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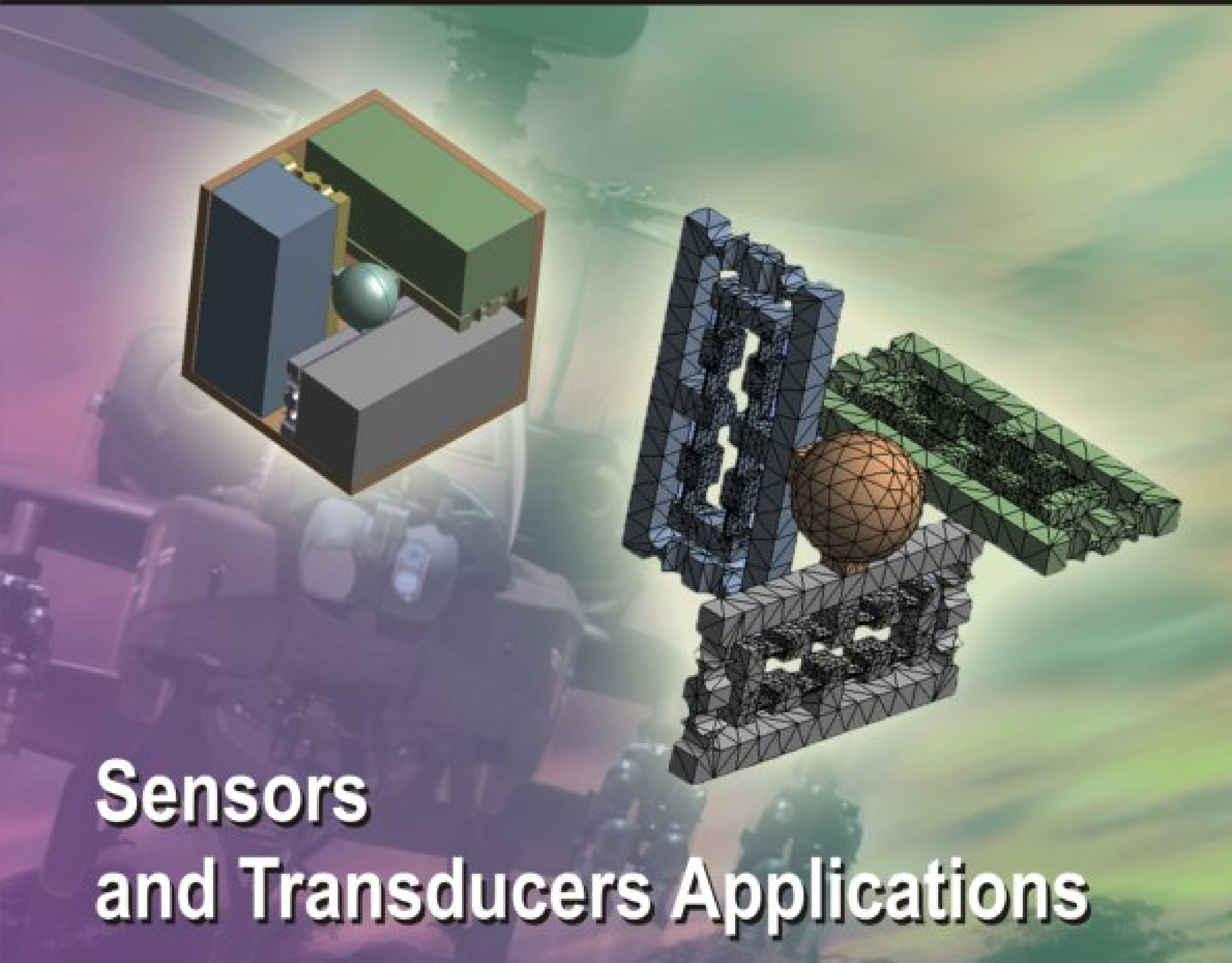

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Contents

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Research Articles

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Parameter Estimation and Speed Control of PMDC Servo Motor using Method of Time Moments

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Abstract: Time moments have been used in identification, model order reduction and controller design because of the analogy between the impulse response of a linear system and a probability function. In this paper, identification and speed control of Permanent Magnet DC Servomotor is presented. An identification algorithm, called method of time moments, is used and applied for identification and speed control of PMDC servomotor. The time constraint is expressed using equality between the time moments of the closed loop system and that of a reference model. The reference model is developed from the classical time, frequency and complex domain specifications which guarantee both stability and performance in a model matching framework. For experimental validation of the theoretical estimation, the parameters of a PMDC servomotor were identified and subsequently a PI controller was designed to control the speed of the motor using the same method. The simulation and experimental validation showed the usefulness of the proposed work. *Copyright © 2010 IFSA.*

Keywords: PMDC servo motor, Parameter estimation, Method of time moments.

1. Introduction

Various techniques have been proposed earlier for the identification of the parameters and speed control of DC motors. Hadef, Bourouina and Mekideche [1] introduced and applied moments method algorithm to identify the parameters of a DC motor and Pal [2] applied the same method for the speed control. Ruff and Grotstollen [3] estimated the electrical parameters of an industrial servo drive system using offline identification. In this paper, a step- by- step method has been used for identifying the electrical parameters. Lee and Blaabjerg [4] established a new scheme to estimate the moment of inertia in servo motor drive system. Here, the observer using radial basis function network has been applied to estimate the motor inertia value. Hori [5], proposed the technique to combine the instantaneous speed observer (robust control) and the adaptive identification of the moment of inertia (adaptive control) for high performance speed control of a servomotor using a low precision shaft encoder. Zhifei, Yuejun, Hongmei and Changzhi [6], applied weighted least square identification approach to estimate the parameters of an underwater robot thruster motor. In this method, the motor equivalent circuit parameters, mechanical model linear parameters and the nonlinear saturated parameters have been estimated using this technique. A simple observer design technique with parameter adaptation for bounded-input bounded-output nonlinear systems has been proposed by Bowes, Sevinç and Holliday [7]. In this technique, no feedback has been used in the observer but parameter estimations are considered as if they are observer inputs and this technique has been successfully applied to speed-sensorless DC servomotors and speed-sensorless induction motors with load torque adaptation schemes. Takahashi, Kenjo and Takeuchi [8] presented an estimation method of the load inertia or torque, motor's cogging torque, winding resistance and back-emf constant of a brushless DC servomotor. Ruben and Roger [9] presented a methodology for closed loop identification of velocity controlled servomotors. This methodology considered a PI controller which has been simultaneously applied to the real servomotor and its model.

The primary objective of a closed loop system is to ensure guaranteed stability and performance and to verify time performances which can be characterized by the settling time and the damping ratio of the step response [10, 11]. This can be achieved after framing a reference model which embodies time, frequency and complex domain specifications of the overall control system with the augmented controller. The closed loop control system is shown below in Fig. 1:

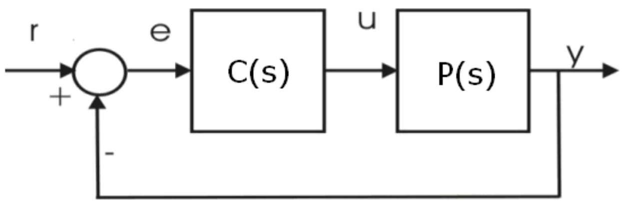

Fig. 1. Closed loop system.

Where $C(s)$ represents the controller and $P(s)$ represents the motor. The controller has to be determined in order that the closed loop transfer function $T(s)$ approximates its reference model that is ideally expressed by the equality:

$$T(s) = (1 + P(s)C(s))^{-1} P(s)C(s) = M_{ref}(s) \tag{1}$$

This corresponds to

$$P(s)C(s)(1 - M_{ref}(s)) = M_{ref}(s) \tag{2}$$

The time characteristics of the reference model are described by time moments [12, 13]. This technique can be applied to a large variety of systems such as electrical motors. Thus, this application is dedicated to the design of PI controller in order to control a PMDC servomotor.

In the present paper, parameter estimation and speed control of a PMDC motor is presented. The parameters of a $24V, 1500\ rpm$ PMDC servomotor are identified using the method of time moments and subsequently a PI controller has been designed to control the speed of the motor using the same method. As the time constraint is expressed using equality between the time moments of the closed loop system and that of a reference model, the reference model has been chosen in the form of $M_{ref}(s) = \dfrac{\omega_n^2}{s^2 + 2\delta\omega_n s + \omega_n^2}$ [14]. The theoretical parameters of the PI controller, which are obtained from simulation, are adjusted in the PMDC motor speed control setup in order to validate the practical simulation results. Finally, the theoretical as well as practical results are compared to show the efficacy of the proposed work.

2. PMDC Servo Motor Model

Fig. 2 represents a PMDC Servomotor which shows an electrical part represented an armature and a mechanical part represented by T and J. As the field excitation is constant, the armature controller depends on armature voltage only.

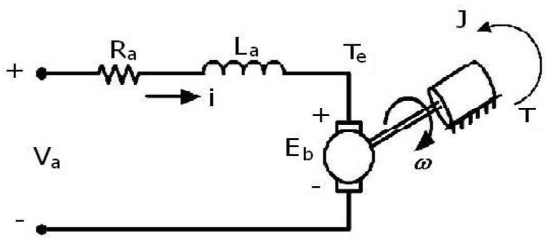

Fig. 2. PMDC motor.

Where: i is the armature current (A), V_a is the armature voltage (V), R_a is the armature resistance (Ω), L_a is the armature inductance (H), K is Torque and back electromagnetic constant ($Nm.A^{-1}$), ω is the rotor angular speed ($rad.\sec^{-1}$), T_e is the electromagnetic torque ($N.m$), T is the total load torque ($N.m$) and J is the rotor inertia ($Kg.m^2$).

The electrical and mechanical equations describing this system can be written as follows [15], [16] with the following assumptions that include losses torque in load torque and by neglecting viscous friction constant:

$$V_a = R_a i + L_a \dot{i} + E_b \tag{3}$$

$$J\dot{\omega} = T_e - T \tag{4}$$

with

$$E_b = K\omega \tag{5}$$

$$T_e = Ki \tag{6}$$

The control input is armature voltage V_a; the total load torque T is the disturbing input. The two state variables are armature current i and angular speed ω. Then the previous equations lead to the state space model of DC motor:

$$\begin{bmatrix} \dot{i} \\ \dot{\omega} \end{bmatrix} = \begin{pmatrix} -\frac{R_a}{L_a} & -\frac{K}{L_a} \\ \frac{K}{J} & 0 \end{pmatrix} \begin{bmatrix} i \\ \omega \end{bmatrix} + \begin{pmatrix} \frac{1}{L_a} & 0 \\ 0 & -\frac{1}{J} \end{pmatrix} \begin{bmatrix} V_a \\ T \end{bmatrix} \tag{7}$$

We are interested by the angular speed in order to perform a speed regulator. So ω is considered as the output of the system and V_a is the input. Considering only these two system variables, the transfer function of the DC motor is:

$$H(s) = \frac{\omega(s)}{V_a(s)} = \frac{1}{K} \frac{1}{(1 + \frac{R_a J}{K^2} s + \frac{L_a J}{K^2} s^2)} \tag{8}$$

The two time constants are defined as:

$$\tau_e = \frac{L_a}{R_a} \text{ - electrical time constant} \tag{9}$$

$$\tau_{em} = \frac{R_a J}{K^2} \text{ - electromechanical time constant} \tag{10}$$

So,

$$H(s) = \frac{\Omega(s)}{U(s)} = \frac{1}{K} \frac{1}{(1 + \tau_{em} s + \tau_{em} \tau_e s^2)} \tag{11}$$

3. Method of Time Moments

The moments form the basis for a non classical representation of linear systems. The characterization of an impulse function response by its moments is equivalent to the moment characterization of a probability density function. Impulse response moments are system invariants. It is not needed to compute infinite moments rather only the first ones are necessary to perform the characterization.

3.1. Temporal Moment of a Function

Let us consider a stable linear system, characterized by its impulse response $l(t)$. Then,

$$L(s) = \frac{B(s)}{A(s)} \tag{12}$$

Expanding e^{-st} in Taylor series about $s = 0$ yields:

$$L(s) = \int_0^\infty \sum_{n=0}^\infty (-1)(s)^n \frac{t^n}{n!} l(t) dt \tag{13}$$

$$L(s)=\sum_{n=0}^{\infty}(-1)^n (s)^n M_{l,n} \tag{14}$$

where

$$M_{l,n}=\int_o^n \frac{t^n}{n!} l(t)dt \tag{15}$$

$M_{l,n}$ is the n^{th} order temporal time moment of $l(t)$. The first three time moments $M_{l,o}, M_{l,1}$ and $M_{l,2}$ are sufficient to describe the time characteristics of a system.

3.2 Moments and Parameters of a Transfer Function

Let $y(t)$ be the step response of a system. It has been proposed to identify the system by the model:

$$L(s)=\frac{Y(s)}{E(s)}=K\frac{1+b_1 s+b_2 s^2+....+b_m s^m}{1+a_1 s+a_2 s^2+....+a_n s^n} \tag{16}$$

From the final value theorem, as time approaches infinity for a stable linear system, the system response approaches a steady state value K given by:

$$K=\underset{t\to\infty}{lt}\ y(t)=y(\infty) \tag{17}$$

If a step input is applied to the system, taking the Laplace transform of the response, we get:

$$L(s)=sY(s) \tag{18}$$

Let Error Function $e(t)$ be given as

$$e(t)=K-y(t) \tag{19}$$

So,

$$E(s)=\frac{K}{s}-Y(s) \tag{20}$$

$$E(s)=\frac{K}{s}\left[1-\frac{1+b_1 s+b_2 s^2+....b_m s^m}{1+a_1 s+a_2 s^2+....a_n s^n}\right] \tag{21}$$

The development of the above equation gives

$$E(s)=K\left[\frac{(a_1-b_1)+(a_2-b_2)s+....+(a_m-b_m)s^{m-1}+....+a_n s^{n-1}}{1+a_1 s+a_2 s^2+....a_n s^n}\right] \tag{22}$$

Now, using Taylor Series expansion, $E(s)$ can be written as

$$E(s)=\sum_{n=0}^{\infty}(-1)^n (s)^n M_{e,n} \tag{23}$$

$$E(s) = M_{e,0} - M_{e,1}s + M_{e,2}s^2 ..... \tag{24}$$

$$M_{e,0} - M_{e,1}s + M_{e,2}s^2 - ..... = K\left[\frac{(a_1 - b_1) + (a_2 - b_2)s + ... + (a_m - b_m)s^{m-1} + ... + a_n s^{n-1}}{1 + a_1 s + a_2 s^2 + ...a_n s^n}\right] \tag{25}$$

$$(M_{e,0} - M_{e,1}s + M_{e,2}s^2 - ..)(1 + a_1 s + a_2 s^2 .. + a_n s^n) = K((a_1 - b_1) + (a_2 - b_2)s... + (a_{n+1} - b_{n+1})s^n) \tag{26}$$

We can deduce the coefficients of the transfer function $L(s)$ by solving the following matrix system:

$$\begin{bmatrix} K(a_1 - b_1) \\ K(a_2 - b_2) \\ K(a_3 - b_3) \\ . \\ . \\ . \\ K(a_{n+1} - b_{n+1}) \end{bmatrix} = \begin{bmatrix} M_{e,0} & 0 & 0 & . & . & . & 0 \\ -M_{e,1} & M_{e,0} & 0 & . & . & . & 0 \\ M_{e,2} & -M_{e,1} & M_{e,0} & . & . & . & 0 \\ . & . & . & . & . & . & . \\ . & . & . & . & . & . & . \\ . & . & . & . & . & . & . \\ (-1)^n M_{e,0} & (-1)^{n-1} M_{e,0} & (-1)^{n-2} M_{e,0} & . & . & . & M_{e,0} \end{bmatrix} \begin{bmatrix} 1 \\ a_1 \\ a_2 \\ . \\ . \\ . \\ a_n \end{bmatrix} \tag{27}$$

3.3. PMDC Servomotor Transfer Function and its Moments

In case of a PMDC servomotor, $n = 2$ and $m = 1$. So the transfer function becomes:

$$L(s) = K\frac{1 + b_1 s}{1 + a_1 s + a_2 s^2} \tag{28}$$

Matrix system is thus reduced as the following:

$$\begin{bmatrix} K(a_1 - b_1) \\ Ka_2 \\ 0 \end{bmatrix} = \begin{bmatrix} M_{e,0} & 0 & 0 \\ -M_{e,1} & M_{e,0} & 0 \\ M_{e,2} & -M_{e,1} & M_{e,0} \end{bmatrix} \begin{bmatrix} 1 \\ a_1 \\ a_2 \end{bmatrix} \tag{29}$$

The resolution of the above matrix system gives the following coefficients:

$$a_1 = \frac{M_{e,1}.M_{e,0} - KM_{e,2}}{M_{e,0}{}^2 - KM_{e,1}} \tag{30}$$

$$a_2 = \frac{-M_{e,1} + M_{e,0}.a_1}{K} \tag{31}$$

$$b_1 = a_1 - \frac{M_{e,0}}{K} \tag{32}$$

3.4. Parametric Identification

The mathematical forms which are deduced above are used for the calculations of the transfer function coefficients and these enable us to calculate the electrical as well as mechanical motor parameters. The stages to be followed for the determination of these parameters are presented below.

Due to the rated voltage, there will be severe loss. So, a low voltage AC supply is to be applied to the armature terminals of the PMDC servomotor. The voltage across the armature and the current through it are to be measured. Thus, the impedance Z_a can be calculated. Then a small DC voltage is to be applied to the terminals across the armature and simultaneously the voltage and the corresponding current is to be measured. Thus, the resistance R_a can be calculated. Subsequently, the value of the inductance L_a can be found out. Applying the required DC voltage to the armature, the back emf and the corresponding speed can be measured. Applying the formula $E_b = K\omega$, K can be calculated.

Retardation Test: The machine has to be run at a very high speed and consequently the supply has to be switched off after measuring the corresponding speed. The input power is to be calculated. Time taken for the speed to be zero is to be measured. This is represented by $\frac{d\omega}{dt}$. As the power can be defined as the rate of change of kinetic energy, using this theory J can be calculated.

Using the transfer function of the PMDC motor model given by:

$$H(s) = \frac{\Omega(s)}{U(s)} = \frac{1}{K}\frac{1}{(1+\tau_{em}s+\tau_{em}\tau_e s^2)} \tag{11}$$

Electrical time constant τ_e and electromechanical time constant τ_{em} can be found out. By identification of denominator of $H(s)$ with that of $L(s)$, we get:

$$a_1 = \tau_{em}; \qquad a_2 = \tau_e.\tau_{em}$$

4. Estimation and Control Using Time Moments

A $24V, 1500\ rpm$ PMDC servomotor has been used to estimate the electrical and mechanical parameters. The armature inductance and the armature resistance of the motor have been measured to be:

$$L_a = 6.3mH \qquad\qquad R_a = 48\,\Omega$$

Firstly, 20 V DC voltage has been applied across the armature terminals of a PMDC servomotor i.e., $V_a = 20V$ .Simultaneously, the back emf has been measured to be $E_b = 19.5V$. The armature current has been measured to be $i = 0.3A$ and the speed of the motor has been found out to be $\omega = 1500\ \ rpm = 157\ \ rad/s$. Using the retardation test method, the time taken by the motor for the speed to be zero has been found out to be $t = 1.1\sec$. The power has been calculated to be:

$$Power\ \ P = V_a.i = 20 \times 0.3 = 6W \tag{33}$$

$$\frac{d\omega}{dt} = \frac{157}{1.1} = 143\ rad\ /\ s^2 \tag{34}$$

$$P = rate\ of\ change\ of\ kinetic\ energy\ = J.\omega.\frac{d\omega}{dt} \tag{35}$$

$$J = 0.0003\ N\ /\ A \tag{36}$$

$$K = \frac{E_b}{\omega} = 0.13\,Nm\ /\ A \tag{37}$$

Thus, $\tau_{em} = 0.85 \quad and \quad \tau_e = 0.00013$

So, $a_1 = \tau_{em} = 0.85 \quad and \quad a_2 = \tau_e \tau_{em} = 0.0001105$

Finally, the transfer function of the motor has been found out to be

$$H(s) = \frac{66667}{s^2 + 7367\ s + 8667} \tag{38}$$

The reference model has been chosen to be a second order system given by the transfer function $T_{ref}(s) = \frac{1}{s^2 + 1.5s + 1}$ where the chosen value of $\omega_n = 1$ and the value of δ should range between $0.7 < \delta < 1$. The chosen value of $\delta = 0.75$.

The controller has been chosen to be of PI type. As the total number of moments (N+1) used in the quadratic criterion has to be at least equal to the number of controller parameters, the number of time moments used in time criterion is given by Table 1:

Table 1. Choice of number of moments for usual controllers.

Controller	**(N+1)**
PI	2
PID	3

The simulated output in MATLAB is presented in Fig. 3.

Subsequently, the transfer function in case of a PI controller is given by:

$$K(s) = 0.01589 + \frac{0.08667}{s} \tag{39}$$

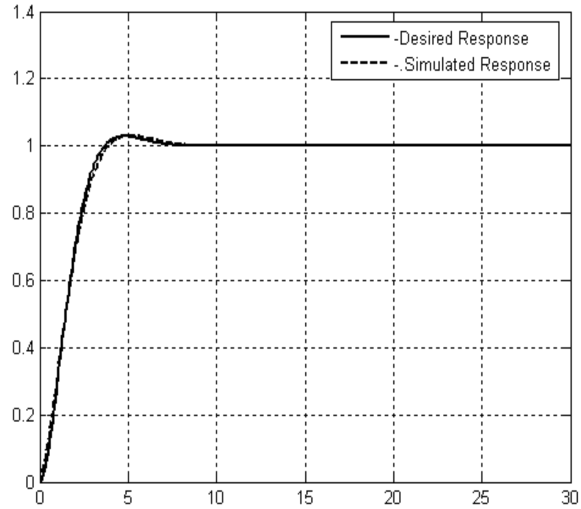

Fig. 3. Closed loop response for PI controller (theoretical).

5. Controller Implementation

The theoretical analysis has been confirmed with the help of a practical circuit where a PI controller is implemented for the PMDC servomotor speed control setup. The block diagram for the circuit implementation is shown below in Fig. 4.

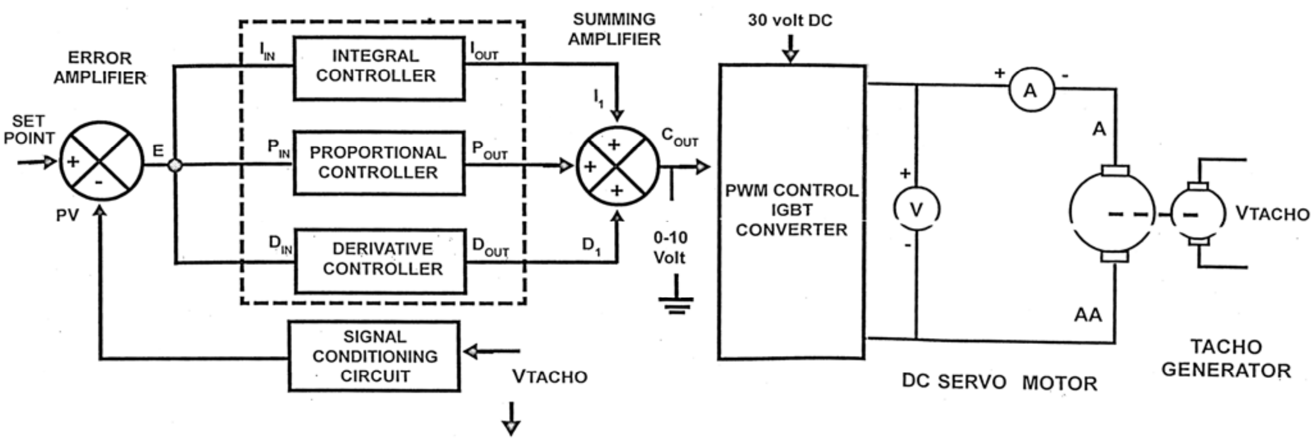

Fig. 4. Block diagram of the PI controller PMDC servomotor.

From the theoretical simulated results given by (39), the following values are set in controller setup:

$$PB = 6294 \qquad K_p = 0.01589 \qquad K_d = 0 \qquad and \qquad K_i = 6$$

Thus,

$$V_a = 16V \qquad E_b = 15.35V \qquad i = 0.3A \qquad \omega = 1200rpm = 125.6rad/s$$

Again, by using the retardation test method, the time taken by the motor for the speed to be zero has been found out to be $t = 0.8\sec$. Thus, the power has been calculated to be:

$$Power \;\; P = V_a . i = 16 \times 0.3 = 4.8\, W \tag{40}$$

$$\frac{d\omega}{dt} = \frac{125.6}{0.8} = 157 \; rad\; / s^2 \tag{41}$$

$$P = rate \;\; of \;\; change \;\; of \;\; kinetic \;\; energy \; = J.\omega.\frac{d\omega}{dt} \tag{42}$$

$$J = 0.00025 \;\; N / A \tag{43}$$

$$K = \frac{E_b}{\omega} = 0.12\, Nm \;/\; A \tag{44}$$

Thus,

$$\tau_{em} = 0.83 \qquad and \qquad \tau_e = 0.00013$$

So,

$$a_1 = \tau_{em} = 0.83 \qquad and \qquad a_2 = \tau_e \tau_{em} = 0.0001079$$

Finally, the transfer function of the motor has been found out to be

$$H(s) = \frac{76923}{s^2 + 7661\, s + 9230} \tag{45}$$

The simulated output is presented as below in Fig. 5:

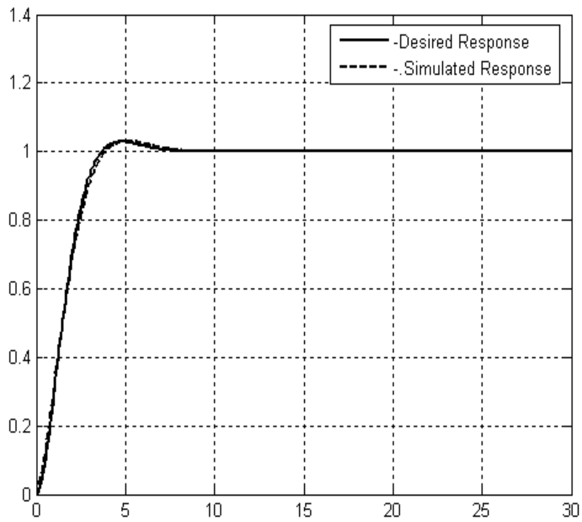

Fig. 5. Closed loop response for PI controller (practical setup).

Subsequently, the transfer function of the controller has been found out to be

$$K(s) = 0.013066 + \frac{0.079993}{s} \tag{46}$$

6. Validation of Results

The experimental results are compared with that of the theoretical results in order to validate the performances of the PMDC servomotor. The Table 2 shows a comparative study of the present work.

Table 2. Validation of results.

Parameters	Theoretical Values	Experimental Values
Speed (ω)	$1500rpm = 157rad/s$	$1200rpm = 125.6rad/s$
V_a	$20V$	$16V$
E_b	$19.5V$	$15.35V$
i	$0.3A$	$0.3A$
Time for the speed to be zero	$1.1s$	$0.8s$
J	0.0003	0.00025
K	0.13	0.12
τ_e	0.00013	0.00013
τ_{em}	0.85	0.83
Transfer Function of the Motor	$\frac{66667}{s^2 + 7367s + 8667}$	$\frac{76923}{s^2 + 7661s + 9230}$
Transfer Function of the Controller	$0.01589 + \frac{0.08667}{s}$	$0.013066 + \frac{0.079993}{s}$
K_P	0.01589	0.013066
K_I	5.45	6.12
DC gain	7.7	8.3

The comparison shown in column 2 and column 3 of Table 2 confirmed that the theoretical and the experimental values of the motor as well as the controller parameters are approximately same.

7. Conclusion

This paper describes a design procedure to synthesize a PI controller satisfying time requirements, specified by a reference model. Method of time moments is used for identification of the motor model and for design of PI controller. The parameters of the controller are found out by matching the time moments of the reference model and that of the closed loop plant model with augmented PI Controller. The theoretical simulation results are subsequently verified with an experimental setup which has been developed in the laboratory. The DC gains in both the cases are found to be approximately equal which is very well reflected from the above table. Also K_p and K_I values obtained from the controller transfer function are nearly equal. Thus, the simulated and experimental results demonstrate the effectiveness of the identification and control scheme presented in this paper for parameter estimation and speed control of PMDC servomotor.

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Guide for Contributors

Aims and Scope

Sensors & Transducers Journal (ISSN 1726-5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because it is an open access, peer review international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per annual by International Frequency Association (IFSA). In additional, some special sponsored and conference issues published annually. *Sensors & Transducers Journal* is indexed and abstracted very quickly by Chemical Abstracts, IndexCopernicus Journals Master List, Open J-Gate, Google Scholar, etc.

Topics Covered

Contributions are invited on all aspects of research, development and application of the science and technology of sensors, transducers and sensor instrumentations. Topics include, but are not restricted to:

- Physical, chemical and biosensors;
- Digital, frequency, period, duty-cycle, time interval, PWM, pulse number output sensors and transducers;
- Theory, principles, effects, design, standardization and modeling;
- Smart sensors and systems;
- Sensor instrumentation;
- Virtual instruments;
- Sensors interfaces, buses and networks;
- Signal processing;
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