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On the Analysis and Optimal Control Design of BLDC Drives

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Abstract

Now a day's Brushless DC motor drives are becoming more popular in industrial applications. The major problem in BLDC drive system is that some disturbances are originated in the drive which will results in errors and reduces the stability of the system. The state variables and control variables of the BLDC drive system are synthesized in this paper. The main objective of this paper is to formulate the optimal control signal which results in minimum performance index. This paper spotlights the design of optimal control systems for BLDC motor drive system based on quadratic performance indexes. This state-space approach to BLDC system analysis reduces the complexity of the mathematical expressions. This optimal design will reduce the burden of tedious computations in control engineers. This optimal design helps to realize the BLDC system with practical components which will provide the desired operating performance.

Key words: Brushless DC (BLDC) motor drives, Optimal Control, State Variables, Performance Index, Control Variables

INTRODUCTION

Development of Brushless DC motor drives has yielded increases efficiency, power factor and reliability. A BLDC machine has several inherent advantages over the machine types. The most important among them are the lower maintenance due to the elimination of the mechanical commutator and brushes [1], [2]. They are more efficient and have lower rotor losses due to the absence of field windings. This drive can be used for variable speed applications like Electrical Vehicles, Robotics etc.

Modeling, simulation and analysis of Permanent magnet synchronous motor drive are described in [1], [2]. A mathematical model of PMSM is given in [3]. A four-switch BLDC motor drive is implemented using digital signal processor in [12]. The precise speed control of a permanent magnet synchronous motor is given in [5]. Ching-Tsai Pan and Emily Fang [7] proposed a PLL-assisted internal model adjustable speed controller for BLDC motor drives. R.Venkitaraman and B.Ramaswami [6] designed a current controller and speed controller for BLDC drive system. An accurate prediction of the system behavior is obtained with the help of digital simulation. A novel digital control technique for Brushless DC motor drives is given in [8], [9]. Anand Sathyan et.al [4] presented an FPGA-based novel digital control scheme for BLDC motor drives. A transfer function for the BLDC drive is derived in this paper. They have not investigated an optimal controller for the BLDC system.

In this paper, an optimal control system is designed for the digitally PWM controlled BLDC motor drive system. For the optimization of control system, state variables and control variables are formulated in this paper. The BLDC performance characteristics close to the optimal control system is synthesized by the use of optimal control theory.

The structure of this paper is as follows. Section 2 describes about the digital PWM control of BLDC drives. The state variable feedback of the BLDC machine is presented in section 3. Section 4 spotlights the optimal system with control energy considerations. Section 5 discuses about the quadratic optimal control in BLDC machine. Conclusion is given in section 6.

DIGITAL PWM CONTROL OF BLDC DRIVES

The speed of a BLDC motor can be controlled by changing the applied voltage across the motor phases. This can be achieved by pulse amplitude modulation, PWM or hysteresis control. Another method of speed control involves sensor less techniques. An FGPA-based novel digital PWM control scheme for BLDC motor drives have been presented in [4]. Fig.1 shows the block diagram for digital PWM control for a BLDC motor drive system. A controller has been designed in this paper.

The torque equation is given by,

$$T_{em} = J\frac{d\omega}{dt} + B\omega + T_L \tag{1}$$

where T_{em}, ω(t), B, J and T_L denote electromagnetic torque, rotor angular velocity, viscous friction constant, rotor moment of inertia and load torque respectively.

$$T_{em} \propto I \tag{2}$$

$$T_{em} = k_t I \tag{3}$$

$$k_t I = J\frac{d\omega}{dt} + B\omega + T_L \tag{4}$$

where K_t= torque constant and I=average current

For the purpose of analysis, the digital controller was considered equivalent to a proportional controller with high gain and saturation.

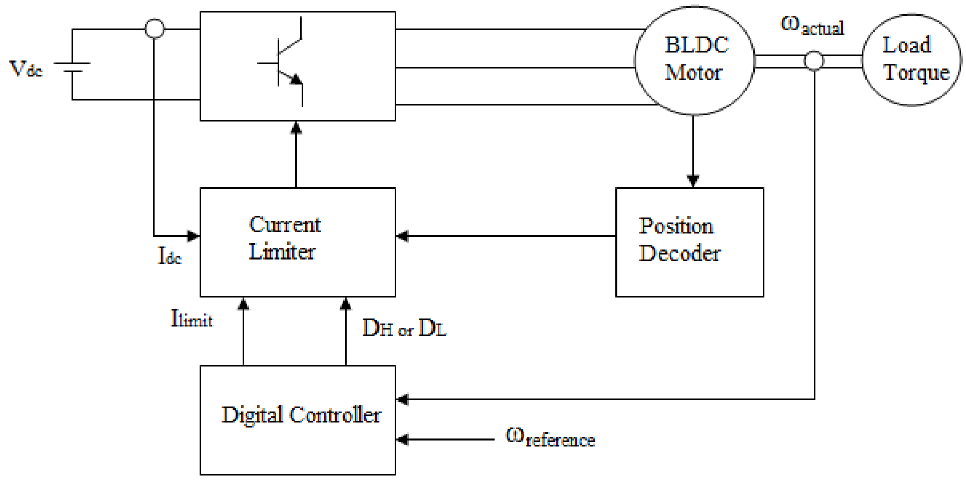

Fig.1 Block Diagram for Digital PWM Control for a BLDC Motor Drive System

The transfer function for a BLDC motor is given by [4],

$$\frac{\omega(s)}{V(s)} = \frac{Kt/JLa}{s^2 + \left(\frac{JRa + BLa}{JLa}\right)s + \left(\frac{BRa + KtKe}{JLa}\right)} \tag{5}$$

The state variable equation for this BLDC drive is given by,

$$\dot{x}_1 = x_2 \tag{6}$$

$$\dot{x}_2 = -\frac{(BRa + k_t k_e)}{JLa} x_1 - \frac{(JRa + BLa)}{JLa} x_2 + \frac{k_t}{JLa} u \tag{7}$$

Arranging in matrix form we get,

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\frac{(BRa + k_t k_e)}{JLa} & -\frac{(JRa + BLa)}{JLa} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{k_t}{JLa} \end{bmatrix} u \tag{8}$$

The output equation is given by,

$$y = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \tag{9}$$

This is in the form,

$$\dot{x} = Ax + Bu \tag{10}$$

$$y = Cx \tag{11}$$

Where

$$A = \begin{bmatrix} 0 & 1 \\ -\frac{(BRa + k_t k_e)}{JLa} & -\frac{(JRa + BLa)}{JLa} \end{bmatrix};$$

$$B = \begin{bmatrix} 0 \\ \frac{k_t}{JLa} \end{bmatrix}; C = \begin{bmatrix} 1 & 0 \end{bmatrix}$$

STATE VARIABLE FEEDBACK

The stability is a major problem in BLDC motor drive system. The design of a state feedback BLDC motor control system is based on a suitable selection of a feedback system structure. 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. The design of a feedback control system for BLDC drive using state variables are discussed in this section [10], [11].

The vector differential equation of BLDC drive system is given in equation (8).

We will choose a feedback control system so that,

$$u(t) = -k_1 x_1 - k_2 x_2 \tag{12}$$

Then the equation (6) and (7) becomes,

$$\dot{x}_1 = x_2$$

$$\dot{x}_2 = -\frac{(BRa + k_t k_e + k_1 k_t)}{JLa} x_1 - \frac{(JRa + BLa + k_2 k_t)}{JLa} \tag{13}$$

Arranging in matrix form, we get,

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\frac{(BRa + k_t k_e + k_1 k_t)}{JLa} & -\frac{(JRa + BLa + k_2 k_t)}{JLa} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \tag{14}$$

which is in the form $\dot{x} = Hx$

where,

$$H = \begin{bmatrix} 0 & 1 \\ -\frac{(BRa + k_t k_e + k_1 k_t)}{JLa} & -\frac{(JRa + BLa + k_2 k_t)}{JLa} \end{bmatrix} \tag{15}$$

Let $k_1 = 1$ and determine a suitable value for k_2 so that the performance index is minimized.

To minimize the performance index J, consider the following two equations,

$$J = \int_0^\infty X^T X dt = X^T(0) P X(0) \tag{16}$$

$$H^T P + PH = -I \tag{17}$$

$$\begin{bmatrix} 0 & -\frac{(BRa + k_t k_e + k_t)}{JLa} \\ 1 & -\frac{(JRa + BLa + k_2 k_t)}{JLa} \end{bmatrix} \begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix} + \begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix}$$

$$\begin{bmatrix} 0 & 1 \\ -\frac{(BRa + k_t k_e + k_t)}{JLa} & -\frac{(JRa + BLa + k_2 k_t)}{JLa} \end{bmatrix} = \begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix} \tag{18}$$

Completing matrix multiplication, addition and solving, we obtain,

$$P_{11} = \frac{(JRa + BRa + k_t k_e + k_t)}{2(JRa + BLa + k_2 k_t)} + \frac{(JRa + BLa + k_2 k_t)}{2(BRa + k_t k_e + k_t)} \tag{19}$$

$$P_{12} = \frac{JRa}{2(JRa + k_t k_e + k_t)} \tag{20}$$

$$P_{22} = \frac{JLa(JLa + BRa + k_t k_e + k_t)}{2(JRa + BLa + k_2 k_e + k_t)(BRa + k_t k_e + k_t)} \tag{21}$$

$$J = P_{11} + 2P_{12} + P_{22} \tag{22}$$

To minimize as a function of k_2,

$$\text{Set } \frac{\partial J}{\partial k_2} = 0 \tag{23}$$

Therefore

$$k_2 = \frac{-JRaBLa}{k_t} \pm \frac{\sqrt{(JRaBLa)^2 - (JLa + BRa + k_t k_e + k_t)(BRa + k_t k_e + k_t + JLa) + J^2 Ra^2 + 2JRaBLa + B^2 La^2}}{k_t} \tag{24}$$

$$k_2 = 1.01499 \tag{25}$$

$$J_{\min} = 1.47 \tag{26}$$

The system matrix H obtained for the compensated system is,

$$H = \begin{bmatrix} 0 & 1 \\ -2629.476 & -2833.7 \end{bmatrix} \tag{27}$$

The feedback control signal is obtained as,

$$u = -x_1 - 1.015x_2 \tag{28}$$

This compensated system is considered to an optimal system which results in a minimum value for the performance index.

OPTIMAL SYSTEM WITH CONTROL ENERGY CONSIDERATIONS

This section considers the expenditure of control signal energy for the BLDC drive system as shown in Fig. 1. To account for the expenditure of the optimal energy of the control signal the performance index $J = \int_0^\infty \left(X^T IX + \lambda u^T u\right)dt$ is chosen where λ is the scalar weighting factor and I= identity matrix [12].

We will choose a feedback control system so that,

$$u = kx = \begin{bmatrix} k & 0 \\ 0 & k \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = kIx \tag{29}$$

Therefore the matrix Q is,

$$Q=\left(I+\lambda k^T k \right)=\left(I+\lambda k^2 I \right)=\left(1+\lambda k^2 \right)I \tag{30}$$

Let

$$X^T(0) = \begin{bmatrix} 1 & 0 \end{bmatrix}$$

$$H^T P + PH = -Q = -\left(1 + \lambda k^2\right)I \tag{31}$$

$$J = P_{11} \tag{32}$$

To simplify the algebra without any loss, let $k_1 = k_2 = k$.

$$\dot{x} = Hx = \begin{bmatrix} 0 & 1 \\ -\dfrac{\left(BRa + k_t k_e + k_t k\right)}{JLa} & -\dfrac{\left(JRa + BLa + k_t k\right)}{JLa} \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \tag{33}$$

$$\begin{bmatrix} 0 & -\dfrac{(BRa+k_tk_e+kk_t)}{JLa} \\ 1 & -\dfrac{(JRa+BLa+kk_t)}{JLa} \end{bmatrix} \begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix} + \begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix} \begin{bmatrix} 0 & 1 \\ -\dfrac{(BRa+k_tk_e+kk_t)}{JLa} & -\dfrac{(JRa+BLa+kk_t)}{JLa} \end{bmatrix} = \begin{bmatrix} -(1+\lambda k^2) & 0 \\ 0 & -(1+\lambda k^2) \end{bmatrix} \tag{34}$$

Completing matrix multiplication, addition and solving we obtain,

$$P_{11} = \frac{(JRa+BLa+kk_t)(1+\lambda k^2)}{2(BRa+k_tk_e+kk_t)} + \frac{(JLa+BRa+k_tk_e+kk_t)(1+\lambda k^2)}{2(JRa+BLa+kk_t)} \tag{35}$$

$$P_{12} = \frac{JLa(1+\lambda k^2)}{2(BRa+k_tk_e+kk_t)} \tag{36}$$

$$P_{22} = \frac{JLa(1+\lambda k^2)(BRa+k_tk_e+kk_t+JLa)}{2(JRa+BLa+kk_t)(BRa+k_tk_e+kk_t)} \tag{37}$$

$$J = P_{11} \tag{38}$$

To obtain minimum performance index,

set $\dfrac{dJ}{dk} = 0$

we get,

$$ak^5 + bk^4 + ck^3 + dk^2 + ek + f = 0 \tag{39}$$

where,

$$a = 8k_t^4\lambda \tag{40}$$

$$b = 8JRaBLak_t^3\lambda + 8BRak_t^3\lambda + 8k_t^4k_e\lambda + 8k_t^3JRa\lambda + 8k_t^3BLa\lambda + 8BRak_t^4k_e\lambda + 2k_t^3JLa\lambda - 2k_t^4 \tag{41}$$

$$c = 4JRaBLak_t\lambda \left[3RaBk_t + 4k_t^2 k_e + JRak_t + BLak_t - {k_t^2}/{\lambda} + 2k_t \right] + 4BJRa\lambda k_t \left(2Ra^2 k_t + 3Rak_t^2 k_e \right) + 4B^2 LaRa\lambda k_t^2 \left(2 + 3k_t k_e \right) + 4BRak_t \lambda \left(BRak_t + 2k_t^2 k_e + BRak_t^2 k_e + k_t^3 k_e^2 \right) + 4k_t^2 \lambda \begin{pmatrix} J^2 Ra^2 + B^2 La^2 + 2BLak_t k_e + \\ J^2 RaLa + BJLa^2 + k_t^2 k_e^2 \end{pmatrix} - 2k_t^4 \tag{42}$$

$$d = \left(J^2 Ra^2 + B^2 La^2 + 2JRaBLa \right) \begin{pmatrix} 6BRak_t\lambda + 6k_t^2 k_e\lambda + 4Jk_t R_a\lambda + 4k_t B L_a\lambda - \\ 2k_t^2 - 2J R_a\lambda k_t - 2B L_a\lambda k_t \end{pmatrix} + 8J^2 R_a^3 B^2 L_a k_t\lambda + 8J R_a^2 B^3 L_a^2 k_t\lambda + 8J^2 R_a^2 B L_a k_t^2 k_e\lambda - 2J R_a k_t^3 - 2B L_a k_t^3 + \left(B^2 R_a^2 + k_t^2 k_e^2 + 2B R_a k_t k_e \right) \begin{pmatrix} 6J R_a k_t\lambda + 6B L_a k_t\lambda + 4k_t B R_a\lambda + 4k_t^2\lambda k_e - 2J L_a\lambda k_t \\ -2B R_a\lambda k_t - 2\lambda k_t^2 k_e \end{pmatrix} + 8B R_a^2 k_t^2 k_e J^2 L_a\lambda + 8B^2 R_a^3 k_t^2 k_e J\lambda - 4B R_a k_t^4 k_e + 8B R_a^2 k_t^3 k_e^2 J\lambda + 8B R_a^2 k_t^2 k_e L_a^2\lambda + 8B^3 R_a^2 k_t^2 k_e J L_a\lambda + 8B^2 R_a k_t^3 k_e^2 L_a\lambda - 2J L_a k_t^3 - 2B R_a k_t^3 - 2k_t^4 k_e \tag{43}$$

$$e = \left(J^2 Ra^2 + B^2 La^2 + 2JRaBLa\right)$$
$$\left(4BJRa^2\lambda + 4B^2 LaRa\lambda + 4k_t k_e J R_a \lambda + 4Bk_t k_e J L_a \lambda\right) -$$
$$4J^2 B R_a^2 L_a k_t^2 - 4JB^2 R_a L_a^2 k_t^2 - 4B R_a k_t^3 k_e J L_a -$$
$$4B^2 R_a^2 k_t^3 k_e - 2B R_a k_t^4 k_e^2 + \tag{44}$$
$$\left(B^2 R_a^2 + k_t^2 k_e^2 + 2B R_a k_t k_e\right)$$
$$\left(\begin{array}{l} 4J^2 R_a L_a \lambda + 4J R_a^2 B\lambda + 4J R_a \lambda k_t k_e + 4BJ L_a^2 \lambda + \\ 4B^2 L_a R_a \lambda + 4B L_a \lambda k_t k_e - 2 k_t^2 \end{array}\right)$$

$$f = -\left(J^2 R_a^2 + B^2 L_a^2 + 2JB R_a L_a\right)$$
$$\left(2J R_a k_t + 2B L_a k_t\right) - \left(B^2 R_a^2 + k_t^2 k_e^2 + 2B R_a k_e k_t\right) \tag{45}$$
$$\left(2J L_a k_t + k_t^2 k_e + 2B R_a k_t\right)$$

The BLDC drive system parameters are shown in Table 1

Table 1: BLDC Drive Parameters

SL. NO.	Parameter	Symb.	Unit	Value
1.	Stator Winding Resistance	Ra	Ω	1.4
2.	Stator Winding Inductance	La	H	0.0066
3.	Rotor inertia	J	Kg-m^2	0.00176
4.	Motor Viscous Friction Coefficient	B	Nm/rad/sec	0.00038818
5.	Torque Constant	kt	Nm/Amp	0.03
6.	Velocity Constant	ke	Volts/rad	0.0000181

When $\lambda = 0$
Solving the above equations we get,

$$k^4 + k^3 + 0.871k^2 + 3.29\times10^{-4}k + 5.61\times10^{-4} = 0 \tag{46}$$

Applying Lin's Method the eqn.(46) becomes,

$$\left(k^2 + 0.998k + 0.868\right)\left(k^2 - 3.63 \times 10^{-4} k + 6.46 \times 10^{-4}\right) = 0 \tag{47}$$

QUADRATIC OPTIMAL CONTROL

This section discusses about the design of a stable control system for BLDC drive based on quadratic performance indexes. The main advantage of using the quadratic optimal control scheme is that the system designed will be stable, except in the case where the system is not controllable. The matrix 'P' is determined from the solution of the matrix Riccatti equation. This optimal control is called the Linear Quadratic Regulator (LQR) [10], [11].

The optimal feedback gain matrix k can be obtained by solving the following Riccatti equation for a positive-definite matrix 'P'.

$$A^T P + PA - PBR^{-1} B^T P + Q = 0 \tag{49}$$

Let

$$Q = \begin{bmatrix} 1 & 0 \\ 0 & \mu \end{bmatrix} (\mu \geq 0) \tag{50}$$

$$\begin{bmatrix} 0 & -\dfrac{(\mathbf{B} R_a + k_t k_e)}{J L_a} \\ 1 & -\dfrac{(J R_a + B L_a)}{J L_a} \end{bmatrix} \begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix} + \begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix} \begin{bmatrix} 0 & 1 \\ -\dfrac{(\mathbf{B} R_a + k_t k_e)}{J L_a} & -\dfrac{(J R_a + B L_a)}{J L_a} \end{bmatrix} - \begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix} \begin{bmatrix} 0 \\ \dfrac{k_t}{JLa} \end{bmatrix} [1] \begin{bmatrix} 0 & \dfrac{k_t}{JLa} \end{bmatrix} \begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ 0 & \mu \end{bmatrix} = 0 \tag{51}$$

Solving we obtain the following three equations,

$$\frac{P_{12}{}^2 \, k_t{}^2}{J^2 \, L_a{}^2} + \frac{2(B\, R_a + k_t k_e)}{J\, L_a} - 1 = 0 \tag{52}$$

$$P_{11} - \frac{P_{12}\left(J R_a + B L_a\right)}{J L_a} - \frac{P_{22}\left(B R_a + k_t k_e\right)}{J L_a} -$$

$$\frac{P_{12} P_{22} k_t^2}{J^2 L_a^2} = 0 \tag{53}$$

$$2 P_{11} - \frac{2 P_{22}\left(J R_a + B L_a\right)}{J L_a} - \frac{P_{22}^2 k_t^2}{J^2 L_a^2} + \mu = 0 \tag{54}$$

Solving these three equations we get,

$$P = \begin{bmatrix} -1.09\times10^{-3} + \sqrt{1+132.98\mu} & 3.8\times10^{-4} \\ 3.8\times10^{-4} & -3.18\times10^{-5} + 3.35\times10^{-5}\sqrt{1+132.98\mu} \end{bmatrix} \tag{55}$$

The optimal feedback gain matrix is obtained as,

$$k = R^{-1} B^T P \tag{56}$$

$$k = \begin{bmatrix} 0.981 & -0.08 + 0.0865\sqrt{1+132.98\mu} \end{bmatrix} \tag{57}$$

$$u = -kx = -0.981 x_1 - \left(-0.08 + 0.0865\sqrt{1+132.98\mu}\right) x_2 \tag{58}$$

This control signal yields an optimal result for any initial state under the given performance index. Figure [2] shows the block diagram for optimal control of the BLDC drive system.

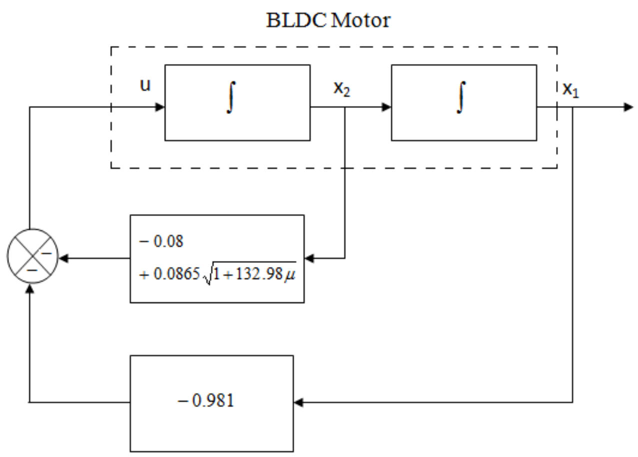

Fig.2 Optimal Control of the BLDC Drive System

CONCLUSION

In this paper a state variable feedback system was designed for BLDC drive system to achieve the desired system response. Also, an optimal control system was designed for BLDC drive which results in a minimum value for the performance index. To account for the expenditure of energy and resources, the control signal is often included in the performance integral.

From the foregoing analysis, the value of K_2 is obtained as 1.0149 so that the performance index is minimized. The minimum value of performance index is obtained as 1.47. This optimal controlled BLDC drive system results in a minimum value for the performance index. Also, the control law given by equation (58) yields optimal result for any initial state under the given performance index. This design based on the quadratic performance index yields a stable control system for the BLDC drive system.

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