va is varied to control the speed.
Power increases with speed.
• Constant Power region (ω > wbase)
– Va is maintained at the rated value and If is reduced to increase speed. However, the power developed by the motor (= torque x speed) remains constant. This phenomenon is known as field weakening.

3. Separately excited dc motor model

A DC motor considered a single input single output system having torque-speed characteristics compatible with most mechanical loads. This makes the DC motor controllable over a wide range of speeds by proper adjustment of its terminal voltage. Therefore DC motors are used in high performance drives applications[7].
The dynamics of the SEDM. As shown in fig. (1) are described by the following electrical and mechanical differential equations:-

$$L_a \frac{di_a}{dt} = -i_a R_a - kw + v_a \text{.............(1)}$$

$$J \frac{dw}{dt} = k i_a R_a - B w T_L \text{ ……………… (2)}$$

Where va is the motor input voltage; ia is the armature current; w is the rotor speed; TL is the load torque; Ra is the armature resistance; La is the armature inductance; J is the motor rotation inertia; B is the damping constant and K is the torque or EMF constant[5].
fig.(5) illustrate Basic mathematical model of separately excited dc motor, where:

- Ta -Time constant of motor armature circuit and Ta=La/Ra (s)
- Tm – Mechanical time constant of the motor Tm=J/B (s)

The parameters of the SEDM are:1800 rpm, 220 volts, La= 0.0025H, Ra=0.5Ω,TL=21.4N.m, J=0.0013kg/m2, B=0.001 N.m, the speed at full-load=1500rpm.

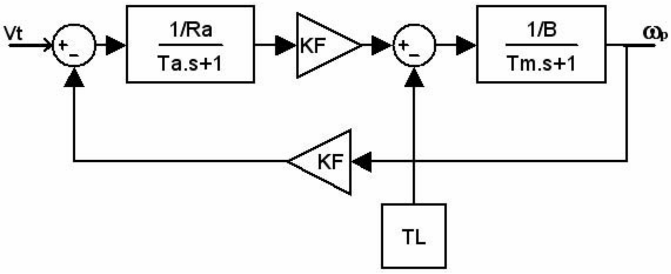


Figure5: The Basic mathematical model of separately excited dc motor.

Simulation of SEDM model
The transfer function block diagram of SEDM can be developed by MATLAB Simulink as shown in fig (6).
And the speed response without controller at no load and full load is shown in fig.(7) when TL=21N.m.

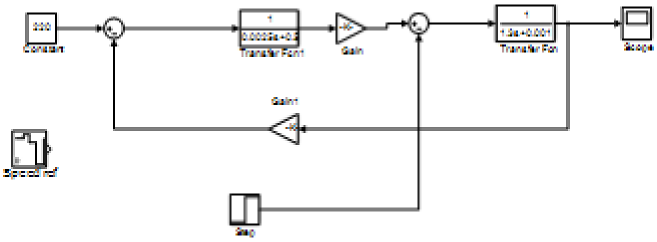


Figure 6: The transfer function block diagram of separately excited D.C. Motor without control

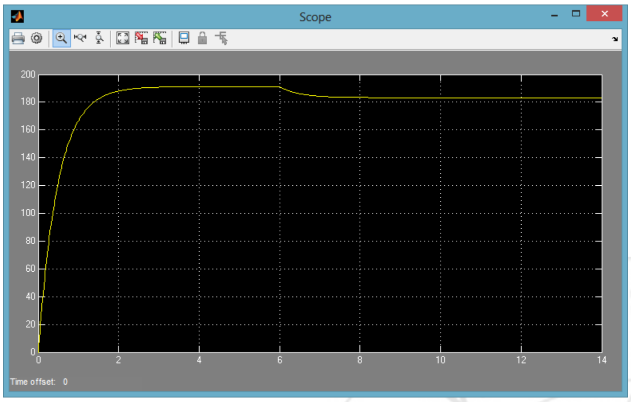


Figure 7: The speed response (w) of the separately excited D.C. motor without control.

Figure 8 show the speed response of SEDM with different reference speed without control.

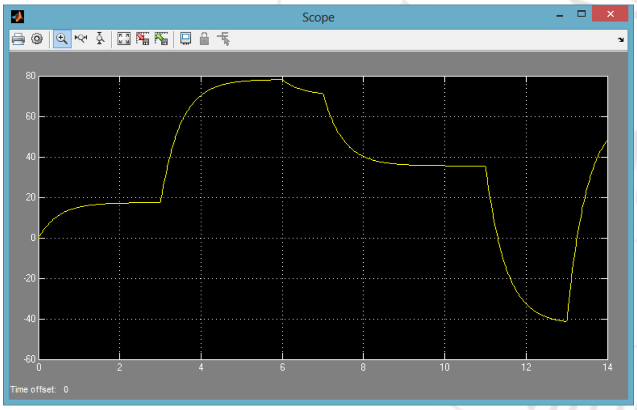


Figure 8: Speed response of SEDM with different reference speed without control

4. PI Controller of SEDM

Since most of the process cannot work with an offset, they must be controlled at their set points and in order to achieve this, extra intelligence must be added to proportional controller and this is achieved by providing an integral action to the original proportional controller. So the controller becomes proportional –Integral controller. The proportion integral (PI) speed controller is initially designed using the symmetrical optimum criterion[8].This controller is used to reduce or eliminate the steady-state error between the measured motor speed (w) and the reference speed (wref) to be tracked. The transfer function of PI controller is given by [9]:

$GC(s)=Kp+K1/s$……………………(3)

- Under PI Controller as long as error is present the controller keeps changing its output and once the error is zero or it disappears the controller does not change its output.
- Integration is the mode that removes the offset or the error but sometimes it may make transient response worse.
- In PI Controller the output of the controller is changed proportional to the integral of the error.

The mathematical expression of the PI Controller is:

$$y = Kp.e + Ki \int e\,.dt$$

Where, Ki = Integral gain of the PI controller.

PI Controller has the following disadvantages:

- The response is sluggish at the high value of the integral time Tn.
- The control loop may oscillate at the small value of integral time Tn.

Figure (9) shows the block diagram of SEDM with PI controller at different load and different reference speed, and the speed response of SEDM with PI controller can be shown in figure (10),(11) at different load and different reference speed respectively.

In the feedback control system, the dynamics of the DC motor can be described by transfer function. The signal will be sent to the plant and the output signal will be obtained, this new output signal (speed)will be sent back to find the new error signal and computes until the error signal becomes so small [10].

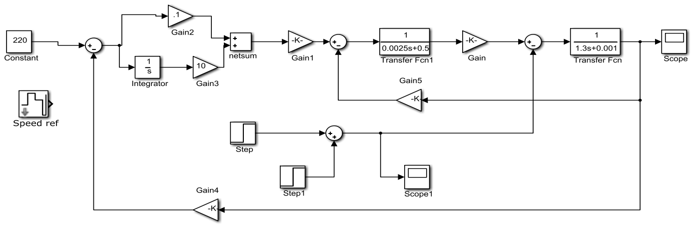


Figure 9:the block diagram of SEDM with PI controller

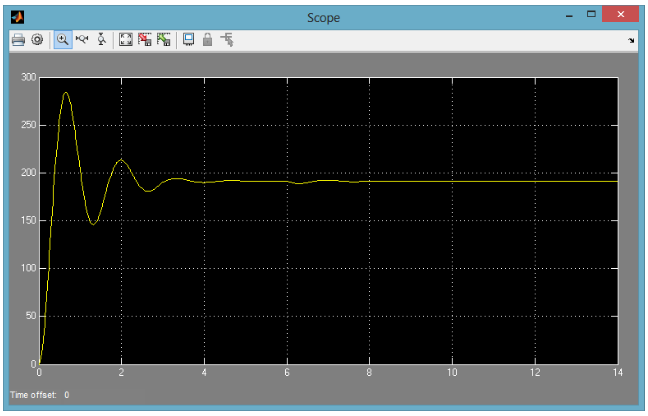


Figure 10: The speed response with PI Controller at different load

Firstly, for controlling the speed of DC motor PI control strategy is applied. The block diagram for the PI control is developed in Matlab/Simulink and the transfer function for the PI control is obtained using Ziegler-Nicholas method.
Where Kp and K1 are the proportional and integral gains (KP=10, K1=0.1).

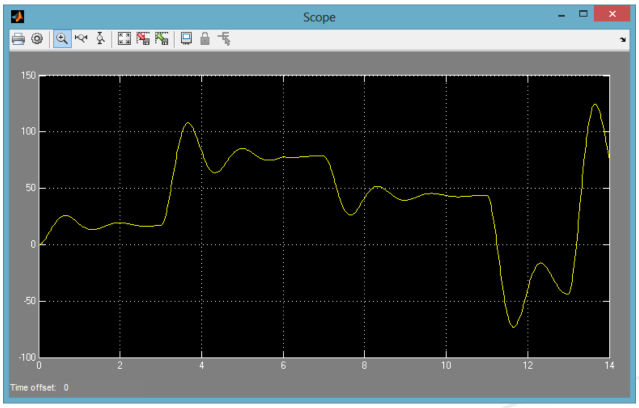


Figure 11: Different reference speed with PI controller

5. Design of Neural Network (NARMA-L2 Controller

5.1 NARMA-L2 Controller

The learning ability, self-adapting, and super-fast computing features of ANN make it well suited for the control of DC motor. In learning process, neural network adjusts its structure such that it will be able to follow the supervisor. The learning is repeated until the difference between network output and the supervisor is low. MATLAB based Subsystem for NARMA L-2 Controller as shown in figure 12.

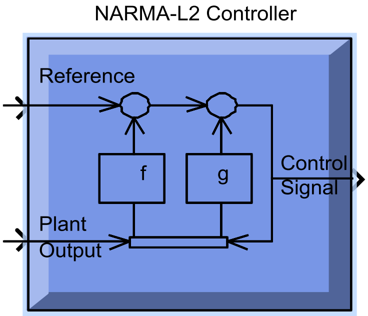


Figure 12: MATLAB based Subsystem for NARMA L-2 Controller

This study uses NARMA-L2 neural controller to control the speed of SEDM, NARMA-L2 (Nonlinear Autoregressive-Moving Average) neural controller requires the least computation and it's simply a rearrangement of the neural network plant model, which is trained off-line, in batch form. The only online computation is a forward pass through the neural network controller [12].

NARMA-L2 controller, a multilayer neural network has been successfully applied in the identification and control of dynamic systems [1]. There are two steps involved in NARMA-L2 controller which are:

- System identification
- Control design.

System identification stage developed a neural network model of the plant to be controlled.

Control design stage, use the neural network plant model to train the controller.

The ultimate objective is to find a combination of parameters which gives a total error of required tolerance a reasonable number of training sweeps[14]. ,fig (13) show the general structure of ANN used in this study which consist of three input represent (Ia ,Vt ,wr) of the SEDM and one output (w) and consist of seven hidden layers. The process of training done by using large numbers of input/output data which obtained from SEDM.

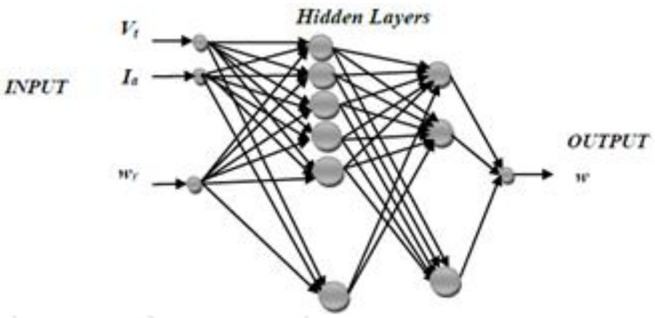
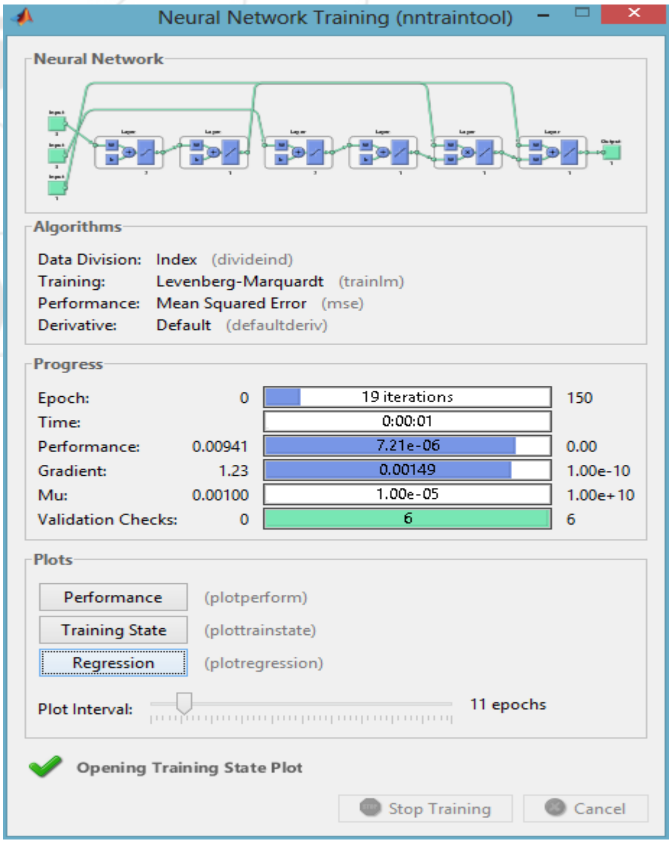


Figure 13: A general ANN structure

Figure 14 shows the neural network training. In the system identification stage a neural network plant model must be developed before the controller is used. The plant model predicts future plant outputs. The specifications of the plant model are given in figure 9.



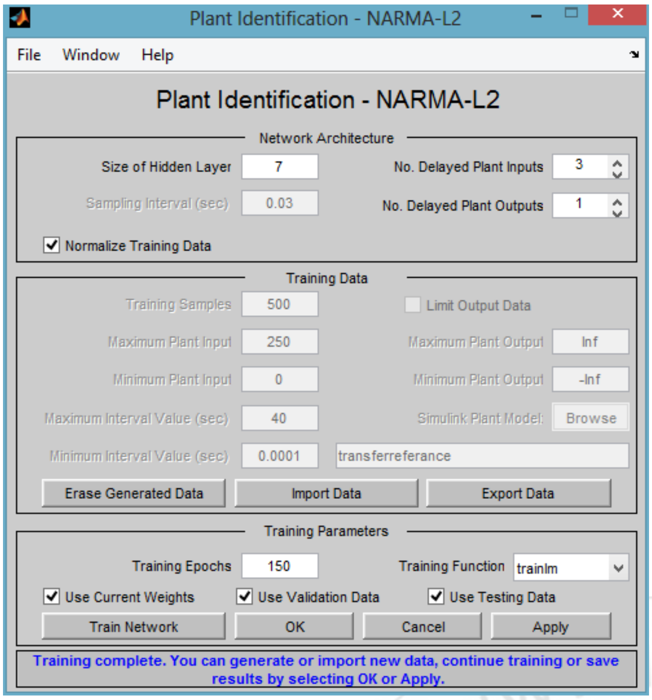
Algorithms
Data Division: Index (divideind)
Training: Levenberg-Marquardt (trainlm)
Performance: Mean Squared Error (mse)
Derivative: Default (defaultderiv)

Progress

Epoch:	0	19 iterations	150
Time:		0:00:01	
Performance:	0.00941	7.21e-06	0.00
Gradient:	1.23	0.00149	1.00e-10
Mu:	0.00100	1.00e-05	1.00e+10
Validation Checks:	0	6	6

Performance (plotperform)
Training State (plottrainstate)
Regression (plotregression)
Plot Interval: 11 epochs
Opening Training State Plot

Figure 14: neural network training



Plant Identification - NARMA-L2

Network Architecture

Size of Hidden Layer 7

No. Delayed Plant Inputs 3

Sampling Interval (sec) 0.03

No. Delayed Plant Outputs 1

☑ Normalize Training Data

Training Data

Training Samples 500

☐ Limit Output Data

Maximum Plant Input 250

Maximum Plant Output Inf

Minimum Plant Input 0

Minimum Plant Output -Inf

Maximum Interval Value (sec) 40

Simulink Plant Model: Browse

Minimum Interval Value (sec) 0.0001

transferferance

Training Parameters

Training Epochs 150

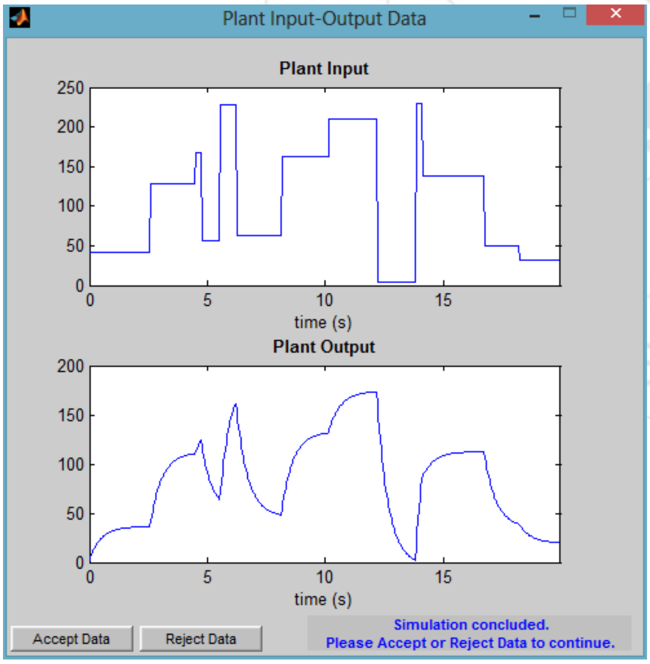
Training Function trainlm

☑ Use Current Weights ☑ Use Validation Data ☑ Use Testing Data

Training complete. You can generate or import new data, continue training or save results by selecting OK or Apply.

Figure 15: Specifications of the plant model

Figure 9 shows the Plant input-output data of NARMA-L2 controller. Sample performance, training state and regression graph as shown in figure 17, 18 and 19 respectively and testing, training and validation data obtained from a NARMA-L2 controller are illustrated in Figure 20, 21 and 22 respectively.



Simulation concluded.
Please Accept or Reject Data to continue.

Figure 16: Plant input-output data of NARMA-L2 controller

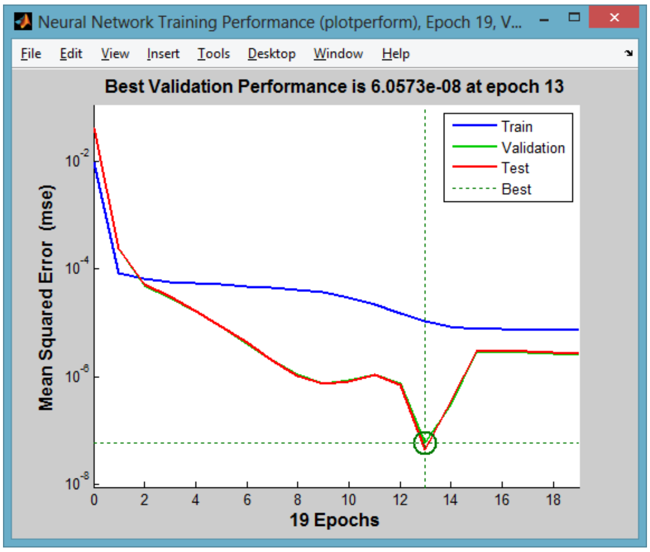


Figure 17: Performance of NARMA L-2 controller

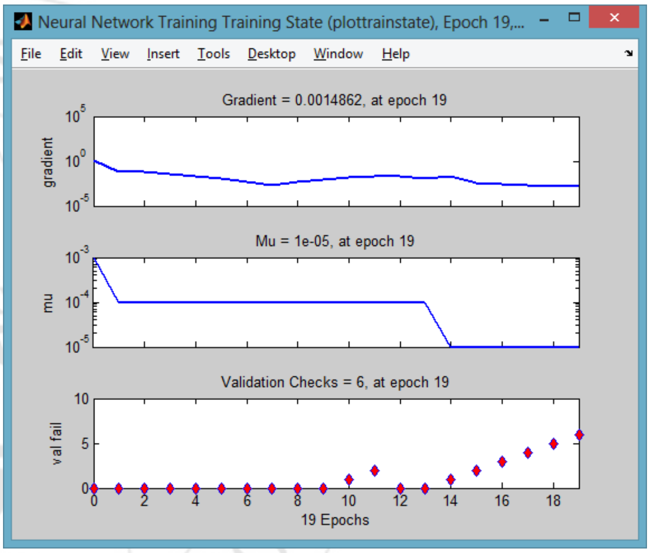


Figure 18: Training state of NARMA L-2 controller

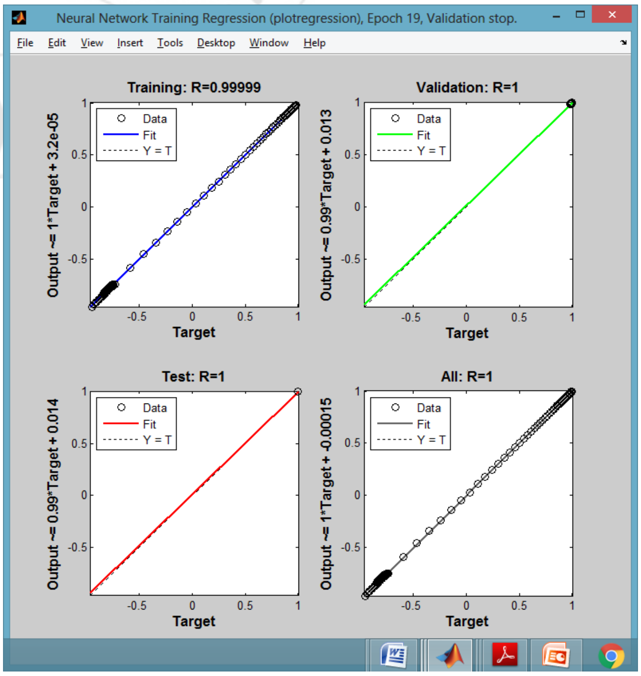


Figure 19: Regression of NARMA L-2 controller

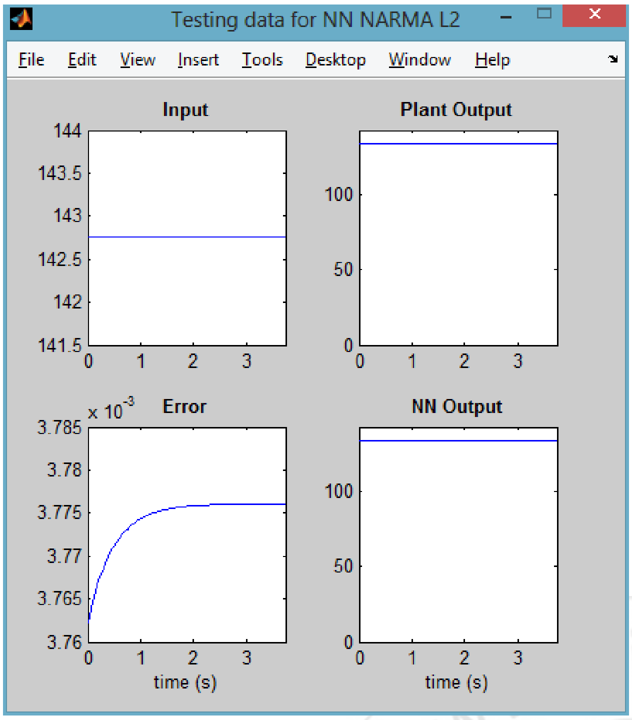


Figure 20: Testing data of NARMA L-2 controller

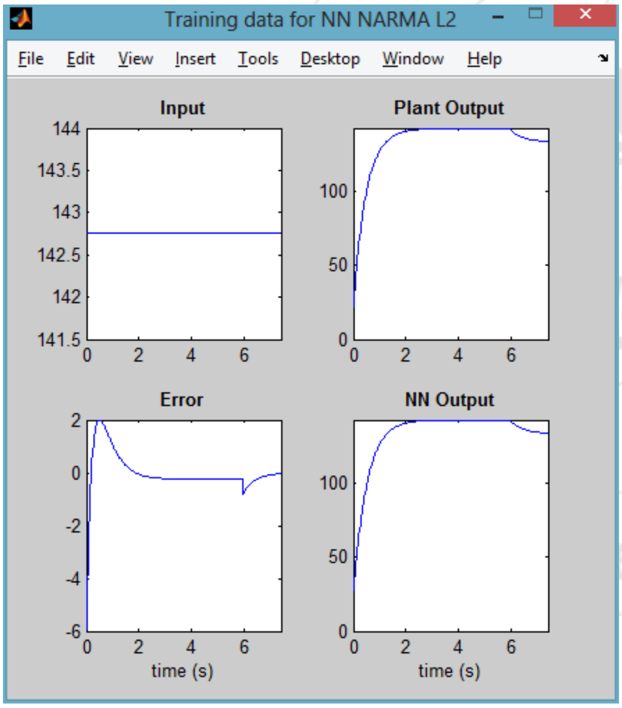


Figure 21: Training data of NARMA L-2 controller

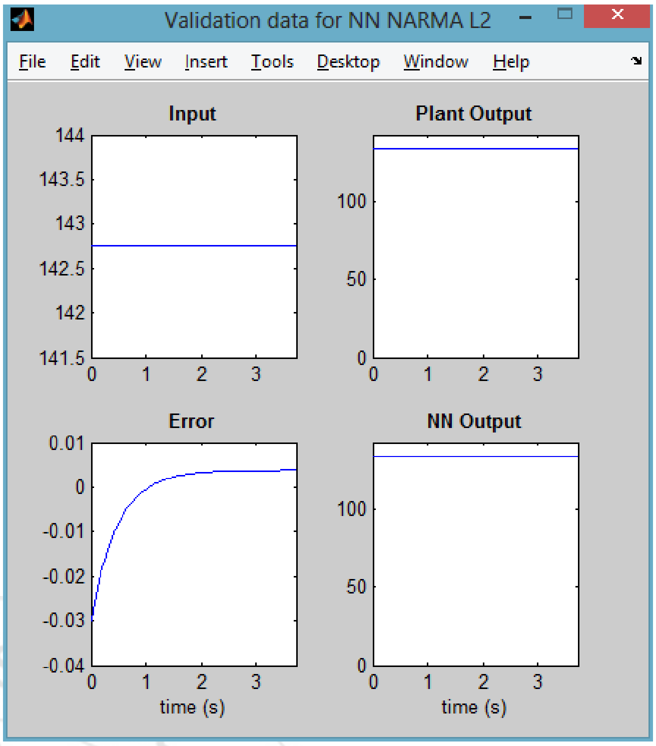


Figure 22: Validation data of NARMA L-2 controller

Simulation results and discussion:

This study proposes the simulation of SEDM to control speed using NARMA-L2 controller which is implemented and compared with conventional PI controller under different load, different reference speed and wide range of different parameters. A complete simulation model for SEDM drive is developed as shown in fig (23), the waveforms of speed control for SEDM at different load and different reference speed can be shown in figure (24) and figure (25) respectively.

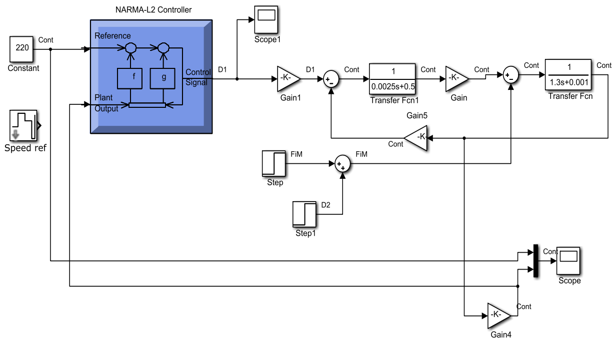


Figure 23: Developed simulation model for SEDM drive

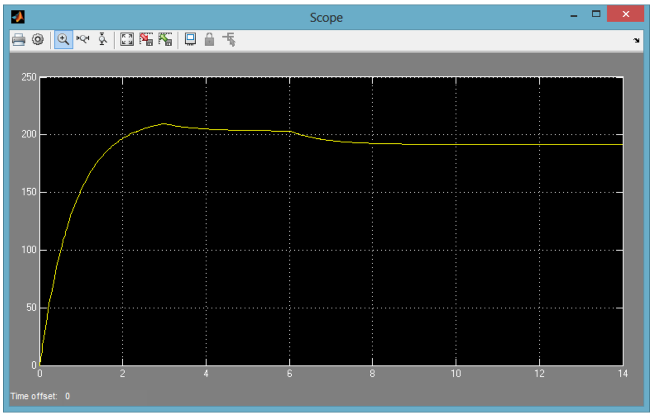


Figure 24: Waveforms of the speed control for SEDM at different load

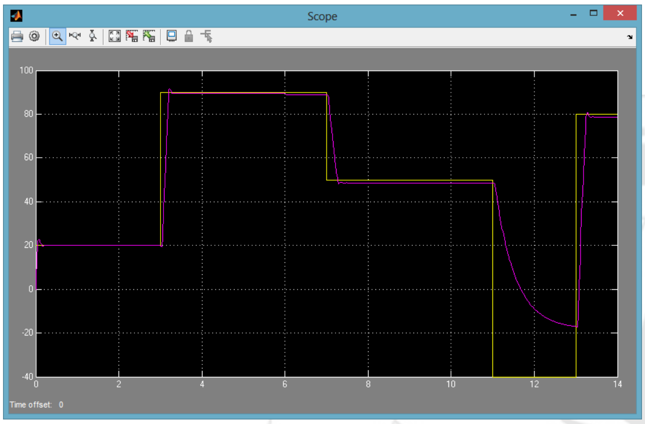


Figure 25: The waveform of model at different reference speed

In this work , the performance of a DC motor with different control strategy, artificial neural network and conventional (PI) is evaluated on the basis of settling time, maximum over shoot and steady state error which can be shown in table (1).

Table 1: The performance of a DC motor with different control strategy

Results	PI- CONTROLLER		NEURAL-CONTROLLER	
	No-Load	Full-Load	No-Load	Full-Load
Maximum overshot (rad/sec.)	100	2	0.00025	-0.00075
Rising time (Sec.)	6 Sec.	0 Sec.	0 Sec.	0 Sec.
Settling time (Sec.)	7.8 Sec.	7.8 Sec.	0 Sec.	0 Sec.
Steady state error (%)	0 %	0 %	0 %	0 %

6. Conclusion

The results shows that, NARMA-L2 controller is the better controller than PI, which is provides satisfactory performance and good response (zero steady state). This controller model shows the excellent step responses at different parameters , different external loads and many reference speed.

The results shows that the implementing NARMA-L2 controller is given simple data processing, effective solution and can be implemented easily in real time.

Finally, the DC motor has been successfully controlled using NARMA-L2 controller and that is possible to applied the artificial network for speed control in wide range of DC machine.

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Author Profile

Dr. Mohammed Ahmed Alhanjouri received Bachelor of Electrical and Communications Engineering (honor) (1998), Master of Electronics Engineering (excellent) (2002), and Ph.D. in 2006. Alhanjouri has worked at Arab Academy for Science & Technology & Maritime Transport (Alex., Egypt) from 2002 to 2006. Then he worked as Assistant Professor, with responsibility: director of projects and research center, and head of computer Engineering department at Islamic University of Gaza, Palestine. Also he worked at University of Palestine as dean of library, then as head of Software Eng. Dept. Currently, he is serving as Associate Professor, Director of Excellence and eLearning Center at Islamic University of Gaza. His primary research interest is in the area of Artificial Intelligence. He also carries out research in many other areas such as: Advanced digital signal processing, Pattern recognition (Image and Speech), data mining, modern classification techniques (neural networks, Hidden Markov Models, Ant colony, Swarm Optimization and Genetic Algorithm).