International Journal of Mechatronics, Electrical and Computer Technology (IJMEC)
ISSN: 2305-0543 (Online), ISSN: 2411-6173 (Print)
Vol. 10(38), Oct. 2020, PP. 4768-4772

Parametric Modeling and PID Control of DC Motor

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***Abstract*— This work attempts to find an identified model of DC shunt motor which can be utilized further to design a controller for speed control of that motor. DCshunt motors are extensively used in servo and mechatronic systems. The parametric model of DC shunt motor has been identified and Proportional-Integral-Derivative (PID) controller has been designed for the control of the speed of the motor. The input-output data for the identification has been collected from the MATLAB SIMULINK model of the DC motor with real DC shunt motor parameters and using these input-output data, parametric Box-Jenkins model of the DC motor has been identified. The identified model has been compared with the classical transfer function model of the system to find out the accuracy of the identification technique in the light of step response and results show that the identified model behaves in a better manner than the classical model of the system. The Proportional-Integral (PI) and PID controllers have been designed to control the speed of the machine based on the identified model. The PID controller gives better performance in terms of steady-state error and transient response specifications. The PID controller also controls the robustly angular speed of the DC shunt motor in presence of parameter variations.**

Keywords*— *Parametric Modeling, System Identification, DC Shunt Motor, PID Controller

I. Introduction

As speed and position controlling equipment, DCshunt motors are widely used in the industry and is one of the common actuators in the control system. Due to the controllability of position; these are used as an integral part of different mechatronic systems. The main applications are robotic movements, hard disk seekers, rolling mills, printers, etc. Every control mechanism needs to apply a control law on the system under consideration. But beforehand we must have the system suitably represented as a model. It may be mathematical such as transfer function. It can be derived with the help of available machine data; supplied by the manufacturer. Sometimes these are not so reliable to give us the proper dynamics of the system. In such a case, the designed controllers will not behave in a fashion in which they are intended to perform. This happens due to wrong machine data or even sometimes data are not available. In such cases, our only helping hand is System Identification.

System Identification is the exercise of building (describing) a relationship between the cause (input) and effect (response) of a system (process) from observed (measured) data [1-2]. With the help of this, we can realize/identify the system in the form of transfer function or any other parametric model. Researchers have already attempted several identification techniques for mechatronic systems, medical processes, robotics, etc. [3-9]. Among them, some researchers have used the non-parametric method of identification and some researchers have applied parametric methods of the identification of the system model.

In this research work, the parametric method of system identification has been used as it gives more accuracy. The input-output data has been collected from the MATLAB SIMULINK model of the DC motor and the acquired data have been used for the identification of the Box-Jenkins (BJ) model of the DC shunt motor. Here 4th order BJ model of the system is identified and it has the capability to predict the output of the DC machine in an almost accurate manner with any given input. The output of the identified model has also been compared with the classical transfer function of the system and the identified BJ model gives a better result. The design of an efficient controller is also required for the control of speed or position of DC motor with respect to different mechatronic systems. The control task is to get a stable and required speed with the application of control input i.e. armature input voltage. In this study, Proportional-Integral (PI) and Proportional-Integral-Derivative (PID) controllers have been designed using Ziegler-Nichol's first method based on parametric BJ model. But PID controller gives superior results than the PI controller and this designed controller also gives a robust performance in the presence of parameter variations

II. Transfer Function Modeling of DC Shunt Motor

The main goal in developing the mathematical model for armature controlled DC shunt motor is to find the relationship between the armature input voltage (V in volts) and the angular velocity (ω in rad/sec) of the motor in terms of some motor parameters. The equivalent circuit of a DC shunt motor is shown in Fig.1 where ía and íf are the armature current and field current respectively; Eb is the back emf; Td is the electromagnetic torque produced by the motor and TL is the load torque. The Laf is the mutual inductance between armature and field circuit and for the derivation of transfer function Laf is neglected. The description of the nameplate parameters of the machine along with their values [5] is given in TABLE 1.

Article History:
Received Date: Apr. 12, 2020, Accepted Date: Jul. 16, 2020, Available Online: Sep. 01, 2020

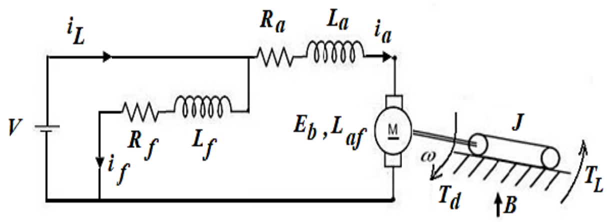

Fig. 1 Equivalent circuit of DC shunt motor

TABLE 1. DC shunt motor nameplate parameters

Parameters	Symbol	Values
Shaft speed	N, ω	1500 rpm, 157.1 rad/sec.
Terminal Voltage	V	120V
Armature Current	I_a	9.2A
Armature Resistance	R_a	1.5Ω
Armature self-inductance	L_a	0.02H
Field resistance	R_f	100Ω
Field self-inductance	L_f	20H
Mutual inductance between armature and field	L_{af}	0.518H
Moment of inertia	J	0.02365Kg.m^2
Damping ration of the mechanical system	B	0.00025Nm/rpm
Torque constant	k_t	0.63Nm/A
Back emf constant	k_b	0.63V/rad.s^{-1}

Neglecting the effect of mutual inductance between armature and field circuit, the dynamics of the armature controlled DC shunt motor is given by the following differential equations.

$$V = i_a R_a + L_a \frac{di_a}{dt} + E_b \quad (1)$$

$$E_b = k_b \omega \quad (2)$$

$$T_d = T_L + B\omega + J\frac{d\omega}{dt} \quad (3)$$

$$T_d = k_t i_a \quad (4)$$

The transfer function of the armature controlled DC motor considering load torque T_L=0 is given by

$$\frac{\omega(s)}{V(s)} = \frac{k_t}{(L_a s + R_a)(Js + B) + k_b k_t}$$

For this problem, the transfer function of the armature controlled DC motor is

$$\frac{\omega(s)}{V(s)} = \frac{0.63}{0.000473s^2 + 0.03548s + 0.3973}$$

III. Identification of the Parametric Model

System Identification deals with the dynamic system's modeling from its input/output information [1-2]. The system's model can be identified using non-parametric and parametric identification methods. The parametric method is computationally more demanding and popular as this method provides better accuracy. In this study, the model of armature controlled DC shunt motor has been identified using the parametric method and this identified model has been used for the design of the controller to control the speed of the motor. In this case, the Box-Jenkins model has been identified for the DC motor which is a natural extension of the output-error model structure [1-2], and the model structure is shown in Fig. 2.

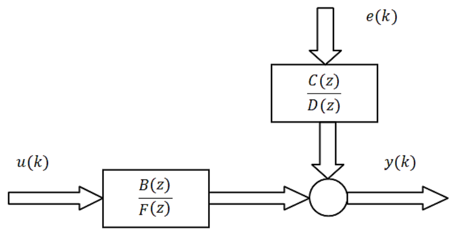

Fig. 2 Box-Jenkins model structure

In this structure, the error signal $e(k)$ is a white noise error term and the output is modeled as an Autoregressive–Moving-Average (ARMA) model [1-2]. The relationship between input $u(k)$ and output $y(k)$ is given by the following relationship.

$$y(k) = \frac{B(z)}{F(z)}u(k) + \frac{C(z)}{D(z)}e(k) \quad (5)$$

where, $B(z), F(z), C(z)$ and $D(z)$ are polynomials of the following form.

$$B(z) = b_1 z^{-1} + \ldots + b_n z^{-n_b} \quad (6)$$

$$F(z) = 1 + f_1 z^{-1} + \ldots + f_n z^{-n_f} \quad (7)$$

$$C(z) = 1 + c_1 z^{-1} + \ldots + c_n z^{-n_c} \quad (8)$$

$$D(z) = 1 + d_1 z^{-1} + \ldots + d_n z^{-n_d} \quad (9)$$

Here z^{-1} is the time-shift operator and $z^{-1}u(k) = u(k-1)$. The structure given by (5) is entirely defined by the four integers n_b, n_f, n_c, and n_d which are basically the order of the polynomials. The objective is to find all the co-efficients b_i $(1 \le i \le n)$, f_i $(1 \le i \le n)$, c_i $(1 \le i \le n)$ and d_i $(1 \le i \le n)$ of the above polynomials given by (6)-(7) to entirely identify the model of a dynamic system in terms of Box-Jenkins. Mean squared error (MSE) method is used to estimate the coefficients of the Box-Jenkins model [5-6]. The goal is to find all the co-efficients to identify the system under consideration such that MSE is minimized. The mean squared error is given by

$$\text{MSE} = \frac{1}{n}\sum_{i=1}^{n}(y_i - \tilde{y}_i)$$

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where, y_i = actual output of the system and $\tilde{y}_i$= predicted output.

In this work, the input & output data which have been used for the identification of the model of the DC shunt motor has been collected from the MATLAB SIMULINK model of the DC shunt motor. The SIMULINK model diagram of the DC motor in an open-loop configuration is given in Fig. 3. The machine data that have been used for modeling are given in TABLE 1. Here the input & output data collected are split into two parts, one part of the collected data was utilized for model identification which is based on the Box-Jenkins model whereas another set of data was used to do the validation [2, 5] of the identified model.

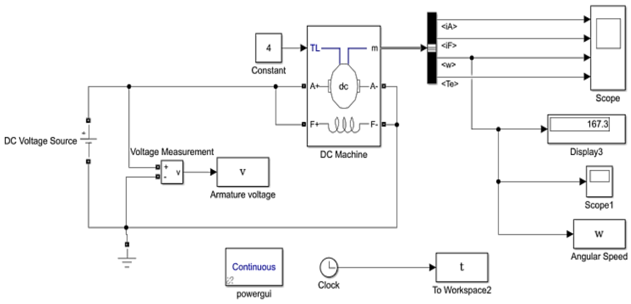

Fig. 3 Simulink model of DC shunt motor in an open-loop configuration

$$B(z) = 0.002658z^{-1}+0.001686z^{-2} - 1.533e^{-5}z^{-3}$$

$$C(z) = 1 - 0.3937z^{-1}-0.2755z^{-2} - 0.2908z^{-3}$$

$$D(z) = 1 - 2.726z^{-1}+2.527z^{-2} - 0.7876z^{-3}$$

$$F(z) = 1 - 2.698z^{-1}+2.441z^{-2} - 0.7405z^{-3}$$

4th order identified model:

$$B(z) = -0.00094z^{-1}+0.01563z^{-2} - 0.02009z^{-3} + 0.0062z^{-4}$$

$$C(z) = 1 - 0.3167z^{-1}+0.29363z^{-2} - 0.1297z^{-3} + 0.384z^{-4}$$

$$D(z) = 1 - 2.457z^{-1}+2.459z^{-2} - 1.361z^{-3} + 0.3863z^{-4}$$

$$F(z) = 1 - 3.574z^{-1}+4.813z^{-2} - 2.895z^{-3} + 0.6561z^{-4}$$

A comparison of different identified model outputs and measured output is shown in Fig. 4. The 3rd order identified model fits 95.92% with measured output whereas the 4th order identified model fits 97.64% with measured output. Fig.7 also shows that the 4th order identified model tracks the measured output in a better way than others. So for this study, 4th order identified model is taken for the analysis and design of the controller.

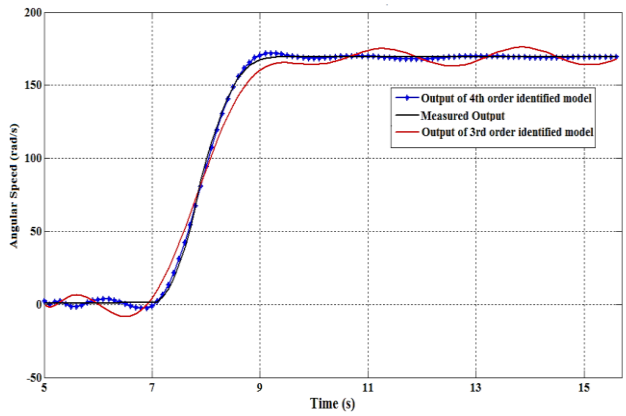

Fig. 4 Measured and simulated model outputs of different orders

IV. PID CONTROL OF DC MOTOR

For controlling the angular speed of the DC motor, the Proportional-Integral-Derivative (PID) controller has been used which is very simple and extensively used in the industry as an efficient controller. In the PID controller, the output of the controller is proportional plus derivative plus integral of the error signal [11]. This controller improves both the transient response and steady-state response of the system. The block diagram of the PID controller is shown in Fig. 5 and the output of the controller are given by the following expression.

$$u(t) = k_p + \frac{k_i}{s} + k_d s$$

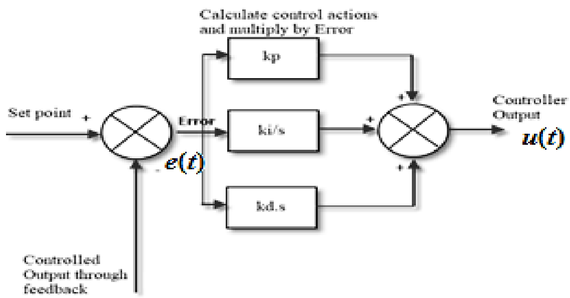

Fig. 5 PID-controller

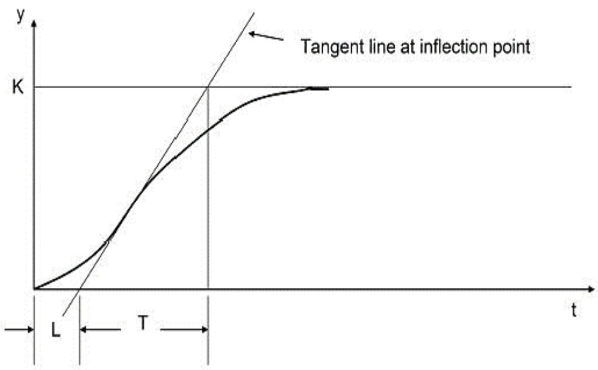

Fig. 6 S-shaped Reaction Curve

There are different methods by which the values of the parameters of the PID controller k_p, k_i and k_d can be tuned. Among them, Ziegler-Nichols' first method for tuning controller parameters is very popularly used for industrial processes. It is used for plants whose unit-step response resembles an S-shaped curve with no overshoot. This S-shaped curve is called the reaction curve which is shown in Fig. 6. The S-shaped reaction curve can be characterized by two constants, delay time L and time constant T, which are determined by drawing a tangent line at the inflection point of the curve and finding the intersections of the tangent line with the time axis and the steady-state level line. According to Ziegler-Nichol's first method the PID tuning rule is given in TABLE 2. In this work, the PID controller is designed for the 4th order identified parametric BJ model and this controller has been used to control the speed of the DC motor.

TABLE 2. Ziegler-Nichols First Method Tuning Rule

Controller	k_p	k_i	k_d
P	$\frac{T}{L}$	0	0
PI	$\frac{0.9T}{L}$	$\frac{0.27T}{L^2}$	0
PID	$\frac{1.2T}{L}$	$\frac{0.6T}{L^2}$	$0.6T$

V. Results

The open-loop response of the SIMULINK model of the DC shunt motor identified 4th order model and transfer function model for 100V armature voltage are given in Fig. 7. From the response, it can be observed that the identified BJ model gives a better result than the conventional transfer function model of the system. The steady-state error for BJ model is also very much less.

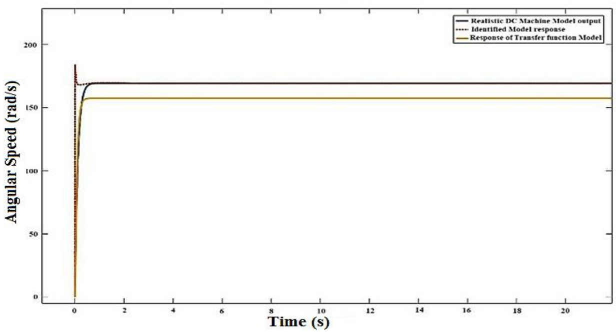

Fig. 7 The open-loop response of SIMULINK machine model, identified model, and transfer function model

To control the speed of the motor, both Proportional-Integral-Derivative (PID) and Proportional-Integral (PI) controllers have been designed for a 4th order BJ model using Ziegler-Nichols first tuning rule. The values of the parameters of the controllers are given in TABLE 3 where L (2.15) and T (5.6) are calculated from the reaction curve. The performance of PI and PID controllers has been tested with the SIMULINK model of the DC machine. The closed-loop system with the controller is shown in Fig.8 and the set-value of the angular speed is taken as the rated value of the motor speed 157.1 rad/s. The angular speed responses for both the controllers are shown in Fig. 9 and the control input is shown in Fig. 10. Fig. 9 shows that PID gives a better result than the PI controller both in terms of steady-state error and settling time. The transient response specifications and steady-state error are given in TABLE 4. It can be observed that the steady-state error of the closed-loop system with a PID controller is only 0.1 rad/s.

TABLE 3. Parameters of the controllers

Controller	k_p	k_i	k_d
PI	2.34	0.3271	0
PID	3.13	0.7269	3.36

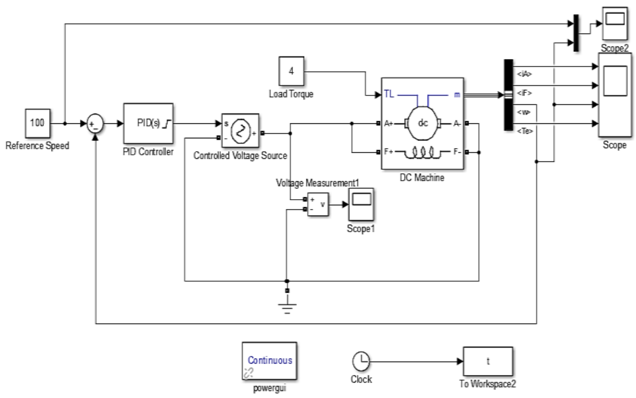

Fig. 8 Closed-loop system with a PID controller

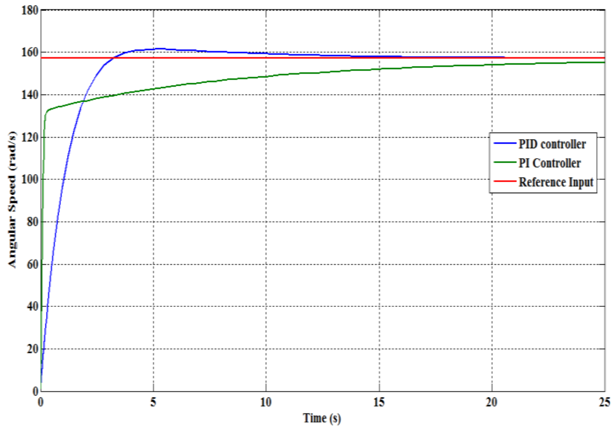

Fig. 9 Closed-loop responses of the system with PI and PID controller

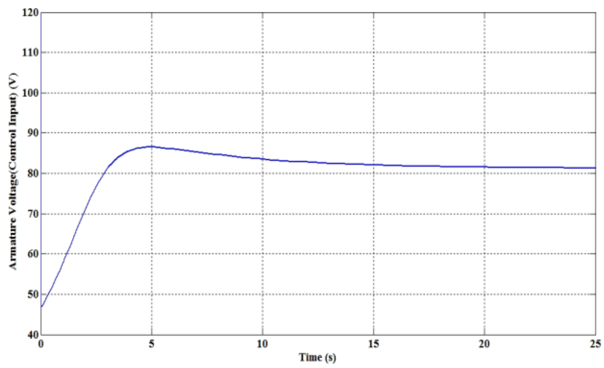

Fig. 10 Control input of the system with PID controller

TABLE 4. Performance parameters of the controllers

Controller	Desired speed	Settling time (s)	Peak overshoot	Steady State Error (rad/s)
PI		20	0	2.1
PID		8.7	18.1%	0.1

A. Robustness Analysis:

The armature resistance of the motor is varying with the temperature. So robustness of the controller is tested by varying the armature resistance R_a of the motor ±50% from its nominal value 1.5Ω. The reference value of the speed taken as the rated speed of the machine i.e. 157.1rad/s. The responses for different R_a along with the reference speed are shown in Fig. 11. From the responses, it is clear that for different R_a controller gives a robust performance.

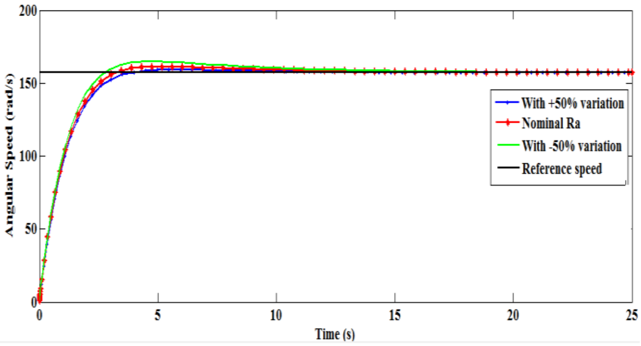

Fig. 11 Angular speed for different R_a

The performance of the PID controller is also tested for different desired speeds ranging from lower speed 50rad/s to higher speed 150rad/s. The responses of the closed-loop system for different desired speed are shown in Fig.12. It can be seen from the responses that in all cases the PID controller tracks the reference speed very well.

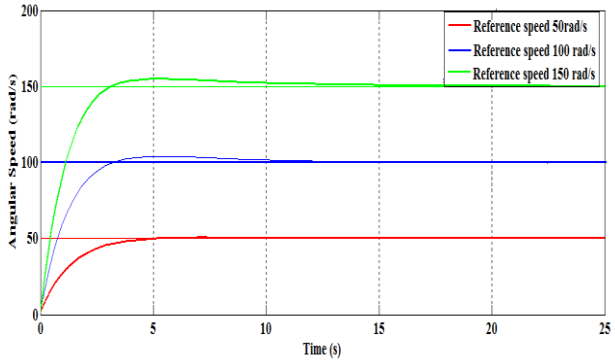

Fig. 12 Angular speed for the different desired speed

VI. Conclusions

In our approach, the parametric 4th order Box-Jenkins model of DC shunt motor is identified. The output of the identified model is compared with that of the output obtained with the transfer function model of the system. The identified model gives excellent results in terms of reproducing the original system input-output relationship. For controlling the angular speed of the DC motor, both PI and PID controllers have been designed based on the identified model. But the PID controller gives better performance in terms of steady-state error and settling-time of the closed-loop response. From the result, it can also be seen that the PID controller is capable of controlling lower speed and as well as the higher speed. The controller also tracks the desired angular speed in the presence of different values of armature resistance. So the PID controller controls the speed of the DC motor robustly with good performance. The performance of the controller can be improved by imposing a robust control technique with online parametric modeling which may be a very interesting scope for the future extension of the work.

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EISSN: 2305-0543, PISSN: 2411-6173