Realtime parameter estimation, calibration and simulation of a DC motor

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Abstract

This paper is about real time estimation and calibration of a brushed wound-pole dc motor parameters, experimantally. An Electrical Machines Test Bed (EMTB), a dc motor with a driver and a data acquisition card (DAQ) installed computer is used in the experiment setup. The software application is developed on Matlab-Simulink platform using Real-Time Windows Target library. Firstly, motor parameters are estimated by using ODEs. Then estimated parameters are simulated within the model and compared with real motor behaviour. Finally, parameters are calibrated with Matlab-Parameter Estimation tool and linear model of the dc motor is acquired according to velocity output.

Key words: parameter estimation, parameter calibration, simulation, modeling, model validation.

1. Introduction

Diagnostics and model development for electro-mechanical systems are quite important in the applications of practical control system design. System diagnostics includes development of a dynamic system model with the the input-output measurements obtained from a real system. The purpose is to establish a reliable mathematical model usually an ordinary differential equations (ODE) or a transfer function representing the input-output relationship of the system. The aim of this model is to predict response, controls and the redirection of the system in the desired course.

The system diagnosis process is constituted of experimental planning, data acquisition, model establishment, prediction of unknown system parameters from the experiment data and test of the validity of the established model. In the design and control optimization of an electric motor, identification of the motor model and parameters accurately provides to obtain a high dynamic performance and energy efficiency from the motor. These parameters are generally acquired either analytically during the motor design or generally from the experimental measurements. Thus, knowing the system model provides the formulization of the system characteristics and this formulization realizes the design and establishment of high performance control systems. [1-4]

There are some studies about the modeling and estimation of the parameters of an electric machine in the literature. In [5], an experimental approach in estimation of the parameters of a dc motor is one of these methods. Motor armature winding resistance and inductance, Back-EMF constant, motor torque constant, moment of inertia and friction coefficient are calculated throughout the experiments. The measurements of the armature current are flattened by using the discrete time Kalman Filter and angular velocity is calculated.

In [6], another study on the experimentally modeling of PM-DC motor and parameter estimation can be seen. First of all, by using standard linear differential equations, a three-mass system model has been developed. Then, it is modeled with numerical input-output data and system linear differential equations. The acquired model has been tested with the discrete-time identification algorithm. The values experimentally acquired from over the model outputs and motor set experiments are observed to be close to each other. The model has been verified with the Root-mean-square (RMS) error method. Open loop and closed loop with PI controller tests have been made.

Linear and non-linear models can be established in order to find the parameters of a system. Basic non-linear parameters like Coulomb friction and dead zone are included in the non-linear model. Hammerstein non-linear system approach is used to estimate the non-linear system model. Thus, a concurrent model of a system like a dc motor can be established by using the linear and non-linear models.[7]

The Hartley modulating functions (HMF) method can be used for physical parameter estimation of the nonlinear continuous-time systems, where a frequency-weighted least squares formulation is applied base on input-output records over a finite time interval. In [8], thyristor driven dc-motor parameters are experimentally estimated by using the HMF-method. Another approach in the modeling of non-linear systems is using NARMAX (Nonlinear AutoRegressive Moving Average with eXogenous input) model which is a method giving quite accurate and efficient results. This method is based on a general parametric model that is constituted of the polynomials that contain various linear and non-linear concepts which unite the inputs, outputs and modeled system errors. In [9], a dc motor is modeled with the NARMAX approach. MLP (Multilayer Perceptron) network is used in order to establish the structure of the NARMAX model.

In [10], DC Decay test has been performed on a 4,5 KW ASEA synchronous machine which is one of the necessary methods of estimating the parameters of synchronous machine. DC Decay test includes holding a machine's rotor at a certain position and applying a small amount of dc voltage and acquiring of the parameters by experimental techniques. This method is also called standstill time-domain test or DC Decay test. This method is quite advantageous and worth noticing since it does not need any special test equipments.

This study is focused on estimating the model parameters of a wound-pole brushed dc motor experimentally to develop a linear model of the system by using ODEs. Open-loop experiments have been performed in order to define and calibrate the response of the sensors and the motor driver. Then, simulation models of the dc motor and the motor driver are established in Matlab-Simulink environment. Measurements and experiments have been performed to acquire data necessary for estimating the motor parameters defined in the simulation model. Estimated parameter values are implemented into the simulation model and evaluated by observing real-time response of the dc motor. Then, Matlab-Parameter Estimation tool has been used for parameter calibration while acquiring approximate values with regard to the real-time output response of the motor.

2. Experiment apparatus setup

Experiment apparatus setup in this study is constituted of an Electric Machines Test Bed (EMTB), an externally-excited wound-pole brushed dc motor with driver, a DAQ card installed computer and a digital multimeter.

Our testing unit, TQ Equipment Company FH2 model (EMTB) is designed to test common electric machines in the range with various fractional horse-powers like Three Phase Wound Pole Motor (FH100), Step Motor (FH150) and Wound-Pole Brushed DC motor (FH50). It has a taco-generator for measuring the rotor speed (rpm), a strain-gauge for obtaining the rotor shaft torque (Nm) and a Foucault-brake for altering the load of the motor. By the help of analog IO ports that EMTB has; measured speed, applied reference voltage to the motor and motor load values can be transferred to the DAQ installed computer. A standard PC and a 100 Ks/S, 12 bit DAQ card is used in this setup. For measuring the motor current, a multimeter that has a computer connection via serial port (rs232) and software support, is preferred. Experiment apparatus setup can be seen in Figure 1.

Figure 1. The view of FH2 EMTB and experiment apparatus setup.

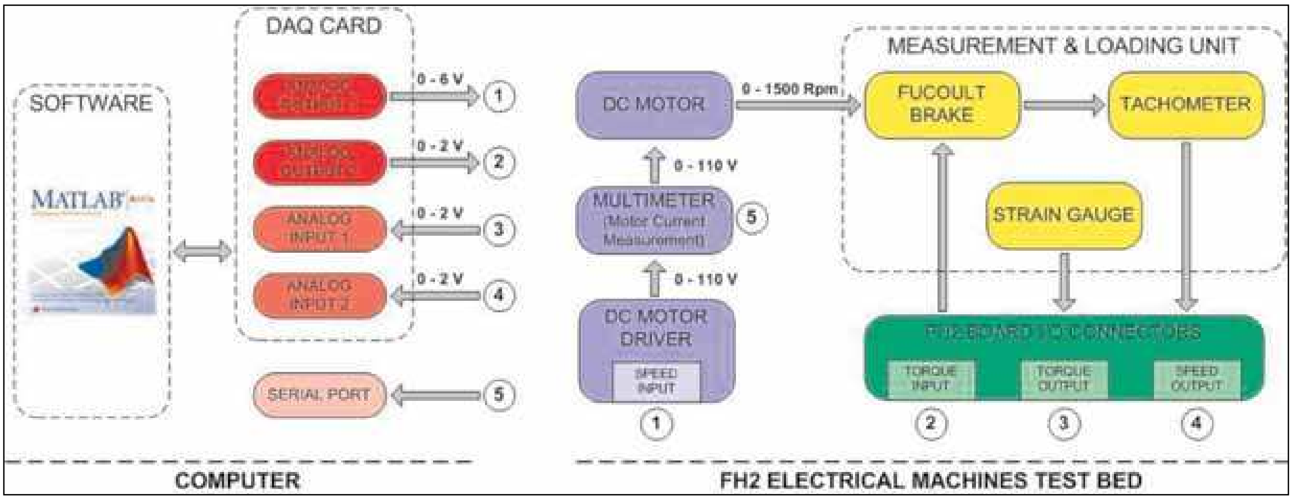

Figure 2. Overall structure of connection scheme in the experiment apparatus setup

The overall electrical signal and connection scheme between the elements of this experiment apparatus setup as in Figure 2.

2.1 The Structure of the DC Motor and Mathematical Correlations

The motor used in the experiment is TQ Equipment Companies' FH50 model which has both serial and shunt winding; in this study, it is used as an externally-excited dc motor. When the machine is operated as a shunt motor and its armature and field are fed with approximately 110 V, the rotor speed increases approximately to 1500 rpm with no-load condition [12]. The electro-mechanical structure of the motor is as shown in Figure 3.

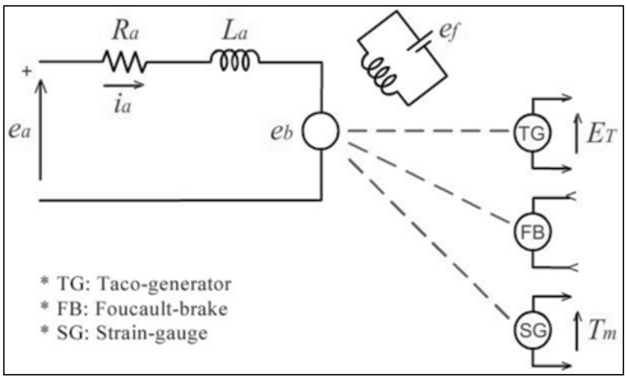

Figure 3. The electro-mechanical structure of the used dc motor.

According to the above scheme, the correlations that will be used to calculate the parameters of the dc motor are as follows [13]:

$$e_a(t) = i_a(t) R_a + L_a \frac{d i_a(t)}{dt} + e_b(t) \quad ..... \ (1)$$

If L_a is neglected in correlation (1) [13];

$$e_a(t) = i_a(t) R_a + e_b(t) \quad .... \ (2)$$

the result will be as shown in correlation (2). Back-EMF is as follows;

$$e_b(t) = K_b.\omega(t) \quad .... \ (3)$$

Shaft torque related to the electrical part;

$$T_m(t) = K_m.i_a(t) \quad .... \ (4)$$

Shaft torque related to the mechanic part;

$$T_m(t) = J \frac{d\omega(t)}{dt} + B\omega(t) + T_L(t) \quad .... \ (5)$$

is as shown above. The terms and explanations of the terms used in these correlations are defined as follows:

$e_a(t)$ = Armature Voltage (110 V)

$i_a(t)$ = Armature current (1 A)

R_a = Armature resistance (Ohm)

$e_b(t)$ = Back-EMF (V)

$\omega(t)$ = Angular velocity (rad/s)

K_b = Back-EMF constant (V/rad/s)

$T_m(t)$ = Shaft torque (Nm)

J = Inertia (Nm/rad/s^2)

B = Friction (Nm/rad/s)

$T_L(t)$ = Load torque (Nm)

K_m = Torque constant (Nm/A)

3. Estimation of the motor parameters

3.1 Estimation of Armature resistance (R_a) and Back EMF Constant (K_b)

If every term in correlation (2) is divided by i_a;

$$\frac{e_a(t)}{i_a(t)} = K_b.\frac{\omega(t)}{i_a} + R_a \quad \text{.................... (6)}$$

(6) is derived. For the estimation of the parameters in (6), the voltage applied to the motor has been started from 0 and increased. The rotation-speed of the shaft and motor current are measured then the graphic in Figure 4 is acquired.

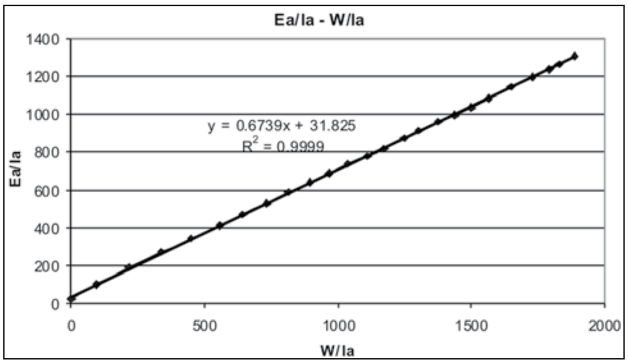

Figure 4. Estimation of armature resistance and Back-EMF constant

After applying curve fitting to this graphic, $y=0.6739x+31.825$ equation has been acquired. When this equation is matched with the equation (6), Back-EMF constant and armature resistance is acquired as follows:

$$K_b = 0.6739\frac{rad/s}{V}, \; R_a = 31.825\Omega$$

In the other method for estimating K_b; the motor is operated as a dc generator while measuring the different values it generates at different rotation-speeds, as a result, the value of K_b has been acquired approximately as 0.7182. Now that this value is close to the value acquired in the first method, found K_b value in the first method will be used as $0.6739\frac{rad/s}{V}$.

3.2 The Estimation of Friction (B):

According to the correlation (5) above, derivative term is zero since the speed will be constant in steady-state and therefore the equation in the correlation (5) will be:

$$\frac{d\,\omega(t)}{dt} = 0 \Rightarrow T_m(t) = B\,\omega(t) + T_L(t)$$

A graphic is drawn by using measured shaft torque $T_m(t)$ and angular velocity $\omega(t)$ values while the motor is operated under a certain load torque $T_L(t)$. B and $T_L(t)$ values are again calculated according to the equation found in the graphic by curve fitting. In this experiment, while the motor is operating at the nominal voltage value (110 V), it is loaded until 0.1 Nm is read in the torque gauge. After this process, the motor rotation-speed is decreased gradually and according to $T_m(t)$ and $\omega(t)$ values at each rotation-speed, the graphic in Figure 5 are acquired.

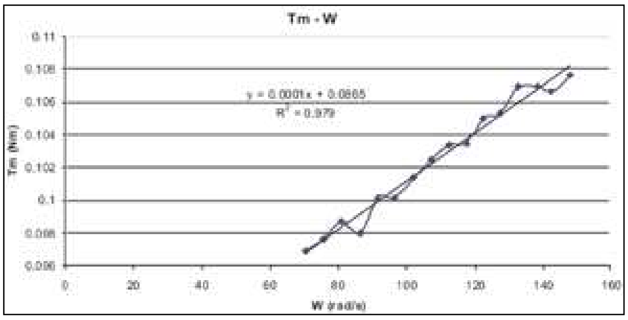

Figure 5. The Estimation of Friction (B).

After the curve fitting process on the graphic, $y = 0.0001x + 0.0865$ equation has been acquired. When this equation is matched with the equation $T_m(t) = B.\omega(t) + T_L(t)$, $B = 0.0001$ and $T_L = 0.0865$ are acquired.

3.3 The Estimation of Torque Constant (K_m):

The correlation (4) can be used to estimate the torque related to the electrical part. Torque constant can be found by using the current absorbed by the motor and measured shaft torque. In the experiment done for this purpose, the motor has been operated at nominal values in the no-load condition, then the applied torque has been increased starting from 0 and $T_m(t)$ values corresponding to $i_a(t)$ values are recorded, the graphic in Figure 6 has been acquired as shown below.

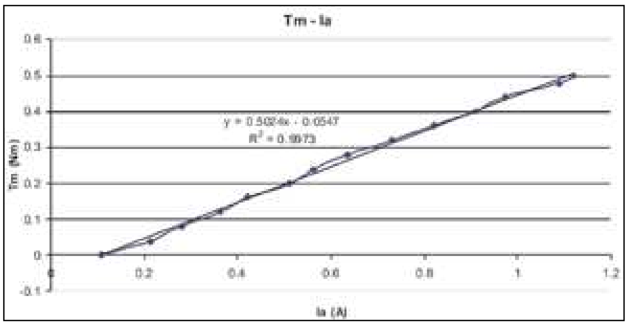

Figure 6. Torque - current graphic.

After the curve fitting process on the graphic, $y = 0.5024x - 0.0547$ equation is found, and from this equation $K_m \cong 0.5024$ is acquired.

3.4 The Estimation of Inertia (J):

Inertia is basically related to acceleration torque $T_a(t)$ and angular velocity $a_w(t)$ as can also be seen in the correlation (7) below [11].

$$J = \frac{T_a(t)}{a_w(t)} \quad \text{..........................} \quad (7)$$

Acceleration torque can be derived from the multiplying of the maximum value of the absorbed current at the instance of first rotation and torque constant K_m.

$$T_a = K_m . i_{a_{\max}} \quad \text{..........................} \quad (8)$$

As for acceleration, it can be derived from the slope of the time-speed graphic that will be acquired when the nominal operating voltage is applied to the dc motor.

$$a_w = \frac{\omega_n}{t_x} \quad \text{..........................} \quad (9)$$

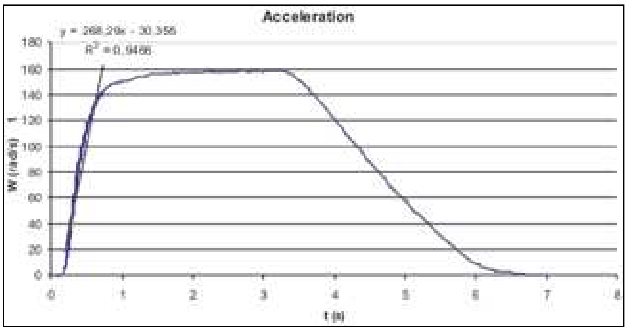

Figure 7. Acceleration graphic and the estimation of inertia

In the current measurement process, the first rotation current of the motor is measured as $i_{a_{\max}} = 1.73\,A$. From the acceleration graphic in Figure 7, it can be observed that the slope value is approximately 268.29. Accordingly it is acquired as follows:

$$T_a = K_m\, i_{a_{\max}} \Rightarrow 0.5349 * 1.73 = 0.92538\, Nm$$

$$J = \frac{T_a}{a_w} \Rightarrow \frac{0.92538}{268.29} = 0.003449178128 \; {}^{Nm}\!/_{rad/s^2}$$

After covering all the calculations, the parameters that belong to the motor have been approximately acquired as follows:

$$R_a = 31.825\Omega, \; K_b = 0.6739 \; {}^{V}\!/_{rad/s}$$

$$K_m = 0.5024 \; {}^{Nm}\!/_{A}, \; B = 0.0001 \; {}^{Nm}\!/_{rad/s}$$

$$J = 0.003449 \; {}^{Nm}\!/_{rad/s^2}$$

4. Analysis and calibration of the estimated parameters

In order to test the accuracy of these estimated parameters; the model of the system is needed to be established and the model should be simulated by using estimated parameters. The results acquired from simulation and the real system responses are needed to be compared. With the experiments done so far, the parameters of the dc motor which is the main component in the system model have been acquired.

As it can be seen in Figure 2, the motor is driven by an electronic-driver which generates dc output voltage (motor operating voltage) between 0-110 VDC with a reference input signal between 0-6 VDC. For this reason, the response of the driver is determined before observing the motor model. Three different levels of step inputs have been applied to the driver and input – output real-time responses are observed. As a result, the following graphic is obtained representing the driver characteristic (Figure 8).

In Figure 8, the response of the driver with regard to the three different step inputs demonstrates certain incline and decline slopes, as 22.5 and -20.4(V/s), respectively. After the driver responses have been acquired, the model of the experiment system has been established in Simulink environment as seen in Figure 9.

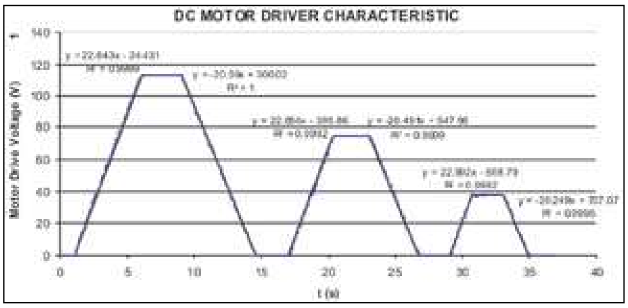

Figure 8. The three different step response of the dc motor driver

After the Simulink Simscape model have been established, the parameters acquired by the experiments, performed in section 3, have been implemented into the simulation. After the comparison of the real system response and the simulation results, it has been observed that the simulation results are almost coincident with the real-time response. In order to have better simulation results, parameter-calibration task has been applied by using Simulink-Parameter Estimation tool, in which the values of unknown parameters in both continuous-time and discrete-time models are estimated

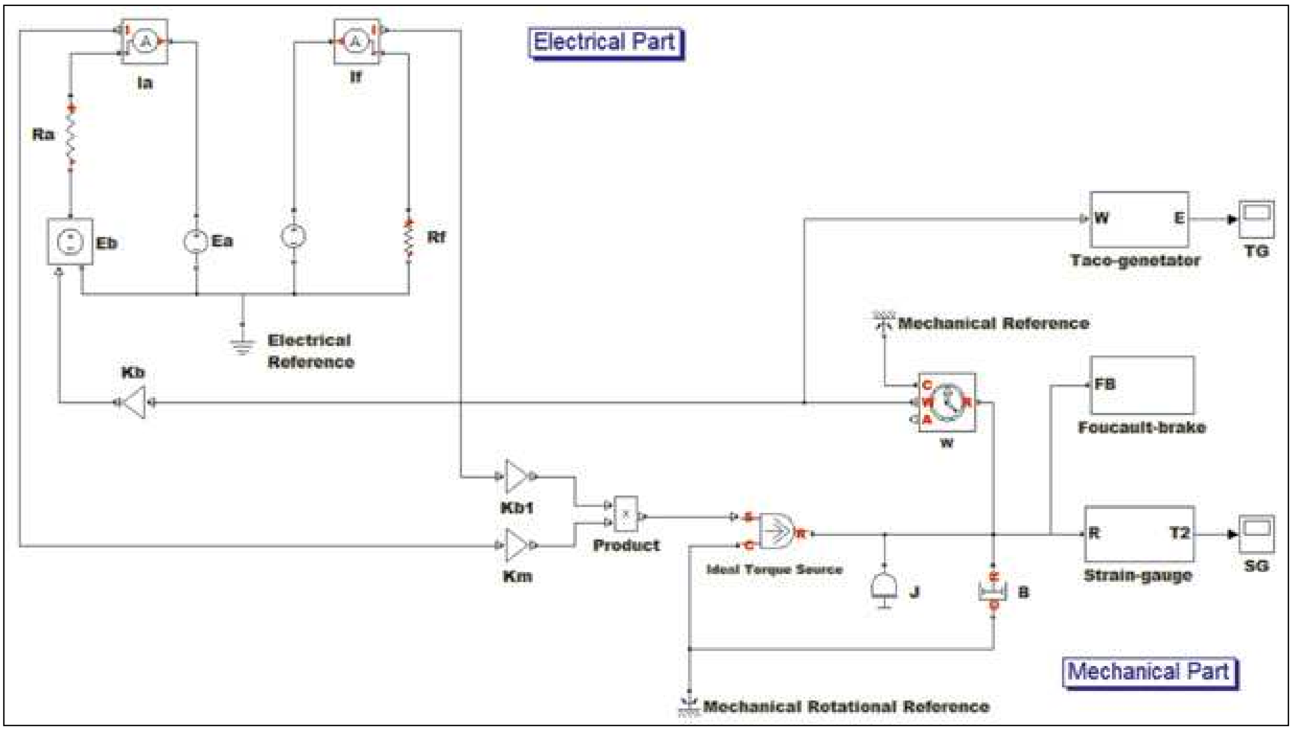

Figure 9. The Simulink Simscape model of the experiment system

and/or known parameters are calibrated by using experimental data. This is especially useful when some parameters cannot be measured experimentally or estimated parameters are needed to be calibrated within acceptable values. When the tool is utilized, it compares the real-time measured data with the data generated by the Simulink model. Using optimization techniques, the software estimates the parameters and (optionally) initial conditions of the states, to minimize a user-selected cost function. The cost function typically calculates a least-square error between the empirical and model data signals [14].

Parameter-Estimation tool is started within the system model created in Simulink environment. Then input data, which will be applied both to the model and the real system, is prepared and applied to real system. Real system response is recorded since it will be a reference for the tool while calibrating the parameter values. After input and output data are imported into the tool, the parameters to be calibrated and their value ranges are defined. When assumed that more than one parameter will be calibrated within the tool, the change in the each parameter values is expected to affect the others. So, it's important to define value ranges in consideration with the calculated values. For example, R_a is estimated as $3\ .825\Omega$ in section 3.1 and by measuring with the ohmmeter, the value of R_a is observed approximately 30 ohm. Therefore, the acceptable initial-guess value range for R_a can be defined as 27 ohm minimum and 35 ohm maximum in the tool.

The results of our experiments show that, ignoring the initial guess min/max values may cause the tool to calculate insensible parameter values, like finding R_a or J negative. This may be due to the use of "non-linear least squares" method with "Trust-Region-Reflective" algorithm in the tool, which only focuses on finding local minimums. Thus, defining the range for the parameters to be predicted improves the accuracy for the results of the calibration process and reduces the computational time elapsed by optimization algorithms. Calibrated and validated motor parameters are seen in Table 1 with respect to the estimated parameters in section 3.

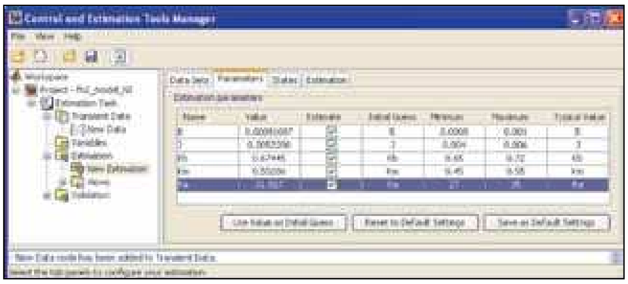

Figure 10. Defining estimation parameter value ranges within Parameter-Estimation tool.

5. Discussion

When the estimated and calibrated parameters in Table 1 are examined, there exists more rational change in Friction (B) -800.00%- and Inertia (J) -44.97%- values than in the other parameters. This is considerable because in physical systems like dc motor, estimating B and J values are harder than the other parameter's estimation. In Figure 11, graphic shows the motor's simulation response with the estimated parameters in section 3 versus the simulation response with the calibrated parameters in section 4 and the motor real output response.

Table 1. Estimated and calibrated parameter values

Parameters	$R_a(\Omega)$	$K_b\left(V/rad/s\right)$	$K_m\left(Nm/A\right)$	$B\left(Nm/\frac{rad}{s}\right)$	$J\left(Nm/rad/s^2\right)$
Estimated	31.825	0.6739	0.5024	0.0001	0.003449
Calibrated	31.606	0.6798	0.5065	0.0009	0.0050
Rate of Change	-0.69%	0.88%	0.82%	800.00%	44.97%

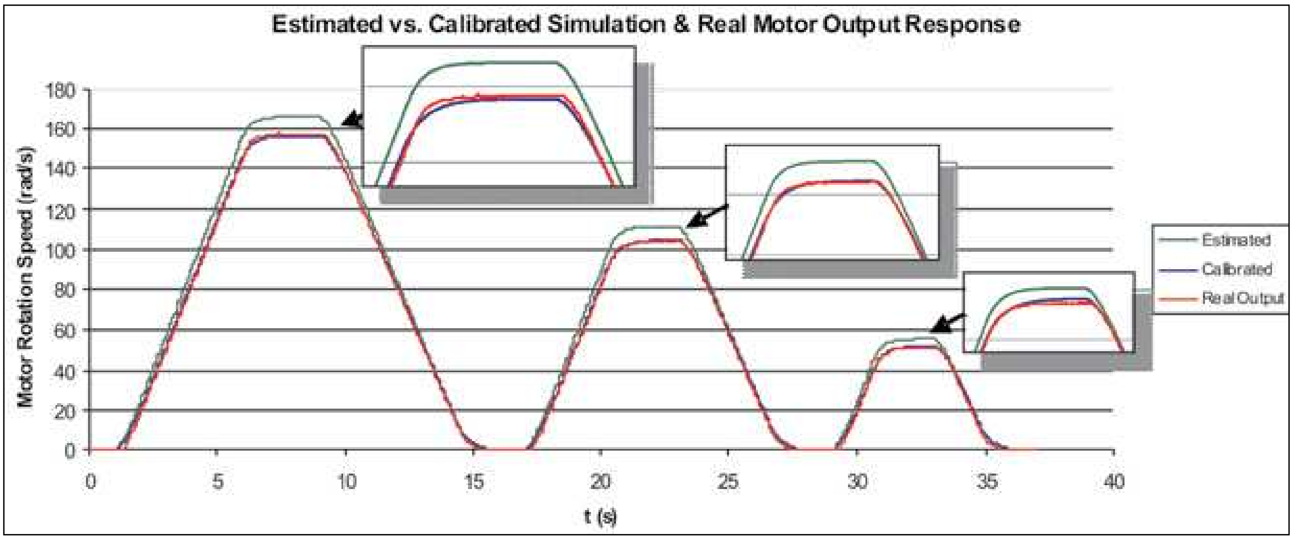

Figure 11. DC motor non-calibrated vs. calibrated parameters simulation and real output response

6. Conclusion

Many physical systems can be represented by using ordinary differential or difference equations with variables, referred to a mathematical model. Primarily, important components and correlations that interact within the system are identified. Variables (parameters) present in the correlations are calculated by analyzing the internal correlations and external responses of the system. Thus, a complete mathematical model of the system is acquired to estimate and control the system responses in different situations. When considered that the systems are getting bigger and complicated nowadays, the importance of modeling the system components and accurately estimating their parameters will be understood better.

A dc motor is one of the basic actuator that can be found in many complicated industrial or home-application systems. It converts electricity into mechanical energy and it includes both electrical and mechanical components. In this study, a dc motor is modeled based on its velocity output data and the parameters in the model have been calculated with the experiments by using mathematical correlations. The identified model and parameter values have been tested on the model established in the Simulink environment. When the real response of the system and the simulation results with estimated parameters are compared, it is observed that simulation acts almost like the real system with little differences. At this point, the estimated parameters are calibrated by using Simulink-Paratmeter Estimation tool. Due to the new parameter values acquired as the result of the estimation process, simulation results and the real system responses are observed to coincide with great proximity.

As a result of this study, mathematical model of a wound-pole brushed dc motor has been identified based on the velocity output data. The identified model and parameters will be the base of further studies related to the control of the same dc motor with different control algorithms.

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