Disturbance Observer Based Current Controller for a Brushed DC Motor

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Abstract— **Current control is essential for torque control. But available current controllers don't provide the required facilities for torque control. Often they produce a sluggish response. In this paper we propose an embedded system based current controlling method using the disturbance observer. Dynamic model of the DC motor is analyzed electrically and mechanically. Then the proposed method is analyzed by introducing the concept of disturbance observer. Real Time Operating System (RTOS) is used in the experiment. Results show the response current variation with and without the disturbance observer. Validity of the proposed method is verified by the results.**

Keywords: PID control;Current Control; Realtime control

I. INTRODUCTION

DC motors are used in wide range of applications ranging from small toys to locomotives [1][2]. Brushed DC motors have become popular due to its simplicity in control and cost. In most of the applications open loop velocity control is implemented simply by controlling the voltage [3]. In most of the applications where velocity control is used, simple feedback control is sufficient for small motors. Fig. 1 shows a simple velocity controller in block form with feedback.

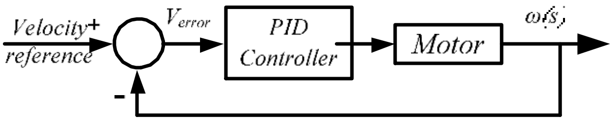

Figure 1. Basic Velocity Controller

As for this arrangement, the dynamic model of the motor is not taken in to account and hence this method can only be used for small motors where motor inertia is small [3][4]. Consider the motor as shown in Fig 2.

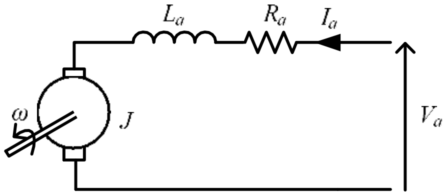

Figure 2. DC Motor Model

Electrical Equation of a motor is represented by (1).

$$V_a = L_a \frac{dI_a}{dt} + R_a I_a + E_b \tag{1}$$

Where E_b is the back emf.

Laplace transformation of (1) can be rearranged as,

$$I_a = \frac{V_a(s) \square K_e \omega(s)}{L_a S + R_a} \tag{2}$$

and

$$E_b = K_e \omega(s) \tag{3}$$

Where K_e is the back emf constant.

The motor torque T in Laplace domain can be represented as follows.

$$T(s) = Js\omega(s) + B\omega(s) + T_l(s) + T_f(s) \tag{4}$$

Where ;

J :*Total inertia of the system*
B :*Viscous friction coefficient*
T_L:*Load torque*
T_f:*Static frictional torque*
ω:*Angular speed of the motor*

Equation 4 can be rearranged as follows,

$$\omega(s) = \frac{T(s) - \left[T_l(s) + T_f(s)\right]}{Js + B} \tag{5}$$

$$T(s) = K_t I_a(s) \tag{6}$$

Where K_t is the torque constant.

From (2) and (5) the total control block shown in Fig 3 can be obtained.

II. MODELING AND ANALYSIS

A. Current Controller

Velocity can be controlled using the voltage [4]. However as for the equation (6) the motor torque can be controlled by controlling the current. Fig. 4 shows a block diagram of a PID based current controller. It is interesting to highlight the electrical/mechanical relationships as depicted in Fig. 4. For current control, back emf also plays an important role as feedback.

Ideally a current controller should have a current reference as as the input and current response as the output. After analyzing the system depicted in Fig 3 the relationship in (7) can be derived.

$$V_a = I_a\left(Ls + R_a + \frac{K_e K_t}{Js + B}\right) - \frac{K_e\left(T_l + T_f\right)}{Js + B} \tag{7}$$

This system works well and the results are presented in the results section. With the intention of improving the responsiveness and robustness, disturbance observer [6] is proposed to be used with the current controller. Then results are compared to validate the applicability of the proposed method.

Based on (7) the system depicted in Fig. 4 can be represented as a current input current output system as shown in Fig. 5.

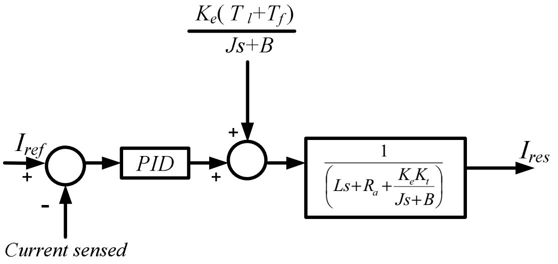

Figure 5. Current input current output representation of a DC motor

B. Disturbance Observer

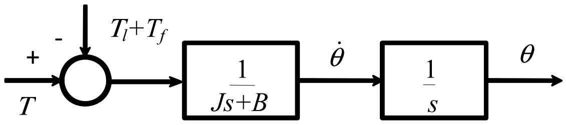

Figure 6. Block diagram of a servo motor

When a servo motor with one degree of motion is considered, under an ideal motor driver, a servo motor in the joint space can be represented as follows (8).

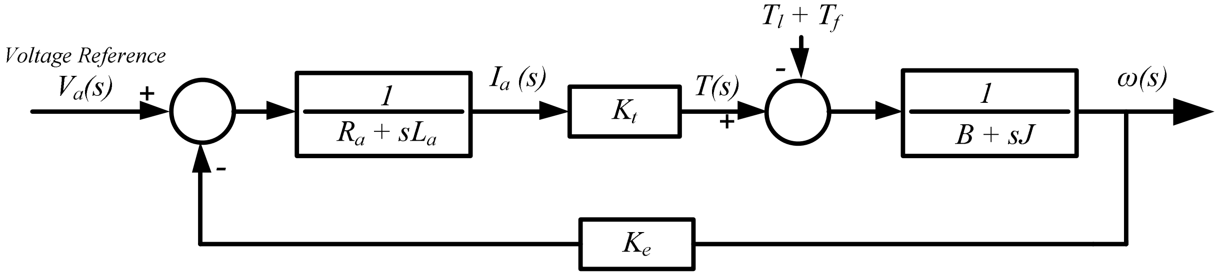

Figure 3. Voltage to Velocity in a block form

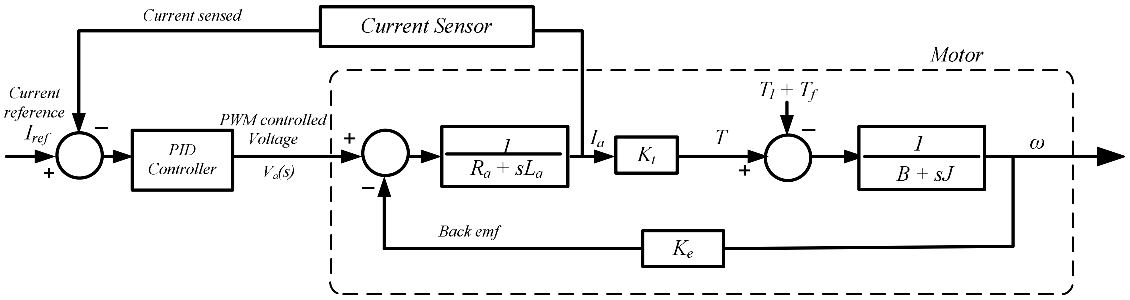

Figure 4. A DC motor in current control

$$J\ddot{\theta} = T_m - T_l \tag{8}$$

Where;

T :*Motor torque*

T_l :*Load torque*

J :*Motor Inertia*

$\ddot{\theta}$:*Angular acceleration*

The load torque is considered as,

$$T_l = T_{\text{int}} + T_{ext} + (T_f + B\dot{\theta}) \tag{9}$$

T_{int} the inertial torque, derived from the Lagrange motion equations is consists of inertia torque and gravity effect. T_{ext} consists of the torque external to the system.

Friction term $T_f + B\dot{\theta}$ is the sum of coulomb and viscosity terms. For a high gain current controller, input current can be assumed as the reference current. Therefore, for a DC servo motor,

$$J\ddot{\theta} = K_t I_f - \left(T_{\text{int}} + T_{ext} + T_f + B\dot{\theta}\right) \tag{10}$$

Above equation has two parameters namely J and torque constant K_t. Inertia can be changed due to the mechanical configuration of the system.

$$J = J_n + \Delta J \tag{11}$$

Similarly parameter K_t may change

$$K_t = K_{tn} + \Delta K_t \tag{12}$$

Where J_n and K_{tn} are nominal inertia and the nominal torque constant of the motor respectively.

Disturbance torque T_{dis} is represented as,

$$T_{dis} = T_l + \Delta J\ddot{\theta} - \Delta K_t I_{ref} \tag{13}$$

Dynamic equation yields,

$$(J_n + \Delta J)\ddot{\theta} = (K_{tn} + \Delta K_t) I_{ref} - T_l \tag{14}$$

By rearranging,

$$J_n\ddot{\theta} = K_{tn} I_{ref} - T_{dis} \tag{15}$$

Thus T_{dis} can be calculated as follows.

$$T_{dis} = K_{tn} I_a^{ref} - J_n\ddot{\theta} \tag{16}$$

Equation (16) can be represented by control block shown in Fig. 7.

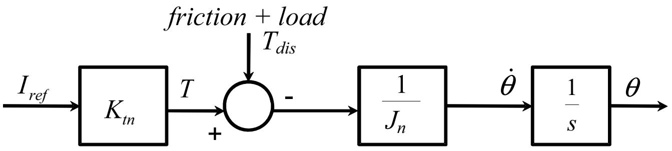

Figure 7. Motor with Disturbance Torque

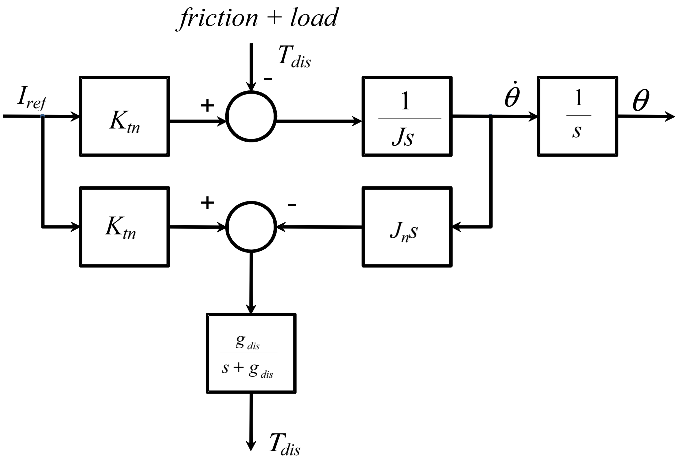

Figure 8. Disturbance based on acceleration with lowpass filter

Equation (16), the unknown values of the left side can be derived using the right side, which is calculable. This structure includes a differentiator which may increase the unnecessary noise in the system. Motor disturbance includes the frictional effects, load and the effects of parameter variations as shown in equation (16). Usually this disturbance is not measurable. However if a control block as shown in Fig. 8 is implemented, the motor disturbance (T_{dis}) will become measurable and it is usually taken out after a lowpass filter as shown in Fig. 8.

g_{dis} is the angular cutoff frequency of the lowpass filter. Disturbance observer observes the disturbance force in the system without using force sensors. It is designed such a way that it is possible to estimate the disturbance from the observer [6][7]. Fig. 9 shows a disturbance observer with a motor. Upper part corresponds to the motor. System represented by Fig. 9 is derived after introducing the pseudo derivative and a lowpass filter[8] which would improve the performance significantly. Estimated T_{dis} is fedback to compensate for unknown disturbances after converting it to a current multiplying by $1/K_{tn}$. Fig 10 shows the disturbance observer based current controller and the system depicted in Fig. 10 is used for the experiment to validate the proposed system.

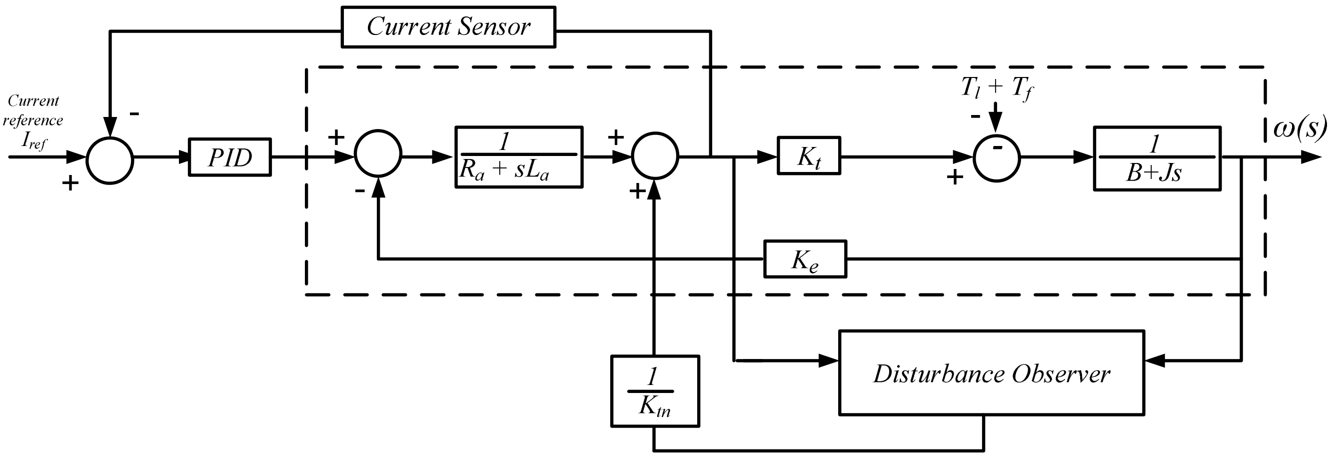

Figure 10. Motor with Disturbance Observer

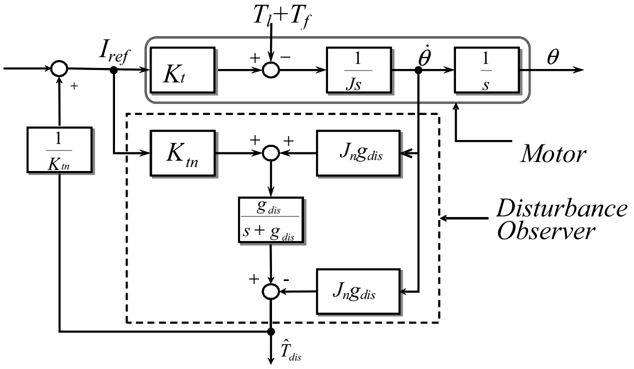

Figure 9. Motor with Disturbance Observer

III. METHODOLOGY

A. Hardware

For this demonstration an *ElectroCraft E240* brushed type DC motor was used. Incremental encoder having a resolution of 2500 pulses per revolution is used. Motor driver is built using MOSFETs. Simplified drive circuit of the DC motor is shown in the Fig 12. Switching signal patterns are built using a microcontroller. Voltage is varied using a PWM signal generated from the microcontroller *(mbed NXP LPC1768)* as described in Fig. 12.

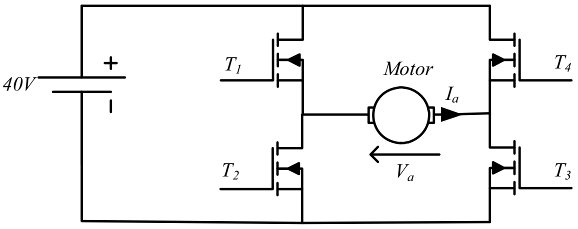

Figure 11. H-Bridge Motor Driver

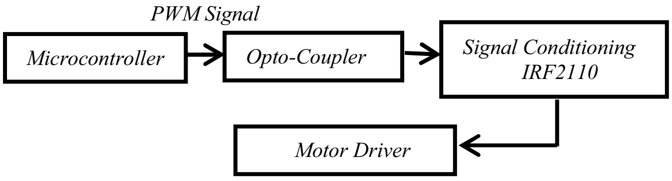

Figure 12. Motor driving block diagram

Current is sensed using a Hall Effect transducer which is having a frequency response of 00kHz. Current is sensed through the inbuilt A/D converter supplied in the *mbed NXP LPC1768* microcontroller. Current sensing is invoked in every 200µs.

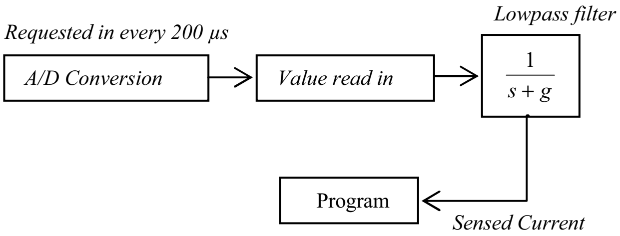

Figure 13. Reading Current

B. Software

Shorter and constant sampling time is one of the most important features in any control system. This study was first attempted using PIC 18F877A microcontroller. However due to many limitations including the speed, accuracy reliability, *mbed NXP LPC1768* microcontroller was used. It runs at a clock speed of 96MHz and by using it rectified many problems faced before. In order to obtain a constant sampling time using a pre-emptive real-time operating system called

MBOS for *mbed NXP LPC1768* is used[9].Basic structure of the real-time tasks are shown in the Fig 14.

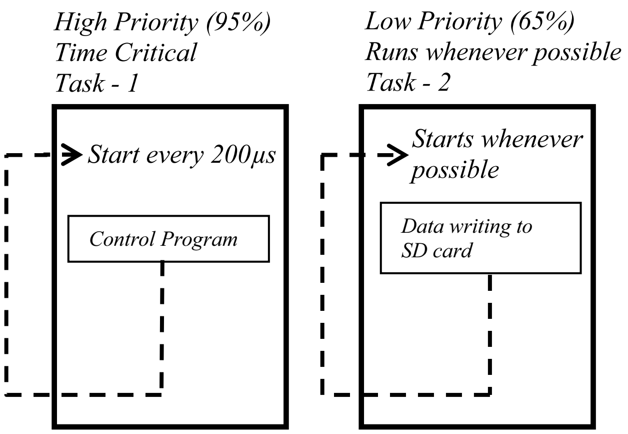

Figure 14. Real time Operating System structure

Time critical main control program is invoked every 200µs, while the data writing task is given the lowest priority. Table 2 shows the priority and speed specific parameters of the hardware and the software setup.

TABLE I. FREQUENCIES USED IN THE SYSTEM

Parameter	**Description**	**Maximum Possible**	**Used in the Study**
dt	Sampling time	130µs	200µs
AtoD conversion frequency	Same as Sampling rate	200kHz	5kHz
PWM Frequency	considerably higher than sampling frequency	1MHz	50kHz
MOSFET frequency	Used at the PWM frequency	>1MHz	50kHz
Optocouple Frequency	Used at the PWM frequency	80kHz	50kHz

Parameters used in the experiment are shown in the Table II.

TABLE II. PARAMETERS

Parameter	**Notation**	**Value**
Propotional Gain	Kp	5.0
Integrating Gain	Ki	0.3
Derivative Gain	Kd	0.001
Current Sensor Cutoff frequency	G_current_f	2kHz
Disturbance Observer cutoff frequency	G_dis	1.2kHz

IV. RESULTS

A 2A command is given to the motor and the controller depicted in Fig. 4 without Disturbance Observer is used first. As the no load current is very much less than this 2A value, a frictional load applied at the rotor. Time response is shown in Fig. 15. Then 2A current was commanded to the system that was described in Fig. 10. Fig. 16 depicts the effect of the disturbance observer. In both these experiments, the PID parameters were not tuned properly to highlight the applicability of the proposed method.

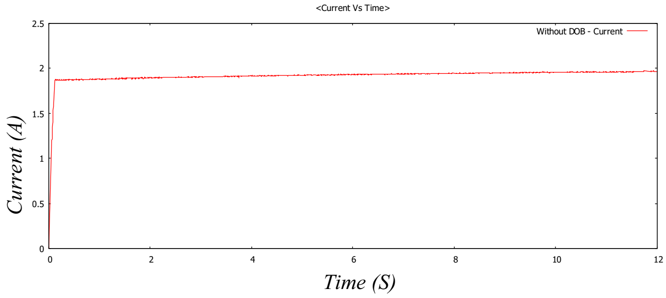

Figure 15. Current response in the absence of DOB

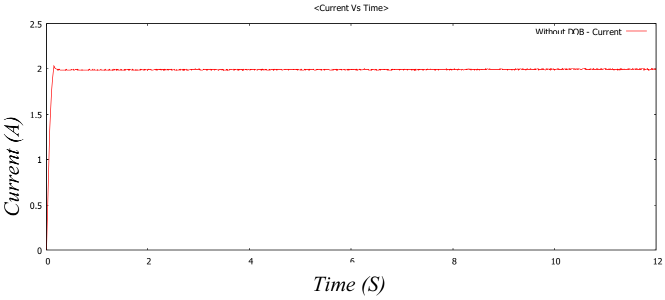

Figure 16. Current response with DOB

Fig.16 shows good results even with an unturned PID.

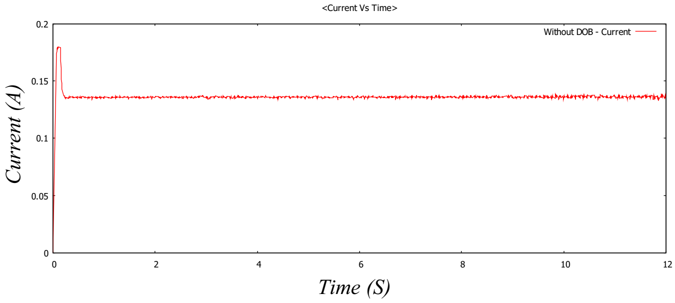

Figure 17. Disturbance current I_{dis}

Fig.17 shows the disturbance current. After the current is stabilized, small but a constant disturbance current was flowing as depicted in Fig. 17. This is necessary to maintain the system robustness by compensating for the frictional effects.

Then an external periodical disturbance was introduced to the system using another DC motor connected to the same shaft in parallel. Then a 0.5A current was commanded and results were taken with and without the disturbance observer. Fig. 18 shows the current output without the disturbance observer. And Fig. 19 shows the current response with the disturbance observer.

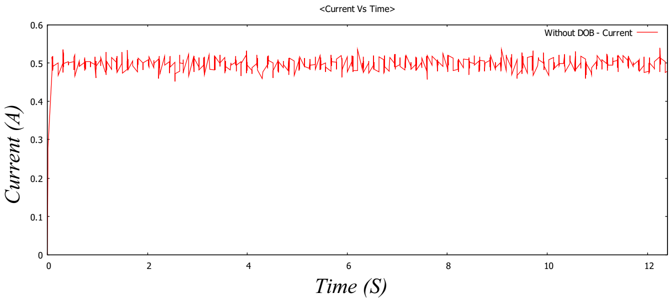

Figure 18. Current response with external periodical disturbance without DOB

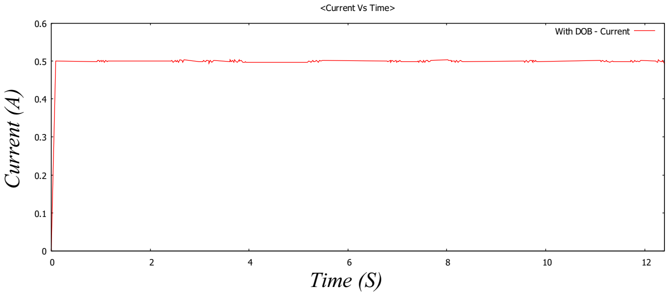

Figure 19. Current response with external periodical disturbance with DOB

V. CONCLUSION

In this paper we proposed a current controlling mechanism that can be applied to brushed DC motors. Different current controlling arrangements were analyzed and finally the disturbance observer based current controller was introduced and analyzed. A better response could be generated when current controllers are used with the Disturbance Observer. This method can be very useful in applications where the plant (motor or inductor) is highly nonlinear. Since disturbance observer compensates for load variations, friction and modeling errors, system response has become highly robust as seen in the results.

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