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Speed Control of DC Motor with Kalman Filter and Fractional Order PID Controller

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***Abstract*- In the industry for better control action, we have a requirement of an exemplary controller along with all the measurable and unmeasurable states. In this paper, Fractional order PID (FOPID) controller with Kalman Filter (KF) is proposed for speed control of DC motor. FOPID is more flexible and robust than the PID controller and KF is a perfect state estimator to estimate all the states. Implementation of the proposed sensorless model is carried out in MATLAB/Simulink environment. In simulation performance of with and without KF, it shows FOPID with KF has better performance than without KF.**

Index Terms—Kalman Filter, FOPID controller, DC drives, speed estimation.

I. INTRODUCTION

DC motor is considered one of the most crucial electrical machines in the industry due to its compactness, robustness, reliability and good efficiency [1], [2]. Proportional+integral+derivative (PID) controllers are widely used in industry to enhance both transient and steady-state behavior [3]. To develop more effective controllers, Researchers design The fractional order PID (FOPID) controller. It is a generalized version of the traditional PID controller [4]. FOPID controllers have less oscillation and overflow than conventional PID controllers, faster response time, stable adjustments to regulated device parameters, and insensitivity to disturbing results. However, for implementing a dc motor, precise knowledge of shaft speed or position is desirable. Positions sensors like tachogenerator or digital shaft encoder are used in modern speed control techniques for DC drives to obtain speed information. However, these encoders are costly, inject noise into computation and degrade the drive system's efficiency; moreover, they are not ideal for use in a hostile environment. In this regard, sensorless speed estimation techniques are preferred with an excellent controller overcoming the problems mentioned earlier.

A lot of literature work has been done to design DC motor controllers with or without the PID or FOPID and Kalman Filter (KF) application. In [5], the authors design a sensorless speed control of dc motor with PI and KF. In this speed of the dc motor is constant irrespective of load torque changes. In [6] the dc motor's speed control was implemented using a nonideal voltage and current sensor with a PID controller and KF estimator. In [7], author design speed control of SPWM fed induction motor drive using Extended Kalman Filter(EKF). In [8] FOPID controller was used to controlling the dc motor speed. In this for tuning FOPID parameters (Kp;Ki;Kd; λ and μ), atom search optimization and chaotic atom search optimization were used. In [9], FOPID parameters were tuned using grey- wolf optimization and their microcontroller implementation is shown. In [8], [9] authors are using speed/position sensor. In [10], dc motor torque control was implemented using a PID controller with state estimator and Kalman Filter. In [11], a control strategy of the servo system's position control based on FOPID and extended state observer (FOESO) has been proposed.

This work aims to achieve better stability and transient response to dc motor speed control, regardless of load torque changes and without using a speed/position sensor. Therefore we use FOPID with KF estimator. In this armature current and voltage are used for estimating the dc motor shaft speed ωest and this ωest are feedbacked to the FOPID controller to generate PWM signal for driving the dc motor. We compare the simulated result from PID controller, PID controller with KF and FOPID controller with KF.

The paper is organized in the following sections: In Section II, system modeling has been presented. FOPID controller design is presented in section III. MATLAB/Simulink model is discussed in section IV. In section, V results are discussed and at last, the concluding remarks are presented in section VI.

II. SYSTEM MODELING

The two major parts of the system modeling one are the dc motor mathematical model and the Kalman filter (estimator) discussed in this section.

A. DC Motor Mathematical Model

State estimating algorithm requires a time-domain mathematical model of DC motor. This paper considers an externally excited Dc motor. The speed of dc motor is controlled with the help of H bridge via varying the armature voltage of motor. The model of DC Motor has two main equations, one being electrical and the other being mechanical [1], [2]. The armature voltage (on considering field current constant) can be obtained by applying KVL into the armature circuit shown in fig.1.

$$v(t) = K_e^{'}\omega_m(t) + R_a i_a(t) + L_a \frac{\mathrm{d}}{\mathrm{d}t} i_a(t) \quad (1)$$

The dynamic equation for the mechanical system is (on considering field current constant):

$$T(t) = K_t^{'} i_a(t) = J\frac{\mathrm{d}}{\mathrm{d}t}\omega_m(t) + T_L(t) + T_f(t) + D\omega_m(t) \quad (2)$$

with the help of equation (1) and (2), the dynamical model of dc motor in a continuous-time domain can be written as:

$$\begin{bmatrix} \dot{\omega}_m \\ \dot{i}_a \end{bmatrix} = \begin{bmatrix} \frac{-D}{J} & \frac{K_t^{'}}{J} \\ \frac{-K_e^{'}}{L_a} & \frac{-R_a}{L_a} \end{bmatrix} \begin{bmatrix} \omega_m \\ i_a \end{bmatrix} + \begin{bmatrix} (T_L - T_f) & 0 \\ 0 & \frac{1}{L_a} \end{bmatrix} \begin{bmatrix} 1 \\ v_t \end{bmatrix} \quad (3)$$

In designing an estimator, we have the system's discrete model requirement, which can be easily obtained with MATLAB's help. The discrete model of the system is :

$$x_{k+1} = A_d x_k + B_d u_k + v_k \quad (4)$$

$$y_k = C_d x_k + w_k \quad (5)$$

In the above equation x is state variable, $x = [\omega_m; i_a]^t$, u is the input vector $u = [1; v_t]^t$, y is output vector, $y = [0; i_a]^t$, v is the process noise with zero mean and covariance Q and ω is measurement noise with mean zero and covariance R. The discretized matrix cofficents A_d;B_d and C_d at sampling interval T_s can be written as:

$$A_d = I + AT_s = \begin{bmatrix} 1 & 0.005 \\ -0.007 & 0.9828 \end{bmatrix} \quad (6)$$

$$B_d = BT_s = \begin{bmatrix} -0.016 & 0 \\ 0 & 0.0067 \end{bmatrix} \quad (7)$$

$$C_d = C = \begin{bmatrix} 0 & 1 \end{bmatrix} \quad (8)$$

The obtained equation (6), (7) and (8) are used in this paper for designing of KF estimator.

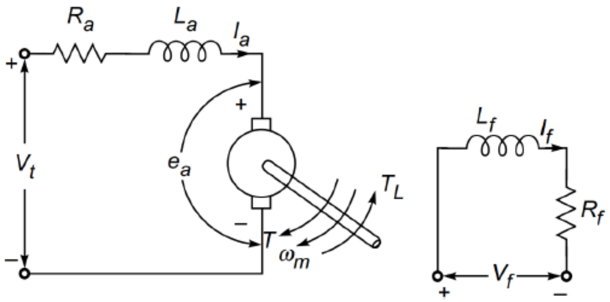

Fig. 1. Schematic of separately excited dc motor.

B. Kalman Filter

Kalman filter is a mathematical tool that uses some mathematical equations to estimate the noisy states with the help of some measurable states and system dynamics, which are corrupted by statistical noise and some other inaccuracies. The Kalman filter facilitated a practical model for determining the motor system's states and issuing revised commands due to the delay between the issues of motor commands and the receipt of noisy sensory feedback. The Kalman filter consists of two steps:

1) Prediction
2) Correction

In the first step, the states are predicted along with uncertainties by using the system dynamics model. The prediction step is:

$$\hat{x}_{k+1/k} = A_d \hat{x}_k + B_d u_k \quad (9)$$

$$P_{k+1/k} = A_d P_k A_d^t + Q \quad (10)$$

Where $\hat{x}_k$ is estimated state of x_k. In the second step predicted states are corrected using measured data and kalman gain. The kalman gain is the relative weight given to measurement and current state estimate to achieve a specific efficiency. The correction step is:

$$K_{k+1} = P_{k+1/k} C_d^t (C_d P_{k+1/k} C_d^t + R)^{-1} \quad (11)$$

$$\hat{x}_{k+1} = \hat{x}_{k+1/k} + K_{k+1}(y_{k+1} - C_d \hat{x}_{k+1/k}) \quad (12)$$

$$P_{k+1} = P_{k+1/k}(I - K_{k+1} C_d) \quad (13)$$

where K_{k+1} is kalman gain and I is the identity matrix.

III. FOPID CONTROLLER DESIGN

The speed estimated as an output of Kalman Filter works as the FOPID speed controller feedback. This estimated speed ω_{est} is subtracted from the reference speed ω_{ref} to obtain the control error signal, for FOPID controller input. The FOPID controllers are the generalized version of the traditional PID controller that uses the fractional derivative integral calculus. The FOPID has five parameters (K_p;K_i;K_d; λ and μ) in omparision to traditional PID (K_p;K_i;K_d) controller. These two additional parameter (λ and μ) adding more flexbility and roboustness to the system. The FOPID controller transfer function is defined as:

$$G_c(s) = K_p + \frac{K_i}{s^{\lambda}} + K_d s^{\mu} \tag{14}$$

IV. MATLAB/SIMULINK MODEL

In this section, MATLAB/ Simulink model of the proposed method for dc motor speed control. The simulink model of the proposed system is presented in fig. 3. In model controller block, PWM signal generator, KF estimator and H-bridge are used to drive dc motor. In the controller block, FOPID speed controller and PID current controller are used as shown in model controller block, pwm signal generator, KF estimator and H-mbridge is used to drive dc motor. In controller block FOPID speed controller and PID current controller is used as shown in fig. 3. FOPID controller is implemented by using FOMCON toolbox. In this work armature current (i_a) of dc motor is measured with the help of current sensor to estimate the unknown dc motor speed. This estimated speed is feed backed to control the dc motor speed. To perform all the simulation, a personal desktop Core i5, 3:5GHz, 12 GB RAM, under Windows 10 was used.

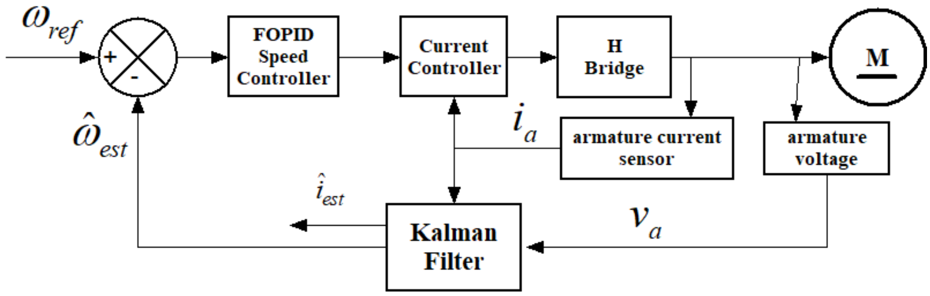

Fig. 2. Block diagram of Speed Control strategy of a DC Motor

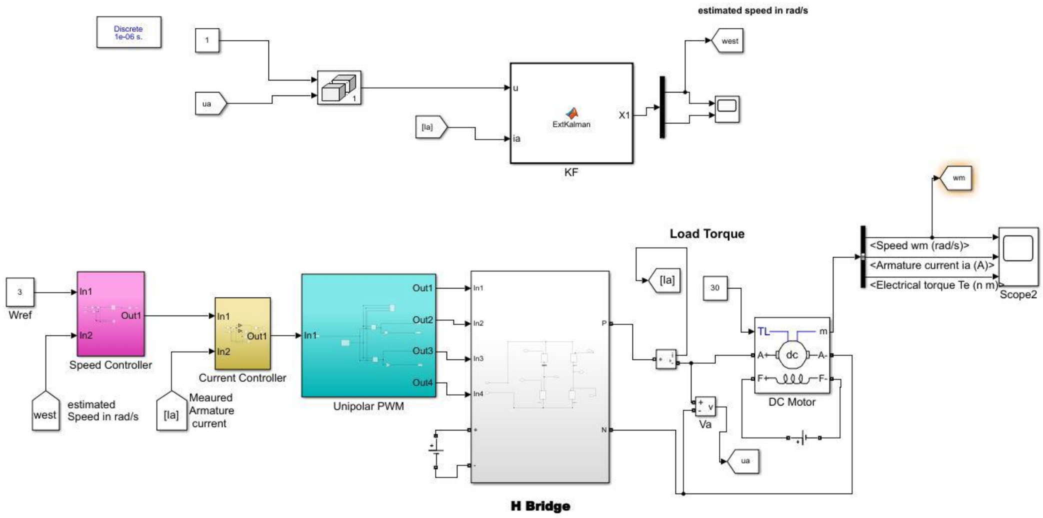

Fig. 3. Simulink model of DC motor speed control

V. RESULT & DISCUSSION

Simulation results of dc motor speed control are shown in fig. 4. The speed and current comparison of KF based FOPID, KF based PID, and standard PID controller is shown at various sudden load conditions. Fig 4.(a) clarifies that whatever the load torque value, the dc motor speed controlling of the KF based FOPID controller shows outstanding reference speed tracking capability. In the starting, KF based FOPID controller takes more current but this current converges very quickly as the error covariance of the Kalman filter reduces. The armature current comparison of the various controller has been demonstrated in fig 4.(b). The transient response analysis of fig 4. (a) are tabulated in table I. From the table, the delay time and rise time of KF based PID is slightly better than KF based FOPID, but reference speed tracking of KF based FOPID is far better than other controllers.

Table I Transient Response Comparision

Controller	Delay time	Rise time	overshoot (%)
PI	0.0558	0.1235	25
PI with KF	0.03543	0.08075	17
FOPI with KF	0.03839	0.07918	7

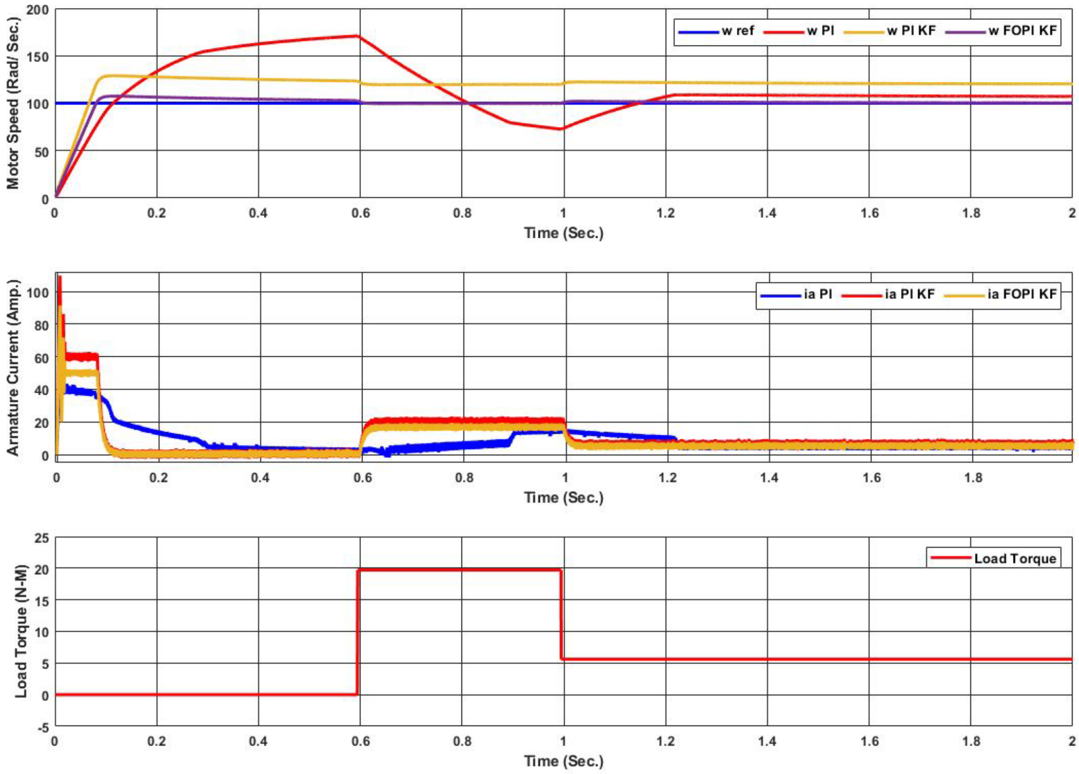

Fig. 4. DC motor speed and armature current comparision

VI. Conclusion

In this paper, a DC motor's sensorless speed control using fractional order PID controller with a Kalman filter is presented. The proposed controller is a robust adaptive controller based only on the few available plant information and without using any speed sensor. The result of the proposed controller is compared with various other controllers. It is observed that KF based FOPID controller reduces the maximum overshoot drastically but rise time slightly higher than KF based PID; this is because of fractional order which increases the computational complexity but makes the controller more adaptive and robust.

Appendix A

MOTOR PARAMETERS

P_{rated} = 5HP, $V_{armature}$ = 240V , V_{Field} = 150V ,
ω_{rated} = 1750r=min, R_a = 2:581Ω, L_a = 0:028H,
L_{af} = 0:9483H, J = 0:02215kgm^2, D = 0:002953Nms,
T_f = 0:5161Nm:

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