LQR based Speed Control of BLDC Motors

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Abstract:

The objective of this paper is to compare performance between two type of controller for BLDC motors. BLDC motors are one of the motor types rapidly gaining popularity. The major problem in BLDC drives are that some disturbances are originated in the drive which will reduce the stability of the system. Conventional controller is used to control the speed of the motor, but the response of the system is affected by steady state error and gives a poor transient response. So we use a Linear Quadratic Regulator controller to regulate the speed of the motor. In this paper LQR based controller is designed and its performance is compared with traditional PID controller using Matlab and Simulink.

Keywords- *LQR, PID, Matlab, BLDC motor*

I. INTRODUCTION

Brushless dc motors are gaining grounds in the industries especially in the areas of appliances production medicine, aeronautics, consumer and industrial automation etc. The BLDC motors are typically permanent magnet synchronous motor, they are well driven by dc voltage and they are electronically commutated motors. Some of the advantages of BLDC motors are their Higher speed ranges, Higher efficiency, Better speed versus torque characteristics, Long operating life, Noiseless operation etc.[5].

The structure of BLDC motor is similar to that of a DC motor but the main difference is nothing but the absence of brushes and commutators. In BLDC motor commutation is done electronically and during this process rotational torque is produced by changing the phase current at regular interval. The commutation process can be done either by sensing the signals generated by a sensor associated with the sensor or by analyzing the back emf developed across the coils. Sensor based commutation is used in several applications where the variation in starting torque is large or where a high initial torque is required. Sensor-less control is implemented in applications where the variation in torque is less and position control is not in focus[8].

Conventional PID controller algorithm is simple, stable, easy adjustment and highly reliable. Tuning PID control parameters is very difficult, poor robustness; therefore, it's difficult to achieve the optimal state under field conditions in the actual production. The other type of control methods can be developed such as Linear Quadratic Regulator (LQR) optimal control. This technique used to find the optimal controller that minimizes a given cost function. This cost function is parameterized by two matrices, Q and R, that weight the state vector and the system input respectively. These weighting matrices regulate the penalties on the excursion of state variables and control signal. One practical method is to Q and R to be diagonal matrix. The value of the elements in Q and R is related to its contribution to the cost function. To find the control law, Algebraic Riccati Equation (ARE) is first solved, and an optimal feedback gain matrix, which will lead to optimal results evaluating from the defined cost function is obtained [1]. In this paper optimal speed control of BLDC motors were done using Linear Quadratic Regulator (LQR) technique. The results of this method compared with traditional PID controller.

II. MODELLING OF BLDC MOTOR

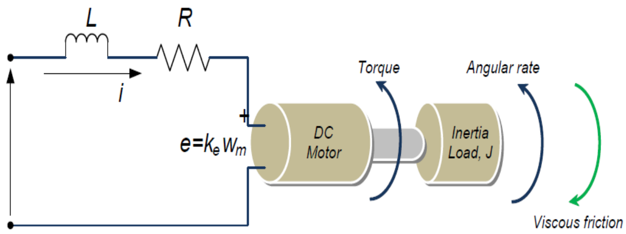

Fig 1.A typical dc motor model

Using KVL,

$$V_s = Ri + L\frac{di}{dt} + e \quad (1)$$

$$e = -Ri - L\frac{di}{dt} + Vs \quad (2)$$

Electromagnetic torque,

$$T_e = K_f \omega_m + J\frac{d\omega_m}{dt} + T_L \quad (3)$$

Put $T_e = k_t \omega_m$ and $e = k_e \omega_m$

$$\frac{di}{dt} = -i\frac{R}{L} - \frac{ke}{L}\omega_m + \frac{1}{L}V_s \quad (4)$$

$$\frac{d\omega_m}{dt} = i\frac{k_t}{J} - \frac{k_f}{J}\omega + \frac{1}{J}T_L \quad (5)$$

Take laplace transform,

$$Si = -i\frac{R}{L} - \frac{K_e}{L}\omega_m + \frac{1}{L}V_s \qquad (6)$$

$$S\omega_m = i\frac{k_t}{J} - \frac{k_f}{J}\omega + \frac{1}{J}T_L \qquad (7)$$

At no load, $T_L = 0$

$$S\omega_m = i\frac{k_t}{J} - \frac{k_f}{J}\omega_m \qquad (8)$$

$$i = \frac{S\omega_m + \frac{k_f}{J}\omega_m}{\frac{k_t}{J}} \qquad (9)$$

Put eqn.(9) in eqn. (6) we get,

$$\left(\frac{S\omega_m + \frac{k_f}{J}\omega_m}{\frac{k_t}{J}}\right)\left(S + \frac{R}{L}\right) = -\frac{K_e}{L}\omega_m + \frac{1}{L}V_s \qquad (10)$$

$$\left(\frac{S^2 J}{K_t} + SK_f + \frac{SRJ}{K_t L} + \frac{K_f R}{K_t L} + \frac{K_e}{L}\right)\omega_m = \frac{1}{L}V_s \qquad (11)$$

$$Vs = \left(\frac{S^2 JL + SK_f L + SRJ + K_f R + K_e K_t}{K_t}\right)\omega_m \qquad (12)$$

Therefore,

$$T.F = \frac{\omega_m}{V_s} = \frac{K_t}{S^2 JL + (RJ + K_f L)S + K_f R + K_e K_t} \qquad (13)$$

By applying some assumptions,

1. K_f tends to zero
2. $RJ >> K_f L_s$
3. $K_e K_t >> RK_f$

T.F will become,

$$G(s) = \frac{\omega_m}{v_s} = \frac{K_t}{s^2 JL + RJS + K_e K_t} \qquad (14)$$

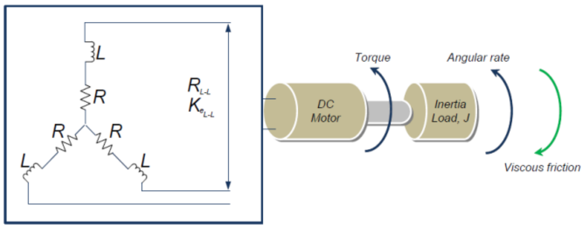

Fig. 2 BLDC Motor Schematic Diagram

Mechanical time constant

$$\tau_m = \frac{3RJ}{K_e K_t} \qquad (15)$$

Electrical time constant,

$$\tau_e = \frac{L}{3R} \qquad (16)$$

Therefore Transfer function of bldc motor is,

$$G(s) = \frac{1/K_e}{\tau_m \tau_e S^2 + \tau_m S + 1} \qquad (17)$$

Table. 1 The Parameter Of Bldc Motor

Armature resistance R(ohm)	1
Armature inductance L(H)	0.046
Back emf constant K_b	0.55
Mechanical inertia J(Kg/m^2)	0.093
Friction coefficient B (N.m/rad/sec)	0.08

So the Transfer function of these BLDC motor is,

$$G(s) = \frac{14.48}{2.44*10^{-6}S^2 + 0.0161S + 1} \qquad (18)$$

III. LINEAR QUADRTIC REGULATOR (LQR)

Linear quadratic regulator or LQR is commonly used technique to find the state feedback gain for a closed loop system. It is the optimal regulator, by which the open-loop poles can be relocated to get a stable system with optimal control and minimum cost for given weighting matrices of the cost function. That is by using the optimal regulator technique, that freedom of choice is lost for both discrete-time and continuous-time systems, because, in order to get a positive- definite Riccatti equation solution, there are some areas where the poles cannot be assigned.

The advantage of LQR is can give better performances of the system by controlling the motor speed and position. Often the magnitude of the control action itself is included in this sum so as to keep the energy expended by the control action itself limited. The LQR algorithm is, at its core, just an automated way of finding an appropriate state-feedback controller.

The design of a state feedback BLDC motor control system is based on a suitable selection of a feedback system structure. The stability of BLDC motor drive system is a major concern. If the state variables are known, then they can be utilized to design a feedback controller so that the input becomes U=KX. It is necessary to measure and utilize the state variables of the system in order to control the speed of the BLDC motor. This design approach of state variable feedback control gives sufficient information about the stability of the BLDC drive system[2].

A description of the linear Quadratic Regulator system considered in this work is show as,

$$A^T P + PA - PBR^{-1}B^T P + Q = 0 \quad (19)$$

This equation is called the Algebraic Ricatti Equation (ARE).For a symmetric positive-definite matrix P. The regulator gain K is given by:

$$K = T^{-1}(T)^{-1} BP = R^{-1}B^T P \quad (20)$$

Where the cost function is,

$$J = \int x(t)^T Qx(t) + u(t)^T Ru(t)dt \quad (21)$$

The two matrices Q and R are selected by the design engineer by trial and error method. Generally speaking, selecting a large value for Q requires the value of J to be small. On the other hand, selecting a large value for R, the control input u must be smaller to keep value of J small. One should select value of Q to be positive semi definite and R to be positive definite. This means that the scalar quantity X^TQX is always positive or zero at each time t. The Q & R matrix is tuned by trial & error method.

A. Matlab Script File

```
num=  [1.818];
den=[7.757e-3 0.507 1];
sys=tf(num,den)
[A,B,C,D]=tf2ss(num,den)
w = 10;
Q = w*C'*C;
R = [3];
K = lqr(A,B,Q,R)
% Our lqr new system will be,
Alqr = A-B*K
Blqr = B;
Clqr = C;
Dlqr = D;
[numlqr, denlqr] =
ss2tf(Alqr,Blqr,Clqr,Dlqr);
syslqr = tf(numlqr,denlqr)
t = 0:0.1:10;
figure(1)
step(sys,t)
hold on
step(syslqr,t)
grid on
legend( 'ori sys' ,'lqr sys' )
hold off
```

From this we get,

K=[4.6963 317.97]

K_1=4.6963

IV. SIMULATION AND RESULTS

The LQR controller Simulink model shows in the figure.3.This model has the step input signal.

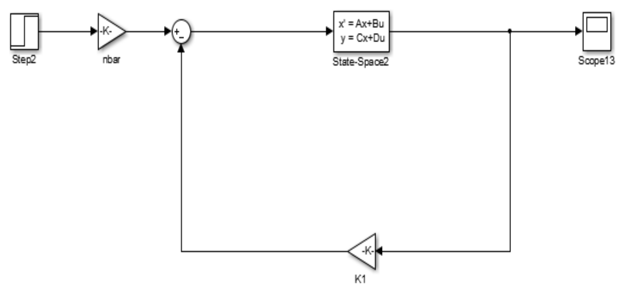

Fig.3 LQR Controller for BLDC Motor

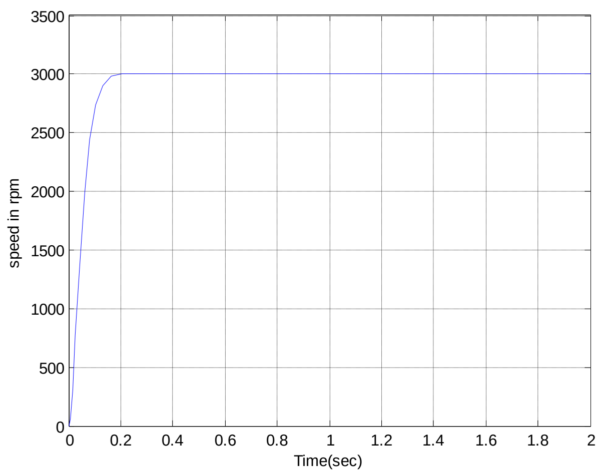

Fig 4 Output Waveform of LQR Controller

The simulink model using PID controller is shown in the figure.5

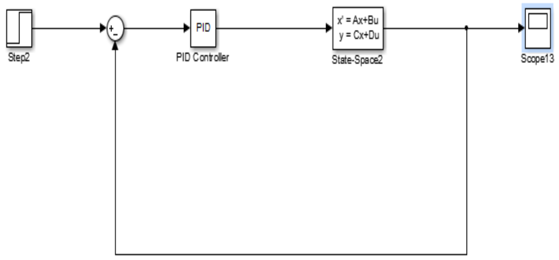

Fig.5 PID Controller for BLDC Motor

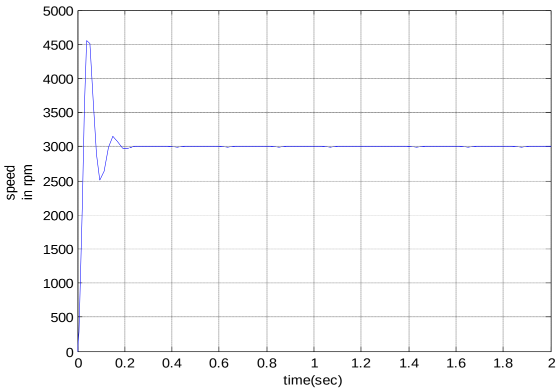

Fig.6 Output Waveform by using PID Controller

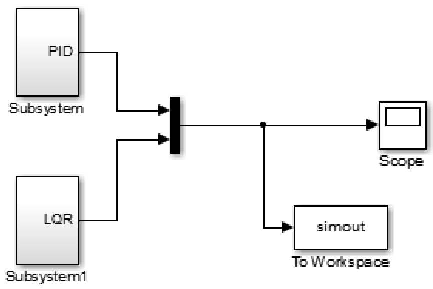

Fig.7 Combined Simulation Using PID and LQR

From this simulation we get the output waveform of both LQR and PID controllers and it is easy to compare the outputs.

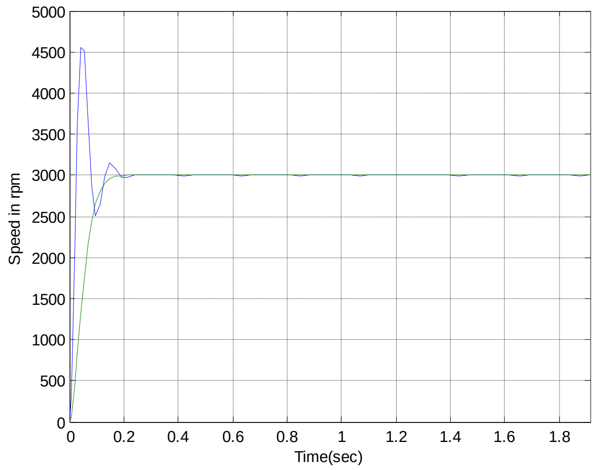

Fig. 8 Combined Output Waveform using PID and LQR

Table.2 The Performance Characteristics

METHODS	Rise time	Settling time	%overshoot
PID controller	16.73 ms	0.3 sec	53
LQR controller	86.17 ms	0.2 sec	0.505

V. CONCLUSION

In this paper a state variable feedback system was designed for BLDC drives to achieve the desired system response. From the simulation results it is clear that the LQR controller has shorter settling time and very small overshoot than that of the PID controller. So the comparison between the speed control of Brushless DC motor by linear quadratic regulator technique and traditional PID controller clearly shows that the linear quadratic regulator technique gives better performance than the other one.

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