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Comparative Analysis of Real Time Discrete PID Controller Design using First Principles and Data Driven Model

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ABSTRACT: This paper deals with the speed control of DC motor with PID controller using two different modelling approaches, viz. first principles modelling and data driven modelling. The objective is to compare the time response analysis of the motor in both the models, first by simulation as well as by a practical implementation at different speeds. This paper outlines the detailed procedure of modelling, design of a PID controller and implementation with hardware. The comparison of results show that the data driven model has a better performance compared to first principles modelling.

KEYWORDS: PMDC, PWM, MATLAB, Arduino, PID.

I. INTRODUCTION

Actuators play an important role in any control system. It serves as a final control element changes in accordance with the signal transmitted by the controller. DC motor is one of the important actuators being widely used in applications such as process control, robotics, avionics, rolling mills and automobiles etc. Several conventional and non-conventional techniques are currently in use to control the speed of a DC motor [1]. This paper presents the speed control of PMDC motor by using conventional PID controller with PWM technique. Theoretical and practical DC motor models were designed using Matlab software. With Arduino mega 2560 hardware, a practical discrete PID controller has been designed, implemented and tested for the speed control of PMDC motor. The Practical values are almost matched with the theoretical ones. A PMDC motor converts electrical energy into mechanical energy by applying the voltage to drive either linear or rotational loads. The model of the system is estimated either by first principles modelling or by data driven modelling [2][3]. In this paper both the models have been designed, analysed and presented.

PID controllers have been widely used in many process controls over 50 years and gaining its popularity. Comparison of different conventional and nonconventional techniques' to control the speed control of a DC motor was presented by Ermira Buzi and Petraq Marango in 2013.PID controller as a conventional and inverse neural networks as a non conventional technique was presented to improve the system dynamics[1]. Villagra, Blas Vinagre, In´es Tejado developed data driven fractional PID control for the control of DC motor [2]. Pravallika Vinnakota from Mathworks presented an article on use of data driven model for position control of DC servo motor[5]. In this paper the design and implementation of PID controller in real time for DC motor speed control is presented and a comparison of its time response characteristics such as rise time and settling time are outlined.

II. FIRST PRINCIPLES MODELING

The first principles modelling require the knowledge of physical laws and its governing equations. Modelling through the first principles approach is difficult for the complex models as it requires skills in mathematics and physics.

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The generalized mathematical model for a DC motor to obtain the transfer function is as shown in Fig.1 and the governing equations are listed below.

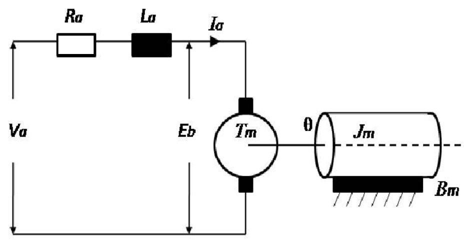

Fig.1 Equivalent Circuit of a DC motor model

$$V_a(t) = R_a I_a(t) + L_a \frac{dI_a(t)}{dt} + E_b(t) \quad (1)$$

$$E_b(t) = K_b \omega(t) \quad (2)$$

$$T_m = K_m . I_a(t) \quad (3)$$

$$T_m(t) = J_m . \frac{d\omega(t)}{dt} + B_m . \omega(t) \quad (4)$$

$$\frac{\omega(s)}{V_a(s)} = \frac{K_m}{L_a . J_m S^2 + (R_a . J_m + L_a . B_m) . S^2 + (R_a . B_m + K_b . K_T) . S} \quad (5)$$

$$\frac{\theta(S)}{V_a(S)} = \frac{K_m}{L_a . J_m S^3 + (R_a . J_m + L_a . B_m) . S^2 + (R_a . B_m + K_b . K_T) . S} \quad (6)$$

$$\theta(S) = \frac{1}{S}\, \omega(s) \quad (7)$$

Where
R_a = armature resistance (Ω- ohm).
L_a = armature inductance (H-Henry).
I_a = armature current (A).
$V_a(t)$ = armature voltage (V).
E_b = back emf (V).
ω = angular speed (rad/s).
T_m = motor torque (N m).
θ = angular position of rotor shaft (rad).
J_m = rotor inertia (kg.m^2)
B_m = viscous friction coefficient (N_m.S/rad).
K_m = motor torque constant (Nm/A).
K_b = back emf constant (V S/rad).

A Transcoil 12V DC motor with inbuilt tachometer which runs at the maximum speed of 4500 rpm is used in this paper. The model of DC motor can be designed in Matlab either through Simulink toolbox or through Simscape toolbox [4]. Most of the times all the parameters may not be available from the manufacturer to design the model. Some of the parameters are not specified by the manufacture for the above motor. Simscape is an extension to Simulink provided by MATLAB software to derive the DC motor model from its electrical and mechanical ratings. The Simscape toolbox has been used to design the DC motor model. The Fig.2, 3 shows the Simscape model of the DC motor designed with the stall torque and no load speed parameters.

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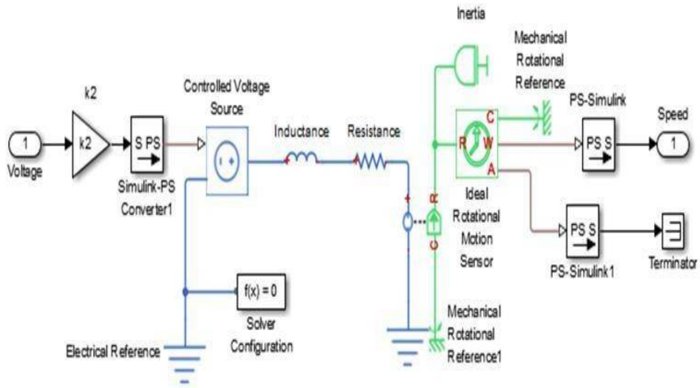

Fig.2 Simscape model of DC motor in Matlab

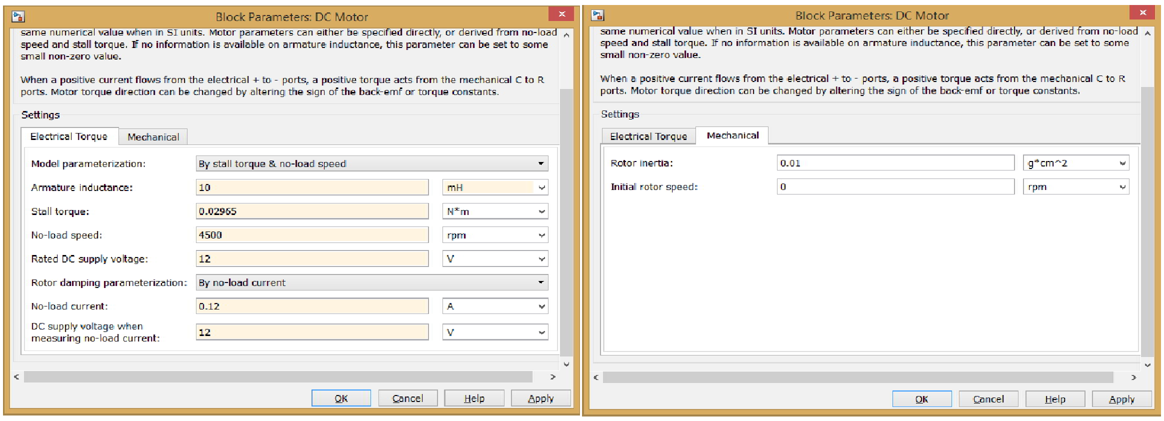

Fig.3 DC motor electrical and mechanical parameters

III. DATA DRIVEN MODELING

Data driven approach model is an alternative to derive the model from the measured input and output data. Linear and non linear transfer functions can be estimated by the use of Matlab system identification tools.Fig.4, 5 shows the estimated linear transfer function from the acquired input output data of the PMDC motor.

The estimated linear transfer function is

$$TF = \frac{4.953}{1-0.5655Z^{-1}-0.07807Z^{-2}} \quad (8)$$

In dead-zone and saturation conditions motor fails to respond linearly due to static friction and output non-linearities. Several methods are exists in literature to obtain non-linear models such as neural networks, sigmoid networks, wavelet transform etc. Hammerstein-wiener method was used to design non-linear model. Eight data sets were collected out of which five data sets were used for data and three were used for validation. Fig.6 shows the estimated Non-linear Transfer function from the acquired input output data.

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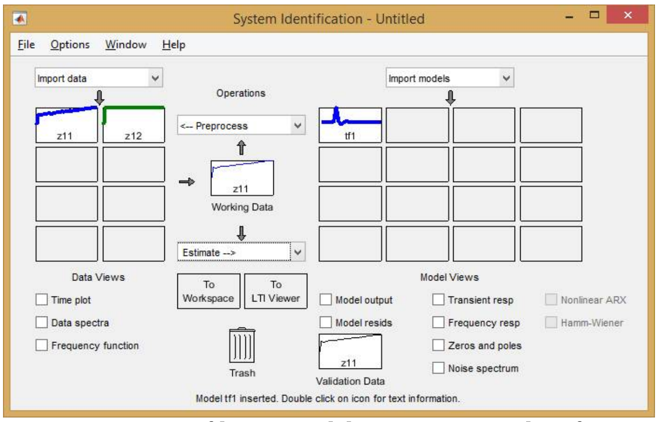

Fig.4 Estimation of linear model using System Identification Toolbox

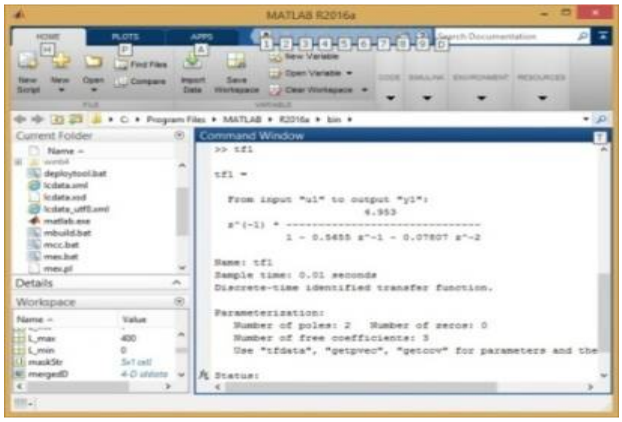

Fig.5 Linear Transfer Function

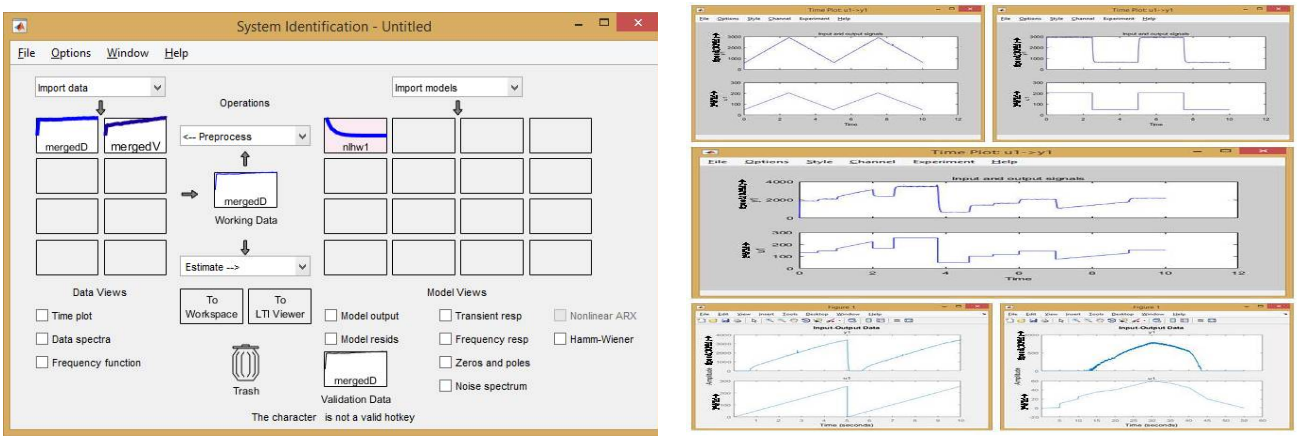

Fig.6 Estimation of Non-linear model from system identification toolbox and its data sets.

The estimated Non-linear transfer function is

$$TF = \frac{0.04978706836 + 0.3967Z^{-1} - 0.1197Z^{-2}}{1 - 0.9134Z^{-1} - 0.9859Z^{-2}} \quad (9)$$

IV.DESIGN OF PID CONTROLLER

Fig.7 shows the generalized block diagram of a closed loop feedback control system. The controller takes the error as an input signal and produces the output signal based on the type of the controller. The error signal is the difference between the set point and the measured value. The type of controller can be conventional PID or Non-conventional controllers such as fuzzy, neural or neuro-fuzzy controllers etc [6]. PID controller is the most generally used feedback controller widely adopted to control any process due to its simplicity. The controller generates the manipulated variable based on the present, past and future error through proportional, integral and derivative terms.

$$u(t) = K_p e(t) + K_i \int e(t)\, dt + K_d \frac{de(t)}{dt} \quad (10)$$

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Where,
u(t) = Controller output
K_p = Proportional constatnt
K_i = Integral constatnt
K_d = Derivative constant
e(t) = Error signal

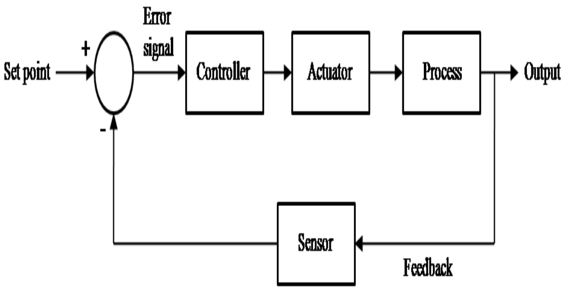

Fig.7. Block Diagram of feedback Control system

Implementing a PID or other dynamic compensators requires skills in digital control, programming and the support of advanced processors [7].The main disadvantage of the PID is tuning of the PID parameters. Tuning of the PID controller is done either offline or online. Different offline tuning techniques such as Ziegler Nicholas and open reaction curve method exists in literature [8]. This paper illustrates the tuning of PID in offline with Matlab automatic tuning tool kit [9][11].

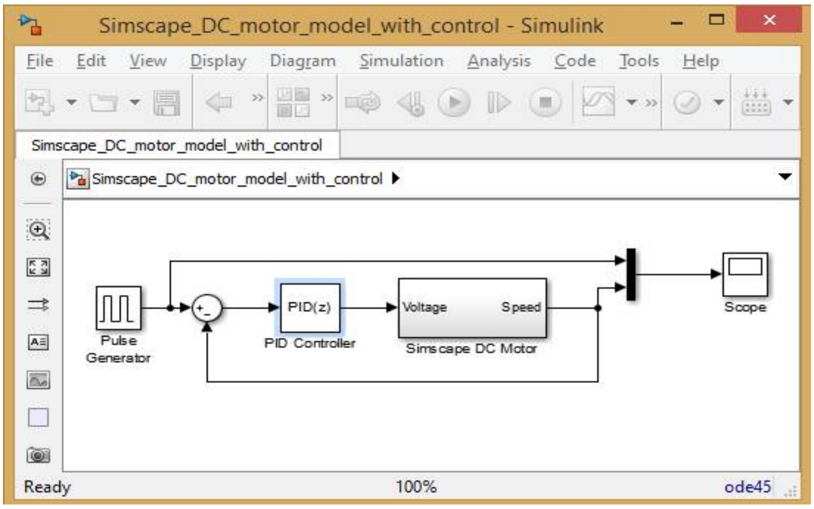

Fig.8 General Matlab Simulink model

In order to design the PID controller, model of the DC motor is essential. Fig.8 shows the general Matlab Simulink model to tune the PID parameters. Fig.9. shows the tuned parameters for the first principles model and its step response for the PMDC motor at a speed of 2500 rpm.

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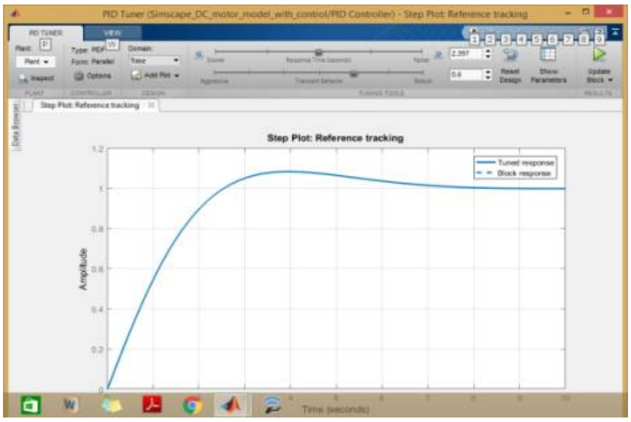


Controller Parameters

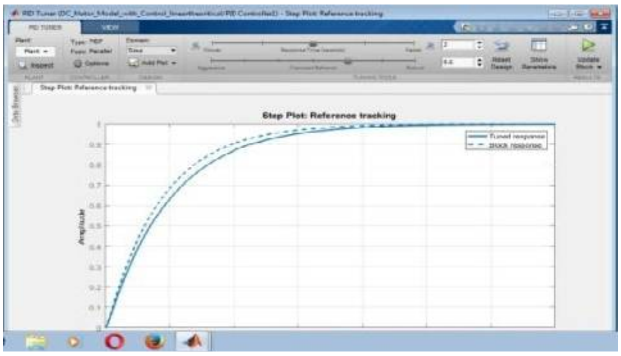
	Tuned	Block
P	1.6664	1.6664
I	1.287	1.287
D	-0.26997	-0.26997
N	0.831	0.831

Performance and Robustness

	Tuned	Block
Rise time	1.84 seconds	1.84 seconds
Settling time	6.65 seconds	6.65 seconds
Overshoot	8.22 %	8.22 %
Peak	1.08	1.08
Gain margin	51.9 dB @ 314 rad/s	51.9 dB @ 314 rad/s
Phase margin	69 deg @ 0.835 rad/s	69 deg @ 0.835 rad/s
Closed-loop stability	Stable	Stable

Fig.9. Tuned PID step response and its parameters of first principles model

The above procedure is repeated for the data driven linear and non linear models as shown in Fig.10, 11.



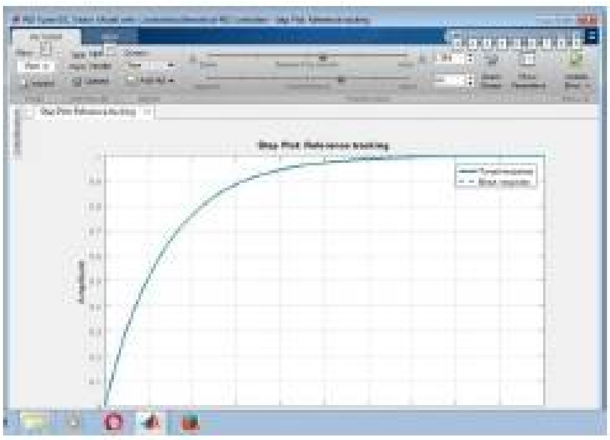
Controller Parameters

	Tuned	Block
P	0.00035999	0.00035999
I	0.071998	0.071998
D	0	0
N	100	100

Performance and Robustness

	Tuned	Block
Rise time	2.13 seconds	2.13 seconds
Settling time	3.82 seconds	3.82 seconds
Overshoot	0 %	0 %
Peak	1	1
Gain margin	47.4 dB @ 91.1 rad/s	47.4 dB @ 91.1 rad/s
Phase margin	88.3 deg @ 1 rad/s	88.3 deg @ 1 rad/s
Closed-loop stability	Stable	Stable

Fig.10 Tuned PID step response and its parameters of data driven linear model



Controller Parameters

	Tuned	Block
P	6.1567e-05	6.1567e-05
I	0.12313	0.12313
D	0	0
N	100	100

Performance and Robustness

	Tuned	Block
Rise time	1.51 seconds	1.51 seconds
Settling time	2.7 seconds	2.7 seconds
Overshoot	0 %	0 %
Peak	1	1
Gain margin	59.4 dB @ 710 rad/s	59.4 dB @ 710 rad/s
Phase margin	89.8 deg @ 1.45 rad/s	89.8 deg @ 1.45 rad/s
Closed-loop stability	Stable	Stable

Fig.11 Tuned PID step response and its parameters of data driven non-linear model

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Table 1 shows the comparison of tuned values of PID parameters obtained.

Table1. PID parameters of first principles and data driven models, rise time, settling times

	Simscape Model	Linear Model	Non-Linear Model
P	1.664	0.00035999	0.04148351828
I	1.287	0.071998	0.12313
D	-0.26	0	0
Rise Time (Sec)	1.84	2.13	1.51
Settling Time (Sec)	6.65	3.82	2.7

Fig.12. shows the Simulink model with linear transfer function to simulate the motor speed at 2500rpm square stimulus to analyse the time response characteristics.

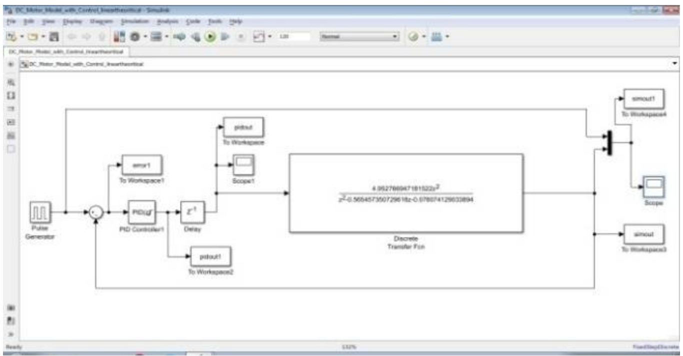

Fig.12 Closed loop PID control Simulink model with DC motor linear transfer function

Fig.13. shows the Simulink model with linear model to simulate the motor speed at 2500rpm square stimulus to analyse the time response characteristics.

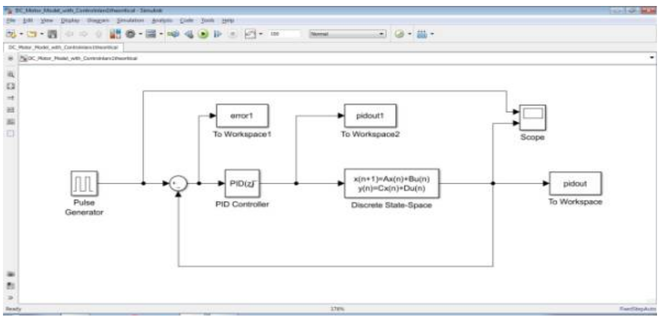

Fig.13 Closed loop PID control Simulink model with DC motor Non-linear transfer function

To validate the simulated results a practical Simulink model is designed by using Matlab Arduino hardware support packages [9][10]. Fig.14.shows the real time closed loop PID controller Simulink model for validating the simulation.

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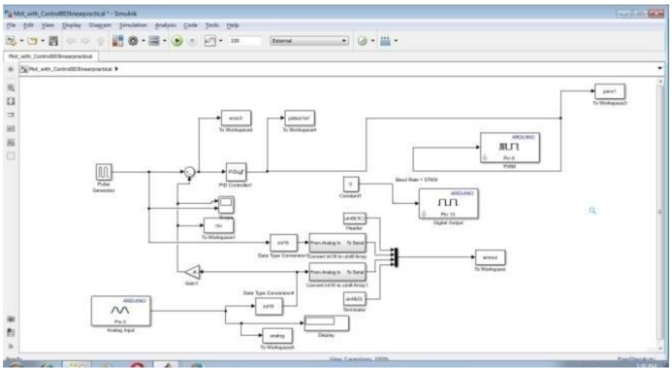

Fig.14 Real time closed loop PID control Simulink model

The DC motor is tested for various speeds and the theoretical and practical values are satisfactory.

IV. HARDWARE SET UP

The data required for the data driven model is collected by using Arduino Mega 2560 microcontroller and L293D H-bridge driver with PWM control technique. Fig.14 shows the block diagram of hardware set up for data acquisition

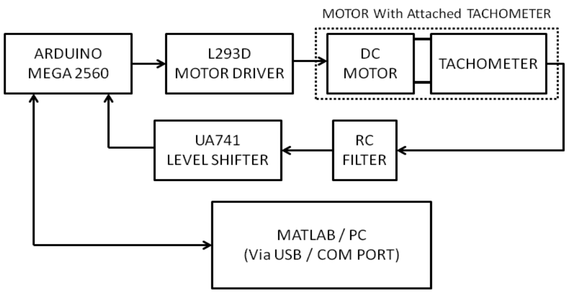

Fig.15 Block diagram of speed control of dc motor

The sensitivity of the DC motor is 1.9V/1000 rpm. At 4500 rpm the output voltage from the motor is 8.5V.However the microcontroller accepts the maximum analog input voltage of 0 to 5v.A level shifter is designed to reduce the voltage of 0 to 8.5v to 0 to 5v range. To remove noise from the output of the tachometer a RC filter has been designed. The voltage is measured with Arduino Mega 2560 board with a sampling rate of 0.001 sec and converted into speed.PID controller takes the error as an input and generates the PWM duty cycle accordingly.

The DC motor is controlled using L293D H-bridge controller. Pin numbers 6, 13 of the Arduino board are used to generate the PWM signal and are interfaced to the control inputs 1A and 2A of the H-bridge controller. The motor is connected in between the output pins 1Y and 2Y of the driver. The speed of the motor is proportional to PWM signal. The motor has in built tachometer that generates the voltage proportional to its speed. The output of the tachometer is given to the DC level shifter through an RC filter. The signal from DC level shifter is given to analog input A0 of Arduino board.

Fig.16, 17 shows the circuit diagram and the hardware setup designed to control the DC motor practically using L293D motor driver and DC level shifter.

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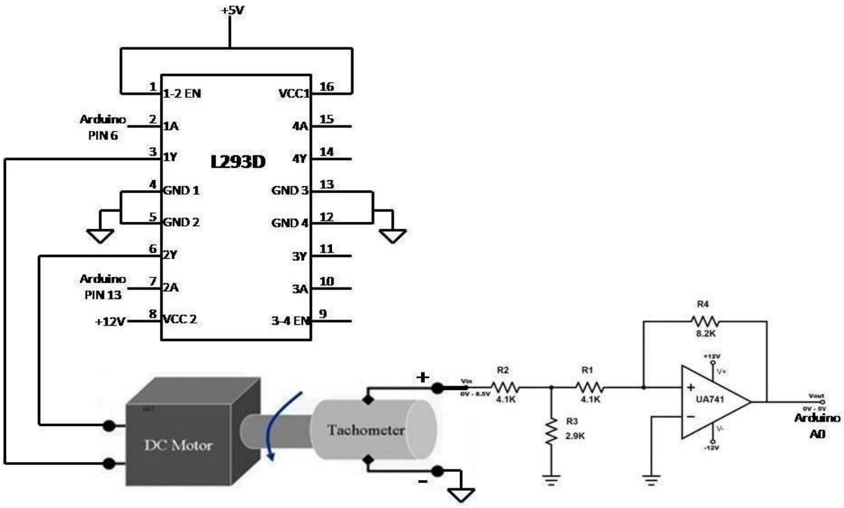

Fig.16 Circuit diagram of the DC motor speed control

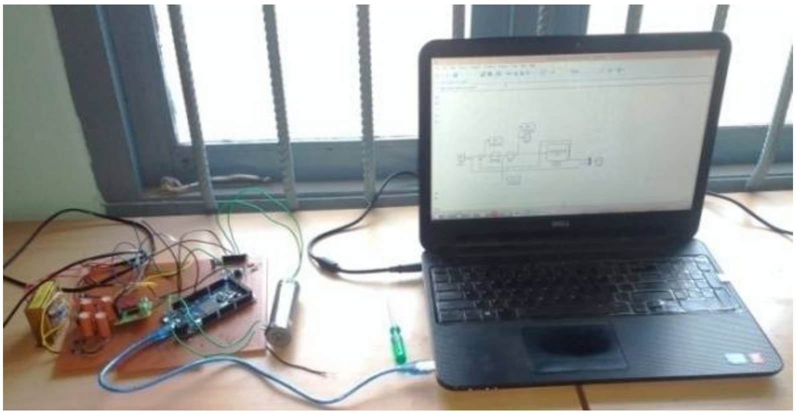

Fig.17 Experimental Setup

VI. RESULTS AND DISCUSSIONS

The experiment was conducted at different speeds. Fig. 18, 19, 20, 21 shows the responses of first principles modelling, data driven linear and non-linear models at the speed of 2500rpm respectively. It has been observed that the speed of the motor follows the set point. The practical values are compared with the theatrical values, matched satisfactorily. The time response characteristics are observed and the non-linear data-driven model has better performance characteristics like “raise time”, “settling time” when compared to first principles approach and linear data-driven model. From the above responses, settling time and raise time of non-linear data driven model is 30% faster than linear data driven model. The data driven model with non linear model is preferred where the more accuracy is desired. Data driven model is currently being used in systems where the mathematical equations for input and output of the systems are now known.

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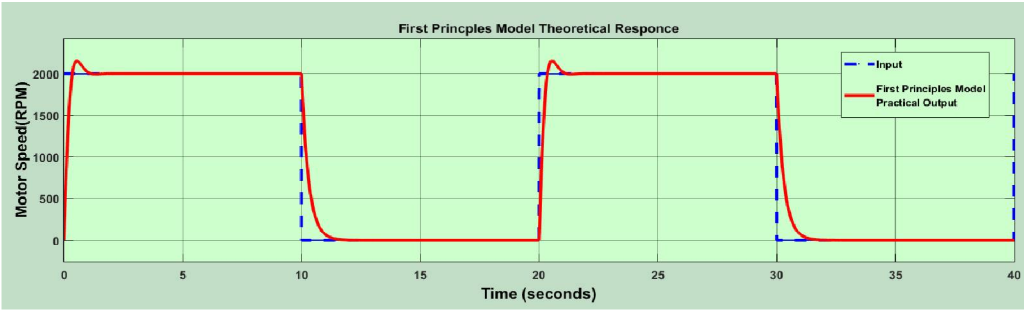

Fig. 18 Theoretical Response with First Principles model

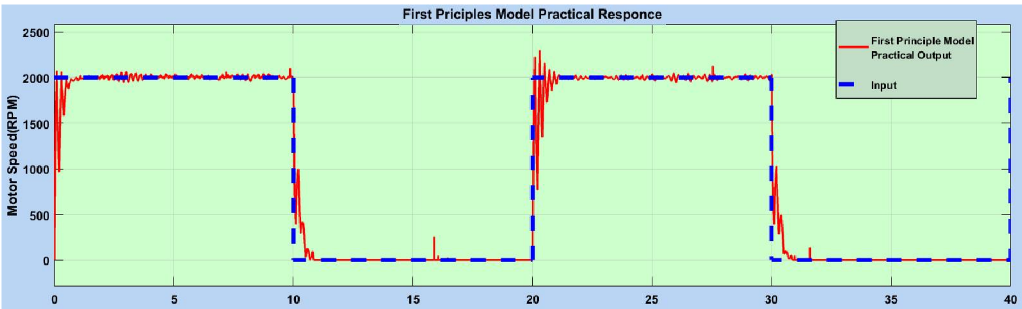

Fig. 19 Practical Response with First Principles model

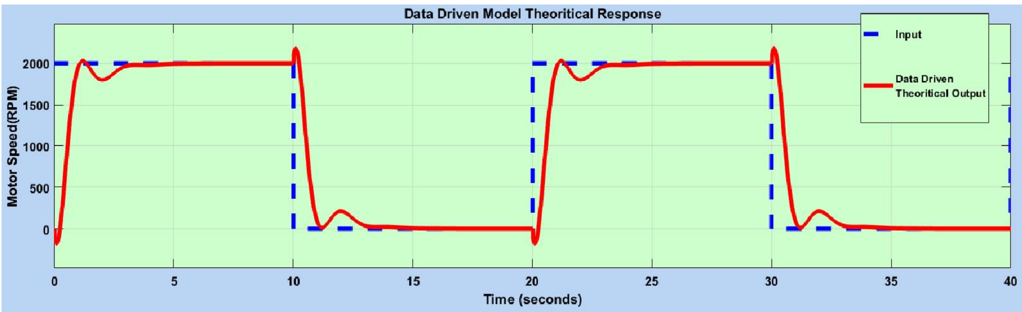

Fig. 20 Theoretical Response with Data Driven model

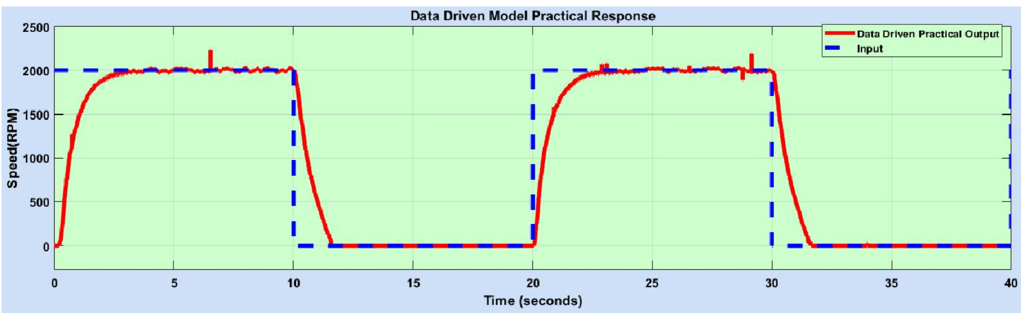

Fig. 21 Practical Response with Data Driven model

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V.CONCLUSIONS

The Speed of the DC motor has been controlled with PWM technique. The theoretical model has been designed and simulated .The simulation results are validated practically by Arduino hardware and results are matched satisfactorily. As the model becomes complex a non conventional techniques such as hybrid models such neuro fuzzy, genetic algorithms or adaptive predictive control techniques can be preferred as a future scope.

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