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OPTIMAL STATE FEEDBACK CONTROLLER FOR SEPARATELY-EXCITED DC MOTOR

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ABSTRACT- In this paper, a state feedback controller for separately-excited DC motor (SEDM) is presented. The controller is designed using the Optimal Control approach. The motor, with and without the controller, is modeled as a multi-input multi-output (MIMO) system with state-space and transfer function representations. The control inputs are the motor armature and the motor field voltages. The controlled outputs are the motor angular speed and the motor field current. The system states are the same as the system outputs. The performance of the system with the designed controller is simulated using MATLAB(R)/SIMULINK(R), and is compared with that of the open loop system. The results show excellent performance of the controlled system, in terms of steady-state error, output decoupling, response speed and general system behavior.

Keywords- optimal control, separately excited DC motor, motor speed, speed controller

I. INTRODUCTION

DC motors are widely used in industrial applications, because of their excellent control characteristics. The DC motor has two windings, the armature winding and the field winding. The two motor windings can be connected in different configurations as, series, shunt, compound or can be separated. Series, shunt or compound connections of the two motor windings produces a system with single degree of freedom. Motors with separated armature and field windings have two degrees of freedom, as they have two control inputs, which are the armature supply voltage V_a and the field supply voltage V_f.

The figure below shows the schematic diagram of the separately excited DC motor.

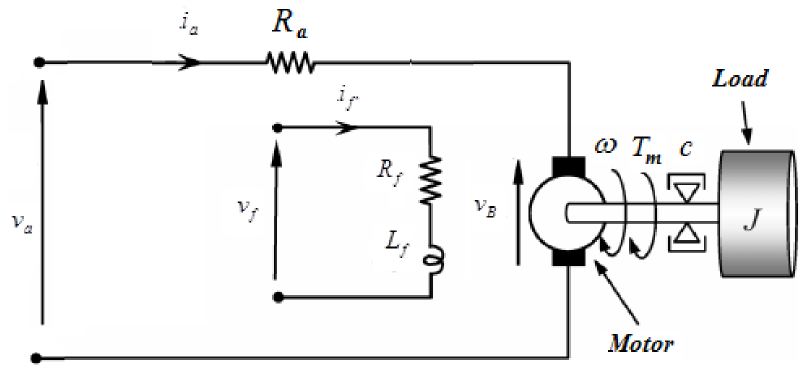

Figure. 1. The Schematic Diagram of the Separately Excited DC Motor

In this figure:

- V_a and V_f are the armature and the field voltages.
- i_a and i_f are the armature and the field currents.
- R_a and R_f are the resistances of the armature and the field windings.
- L_f is the self inductance of the motor field winding.

- V_B is the back electromotive force.
- ω is the motor angular speed.
- T_m is the motor shaft torque.
- c is the viscous friction coefficient.
- J is the moment of inertia of the motor and the load.

Note that, the leakage inductance of the motor armature circuit is neglected, as usually its value is very small, as compared to other motor parameters.

As a MIMO system, different approaches can be used to design the controller of the separately excited DC motor. Of these approaches are the optimal control approach, from the modern control theory, and the Inverse Nyquist Array approach, from the classical control theory. In this paper, the optimal control approach is used. In this approach, state feedback is applied. The design objective is to find a state feedback matrix that will locate the poles of the closed loop system in a suitable s-plane location and minimizes a quadratic performance index.

II. Modeling of the separately-excited DC Motor

The motor is modeled as a linear two-input, two-output system. The system inputs are the armature and the field supply voltages, v_a and v_f, respectively. The system states are the motor angular speed ω and the motor field current i_f. The system outputs are the same as the system states.

Referring to Figure.1, it can be seen that the armature supply voltage is equal to the sum of the voltage drop on the resistance of the armature winding and the back electromotive force, or:

$$v_a(t) = R_a i_a(t) + v_B(t) \qquad (1)$$

The back electromotive force is directly proportional to the motor angular speed, or:

$$v_B(t) = k_1 \omega(t) \qquad (2)$$

From these two equations, it is found that:

$$v_a(t) = R_a i_a(t) + k_1 \omega(t) \qquad (3)$$

The torque on the motor shaft is proportional to both the motor armature and field currents, or:

$$T(t) = k_a i_a(t) + k_f i_f(t) \qquad (4)$$

The dynamics of the motor shaft is described by the equation:

$$T(t) = J\frac{d\omega(t)}{dt} + c\omega(t) \qquad (5)$$

From equations (4) and (5), it can be found that:

$$J\frac{d\omega(t)}{dt} = k_a i_a(t) + k_f i_f(t) - c\omega(t) \qquad (6)$$

From equation (3), it is found that:

$$i_a(t) = -\frac{k_1}{R_a}\omega(t) + \frac{1}{R_a}v_a(t) \qquad (7)$$

Substituting (7) in (6), it is found that:

$$J\frac{d\omega(t)}{dt} = -\left(\frac{k_a k_1}{R_a} + c\right)\omega(t) + k_f i_f(t) + \frac{k_a}{R_a}v_a(t) \qquad (8)$$

Or:

$$\dot{\omega} = -\left(\frac{k_a k_1}{JR_a} + \frac{c}{J}\right)\omega(t) + \frac{k_f}{J}i_f(t) + \frac{k_a}{JR_a}v_a(t) \qquad (9)$$

Where:

$$\dot{\omega} = \frac{d\omega(t)}{dt}$$

The field supply voltage is equal to the sum of the voltage drops on the resistance and the inductance of the field circuit, or:

$$v_f(t) = R_f . i_f(t) + L_f\frac{di_f(t)}{dt} \qquad (10)$$

This equation can be written as:

$$\dot{i}_f = -\frac{R_f}{L_f}i_f + \frac{1}{L_f}v_f(t) \qquad (11)$$

Where:

$$\dot{i}_f = \frac{di_f(t)}{dt}$$

Equations (9) and (11) can be written as:

$$\begin{bmatrix}\dot{\omega}\\ \dot{i}_f\end{bmatrix} = \begin{bmatrix}-\left(\frac{k_a . k_1}{J.R_a} + \frac{c}{J}\right) & \frac{k_f}{J}\\ 0 & -\frac{R_f}{L_f}\end{bmatrix} . \begin{bmatrix}\omega\\ i_f\end{bmatrix} + \begin{bmatrix}\frac{k_a}{J.R_a} & 0\\ 0 & \frac{1}{L_f}\end{bmatrix} . \begin{bmatrix}v_a\\ v_f\end{bmatrix} \qquad (12)$$

Equation (12) is the system state equation.

As the system outputs are the same as the system states, thus the system output equation has the form:

$$\begin{bmatrix}\omega\\ i_f\end{bmatrix} = \begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix} . \begin{bmatrix}\omega\\ i_f\end{bmatrix} \qquad (13)$$

Or in general:

$$\dot{X}(t) = A.X(t) + B.U(t) \quad (14)$$

$$Y(t) = C.X(t) + D.U(t) \quad (15)$$

where:

$$A = \begin{bmatrix} -\left(\frac{k_a.k_1}{J.R_a} + \frac{c}{J}\right) & \frac{k_f}{J} \\ 0 & -\frac{R_f}{L_f} \end{bmatrix} \quad (16)$$

$$B = \begin{bmatrix} \frac{k_a}{J.R_a} & 0 \\ 0 & \frac{1}{L_f} \end{bmatrix} \quad (17)$$

$$C = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \quad (18)$$

$$D = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} \quad (19)$$

$$X = Y = \begin{bmatrix} \omega \\ i_f \end{bmatrix} \quad (20)$$

And:

$$U = \begin{bmatrix} v_a \\ v_f \end{bmatrix} \quad (21)$$

The transfer function of the system is found by finding the Laplace transforms, with zero initial conditions, for each of the state equation (14) and the output equation (15), or:

$$s.X(s) = A.X(s) + B.U(s) \quad (22)$$

and:

$$Y(s) = C.X(s) + D.U(s) \quad (23)$$

From these two equations, it is found that:

$$Y(s) = \left[C.(s.I - A)^{-1}.B + D\right]U(s)$$

Or, the system transfer function is:

$$G(s) = \frac{Y(s)}{U(s)} = C.(s.I - A)^{-1}.B + D \quad (24)$$

In this equation, matrix I is the identity matrix of order as that of matrix A.

For a strictly proper system, $D = 0$, and the system transfer function becomes:

$$G(s) = \frac{Y(s)}{U(s)} = C.(s.I - A)^{-1}.B \quad (25)$$

Or the transfer function of the separately-excited DC motor is:

$$G(s) = \frac{1}{(J.R_a.s + R_a.c + k_a.k_1).(L_f.s + R_f)} \begin{bmatrix} k_a.(L_f.s + R_f) & k_f.R_a \\ 0 & J.R_a.s + R_a.c + k_a.k_1 \end{bmatrix} \quad (26)$$

As:

$$U(s) = [v_a(s) \quad v_f(s)]^T \quad (27)$$

$$Y(s) = [\omega(s) \quad i_f(s)]^T \quad (28)$$

Hence:

$$\begin{bmatrix} \omega(s) \\ i_f(s) \end{bmatrix} = \frac{1}{(J.R_a.s + R_a.c + k_a.k_1).(L_f.s + R_f)} \begin{bmatrix} k_a.(L_f.s + R_f) & k_f.R_a \\ 0 & J.R_a.s + R_a.c + k_a.k_1 \end{bmatrix} . \begin{bmatrix} v_a(s) \\ v_f(s) \end{bmatrix} \quad (29)$$

III. The Optimal Feedback Controller

In the optimal control method, state feedback is implemented. The control law is assumed to be:

$$U(t) = -K.X(t) \quad (30)$$

Where K is a constant matrix.

The block diagram of a linear system with an optimal controller is as shown below.

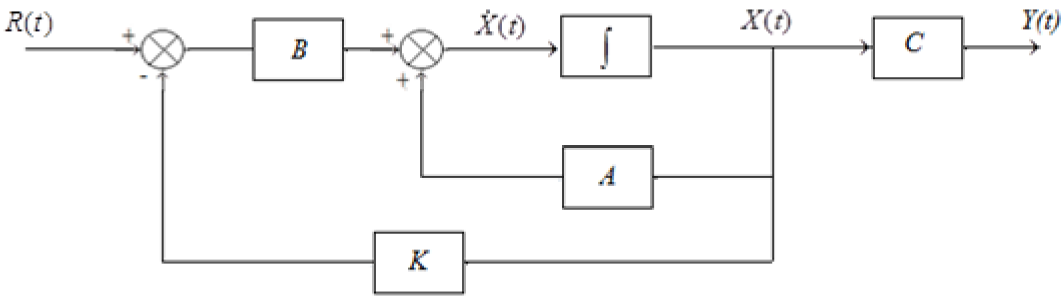

Figure. 2. Linear system with the optimal control method.

Substituting equation (30) in equation (14), yields:

$$\dot{X}(t) = (A - B.K).X(t) \quad (31)$$

This equation indicates that the system behavior depends on the eigenvalues of the matrix $(A - B.K)$, which are the roots of the characteristic equation:

$$|\lambda.I - (A - B.K)| = 0 \quad (32)$$

It is known that, in order the closed-loop system to be stable, the roots of equation (32) should have negative real parts. So, for a linear system with A and B matrices, the design objective is to find the matrix K that will place the poles of the closed loop system in suitable s-plane locations and minimizes the quadratic performance index J , defined as:

$$J = \int_0^\infty (X^T Q.X + U^T R.U).dt \quad (33)$$

In this definition, Q and R should be square, symmetric and positive definite or positive semi-definite matrices. They are the weighting matrices of the state and the input vectors, respectively.

An alternative definition of the performance index J , can be defined as:

$$J = \int_0^\infty (Y^T Q.Y + U^T R.U).dt \quad (34)$$

In this definition, the state vector X is replaced by the output vector Y .

The gain matrix K is determined as:

$$K = R^{-1} B^T . P \qquad (35)$$

Where P is found by solving the Algebraic Riccati Equation (ARE):

$$A^T P + PA - PBR^{-1} B^T P + Q = 0 \qquad (36)$$

A good initial selection of the weighting matrices, Q and R, is that:

$$Q = \begin{bmatrix} q_1 & 0 & 0 & \dots & 0 \\ 0 & q_2 & 0 & \dots & 0 \\ 0 & 0 & q_3 & \dots & . \\ . & . & . & . & . \\ 0 & 0 & 0 & \dots & q_n \end{bmatrix} \qquad (37)$$

and:

$$R = \begin{bmatrix} r_1 & 0 & 0 & \dots & 0 \\ 0 & r_2 & 0 & \dots & 0 \\ 0 & 0 & r_3 & \dots & . \\ . & . & . & . & . \\ 0 & 0 & 0 & \dots & r_n \end{bmatrix} \qquad (38)$$

Where:

$$q_i = \frac{1}{(x_{i,\max})^2} \qquad (39)$$

And:

$$r_i = \frac{1}{(u_{i,\max})^2} \qquad (40)$$

After simulating the system with these initial values of the weighting matrices, the elements of these matrices are adjusted till the required performance of the system is achieved.

To achieve output decoupling at steady- state, the loop-gain matrix K can be decomposed into a forward path gain matrix, K_e, and a backward path gain matrix, H. Or:

$$K = K_e . H \qquad (41)$$

Where, K_e is found from the equation:

$$K_e = G^{-1}(0)[I + G(0).K_e..H].S_S \qquad (42)$$

In this equation S_S is the steady state matrix.

For zero steady state interaction, the matrix S_S is the identity matrix. Otherwise, it would have small off-diagonal elements.

It has to be said, that in order to implement the optimal feedback controller for a given system, the system has to be a controllable and observable.

Controllability can be investigated by checking the rank of the controllability matrix S, defined as:

$$S = [B \quad AB \quad A^2 B \quad \dots \quad A^{n-1} B] \qquad (43)$$

For a system, with a state matrix A and an input matrix B, to be completely state controllable, the rank of matrix S must be equal to n, which is the dimension of matrix A.

Similar to controllability, observability can be investigated by checking the rank of the observability matrix V, defined as:

$$V = \left[C^T \quad A^T C^T \quad \left(A^T\right)^2 C^T \quad \ldots \quad \left(A^T\right)^{n-1} C^T \right] \qquad (44)$$

For a system, with a state matrix A and an output matix C, to be completely state observable, the rank of matrix V must also be equal to n.

IV. Optimal Feedback Controller for The Separately-Excited DC Motor

The separately-excited DC motor, for which the optimal feedback controller was designed has the following parameters: $P = 200hp$, $V_a = 400V$, $V_f = 400V$, $R_f = 50\Omega$, $L_f = 23.25H$, $R_a = 0.24\Omega$, $k_1 = 26.96V/(rad/\sec)$, $k_a = 16.33N.m/A$, $k_f = 613.36N.m/A$, $J = 555.kg.m^2$, $c = 1200.24N.m/(rad/\sec)$.

By substituting these parameters in equations (16) and (17), the state and the input matrices of the system become:

$$A = \begin{bmatrix} -54.68 & 11.05 \\ 0 & -2.15 \end{bmatrix} \qquad (45)$$

$$B = \begin{bmatrix} 1.23 & 0 \\ 0 & 0.043 \end{bmatrix} \qquad (46)$$

Or the system state equation is:

$$\begin{bmatrix} \dot{\omega} \\ \dot{i}_f \end{bmatrix} = \begin{bmatrix} -54.68 & 11.05 \\ 0 & -2.15 \end{bmatrix} . \begin{bmatrix} \omega \\ i_f \end{bmatrix} + \begin{bmatrix} 1.23 & 0 \\ 0 & 0.043 \end{bmatrix} . \begin{bmatrix} v_a \\ v_f \end{bmatrix} \qquad (47)$$

and the system output equation is:

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} . \begin{bmatrix} \omega \\ i_f \end{bmatrix} \qquad (48)$$

The transfer function of system is found by substituting the motor parameters in equation (26), hence:

$$G(s) = \begin{bmatrix} \dfrac{1.226s + 2.64}{s^2 + 56.83s + 117.6} & \dfrac{0.475}{s^2 + 56.83s + 117.6} \\ 0 & \dfrac{0.043s + 2.35}{s^2 + 56.83s + 117.6} \end{bmatrix} \qquad (49)$$

Or, the input-output description of the system becomes:

$$\begin{bmatrix} \omega(s) \\ i_f(s) \end{bmatrix} = \begin{bmatrix} \dfrac{1.226s + 2.64}{s^2 + 56.83s + 117.6} & \dfrac{0.475}{s^2 + 56.83s + 117.6} \\ 0 & \dfrac{0.043s + 2.35}{s^2 + 56.83s + 117.6} \end{bmatrix} . \begin{bmatrix} v_a(s) \\ v_f(s) \end{bmatrix} \qquad (50)$$

The system eigenvalues are the roots of the characteristic equation:

$$\left| \lambda.I - A \right| = 0 \qquad (51)$$

Which are:

$\lambda_1 = -54.68$, $\lambda_2 = -2.15$

As all the system eigenvalues lie on the left hand complex plane, then the open-loop system of the SEDM is stable.

The first step in designing the optimal controller is testing the controllability and the observability of the system.

As mentioned before, the controllability matrix of the system is:

$$S = [B \quad AB] \tag{52}$$

Substituting values of A and B matrices into the controllability matrix, results:

$$S = \begin{bmatrix} 1.23 & 0 & -67.256 & 0.47515 \\ 0 & 0.043 & 0 & -0.09245 \end{bmatrix} \tag{53}$$

Since the rank of the controllability matrix S is 2, i.e, matrix S is a full row rank, hence the system is completely controllable.

System observability is tested by finding the rank of the observability matrix, V, defined as:

$$V = [C^T \quad A^T C^T] \tag{54}$$

Or:

$$V = \begin{bmatrix} 1 & 0 & -54.68 & 0 \\ 0 & 1 & 11.05 & -2.15 \end{bmatrix} \tag{55}$$

Since the rank of matrix V is 2, i.e, matrix V is a full row rank, hence the system is completely observable.

As the system is completely controllable and completely observable, an optimal controller for this system can be designed.

The weighting matrices, Q and R, are selected to be diagonal and positive definite ones. Equations (39) and (40) can be used to determine the elements of these two matrices. Or:

$$Q = \begin{bmatrix} q_1 & 0 \\ 0 & q_2 \end{bmatrix} = \begin{bmatrix} \frac{1}{(\omega_{\max})^2} & 0 \\ 0 & \frac{1}{(i_{f,\max})^2} \end{bmatrix} = \begin{bmatrix} \frac{1}{10.96^2} & 0 \\ 0 & \frac{1}{8^2} \end{bmatrix} \tag{56}$$

$$R = \begin{bmatrix} r_1 & 0 \\ 0 & r_2 \end{bmatrix} = \begin{bmatrix} \frac{1}{(v_{f,\max})^2} & 0 \\ 0 & \frac{1}{(v_{a,\max})^2} \end{bmatrix} = \begin{bmatrix} \frac{1}{400^2} & 0 \\ 0 & \frac{1}{400^2} \end{bmatrix} \tag{57}$$

Matrix P is found by solving the Algebraic Riccati Equation (ARE), defined by (36).

The elements of matrix are found to be:

$p_{11} = 0.0000663725$, $p_{12} = p_{21} = 0.0000099384$ and $p_{22} = 0.0030424091$

Or:

$$P = \begin{bmatrix} 0.0000663725 & 0.0000099384 \\ 0.0000099384 & 0.0030424091 \end{bmatrix} \tag{66}$$

The gain matrix K is calculated using equation (35), or:

$$K = \begin{bmatrix} 13.062 & 1.9559 \\ 0.068376 & 20.932 \end{bmatrix} \tag{67}$$

To achieve output decoupling at steady state, this loop-gain matrix is decomposed into a forward path gain matrix, K_e, and a backward path gain matrix, H . Or:

$$K = K_e.H \quad (68)$$

Where, K_e is found from the equation:

$$K_e = G^{-1}(0)[I + G(0).K_e..H].S_S \quad (69)$$

Here, $G(0)$ is calculated by equation (49). Matrix S_S is the steady state interaction matrix. For zero steady state interaction, the matrix S_S is the identity matrix. Otherwise, it would have small off-diagonal elements.

From equations (68) and (69) , and for steady state matrix $S_S = \begin{bmatrix} 1 & 0.1 \\ 0.1 & 1 \end{bmatrix}$,it is found that:

$$K_e = \begin{bmatrix} 56.903 & -1.2872 \\ 7.1658 & 70.981 \end{bmatrix} \quad (70)$$

and:

$$H = K_e^{-1}.K = \begin{bmatrix} 0.2291 & 0.041 \\ -0.02216 & 0.2908 \end{bmatrix} \quad (71)$$

The block diagram of the closed loop system with the optimal controller is shown in figure. 3.

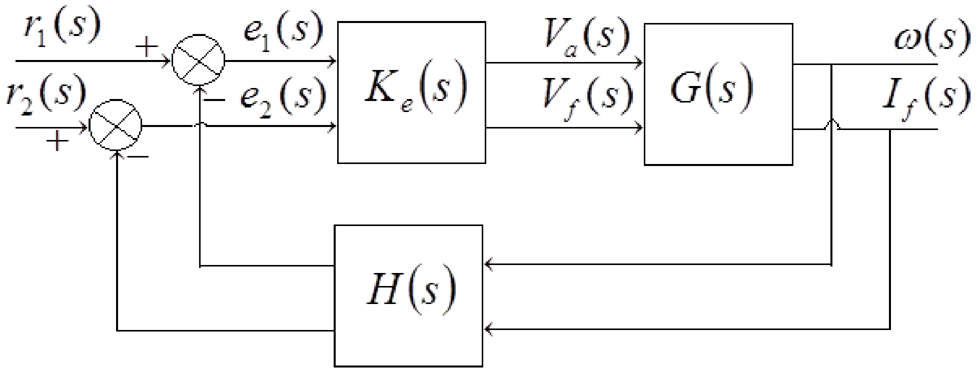

Figure. 3. Block diagram of the closed-loop system with the optimal controller

V. Simulations and Results

To compare the performance of the closed-loop system with that of the open-loop system, models of these two systems were built and simulated using MATLAB®/SIMULINK® .

A model of the open loop system, using the transfer function of the DC motor, described by equation (49), is shown in figure.4. This model was simulated for unit step on each of the two inputs, respectively. The simulation results are shown in figures 5 and 6.

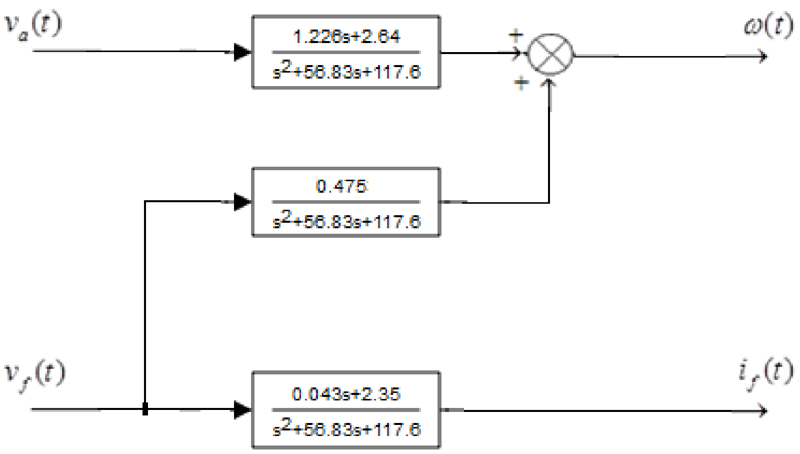

Figure. 4. Block diagram of the separately-excited DC motor, as described by the transfer function.

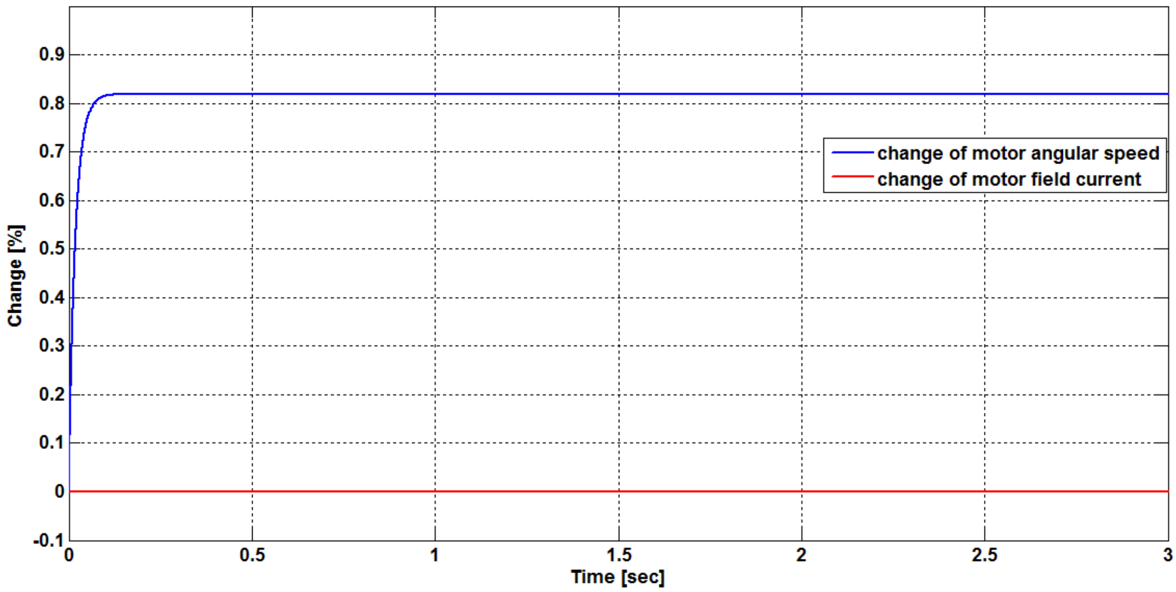

Figure. 5. Open-loop system response for a unit step change in the motor armature voltage, $u_1(t)$, with no change in the motor field voltage, $u_2(t) = 0$.

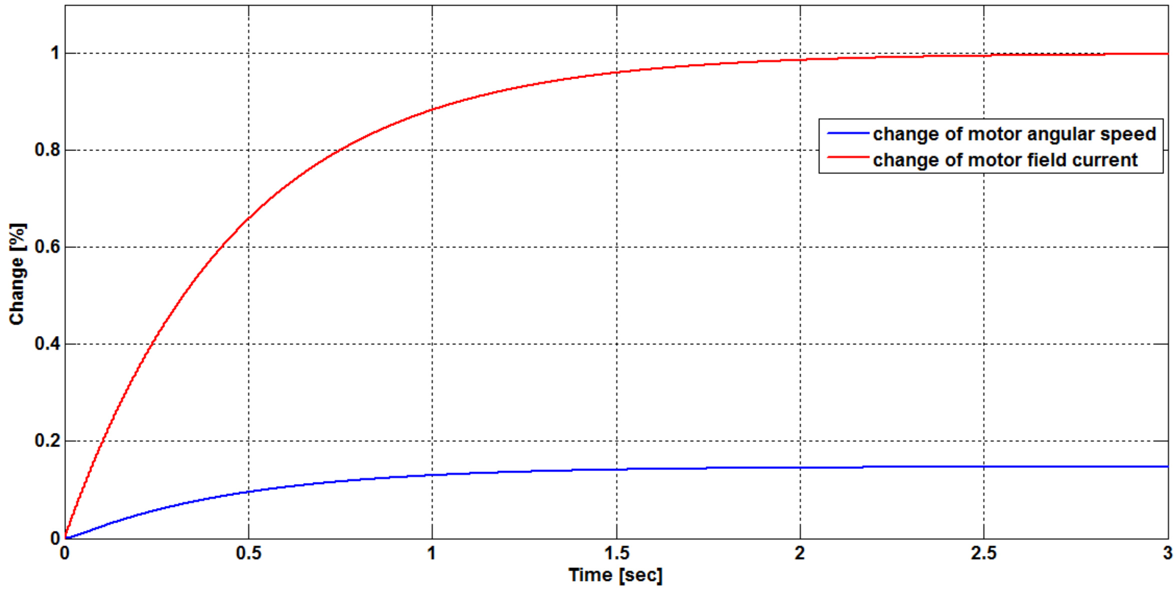

Figure. 6. Open-loop system response for a unit step change in the motor field voltage, $u_2(t)$, with no change in the motor armature voltage $u_1(t) = 0$.

From figure. 5, it can be seen that a unit step change of the motor armature voltage causes only around 0.82% change of the motor angular speed, but no change in the motor field current.

Figure. 9, shows that for a unit step change of the motor field voltage causes a unit step change of the motor field current, and almost 0.15% change of the motor angular speed.

This indicate that even the open-loop system is stable and well behaved, the steady state error is relatively high and a cross-coupling between the system outputs is existing.

The model of the closed loop system, with the values of matrices K_e and H, as given by (70) and (71) , is shown in figure.7 . This model was also simulated for unit step on each of the two inputs, respectively. The simulation results are shown in figures 8 and 9.

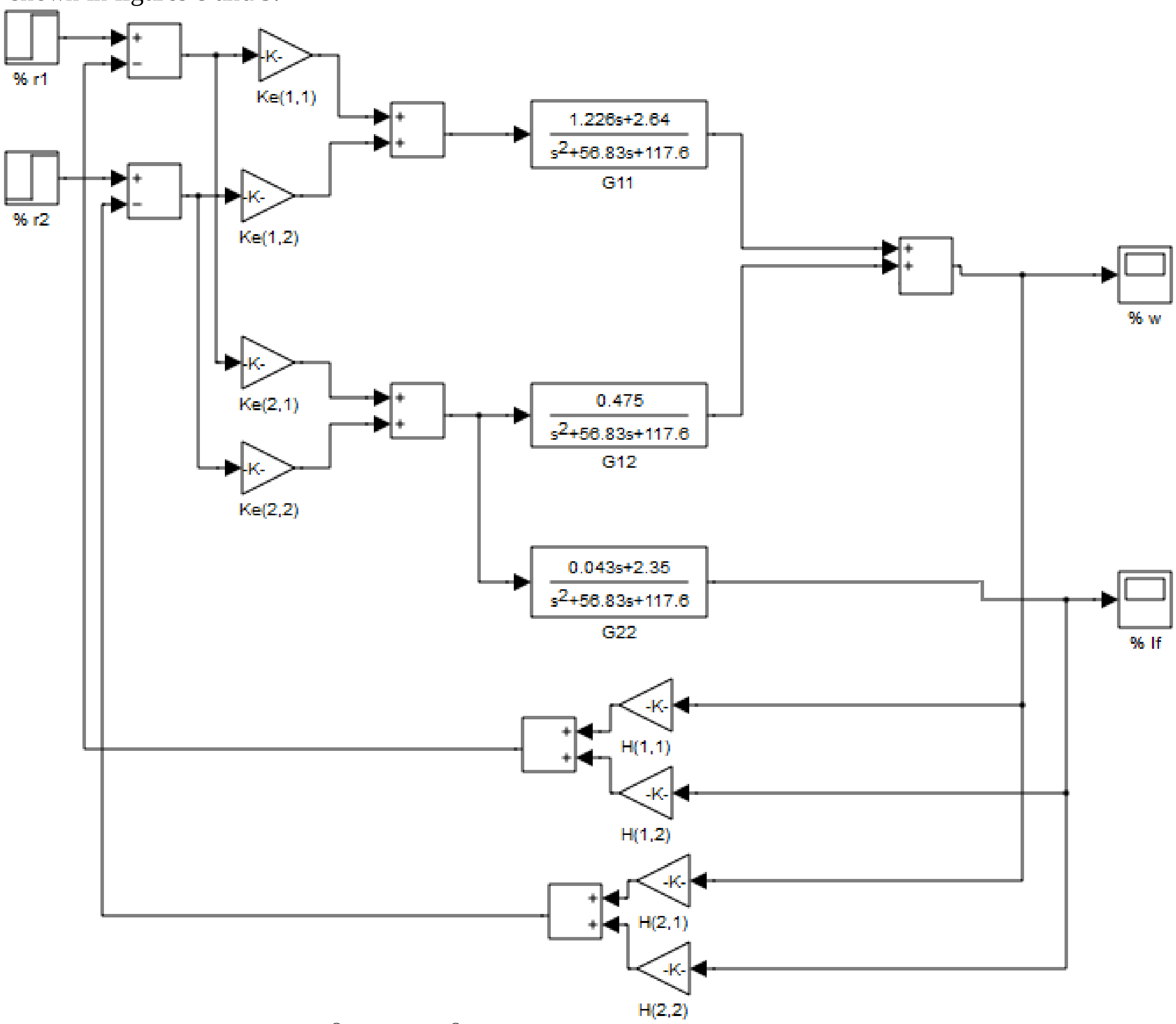

Figure.7. A MATLAB®/Simulink® model of the closed-loop system with the optimal feedback controller.

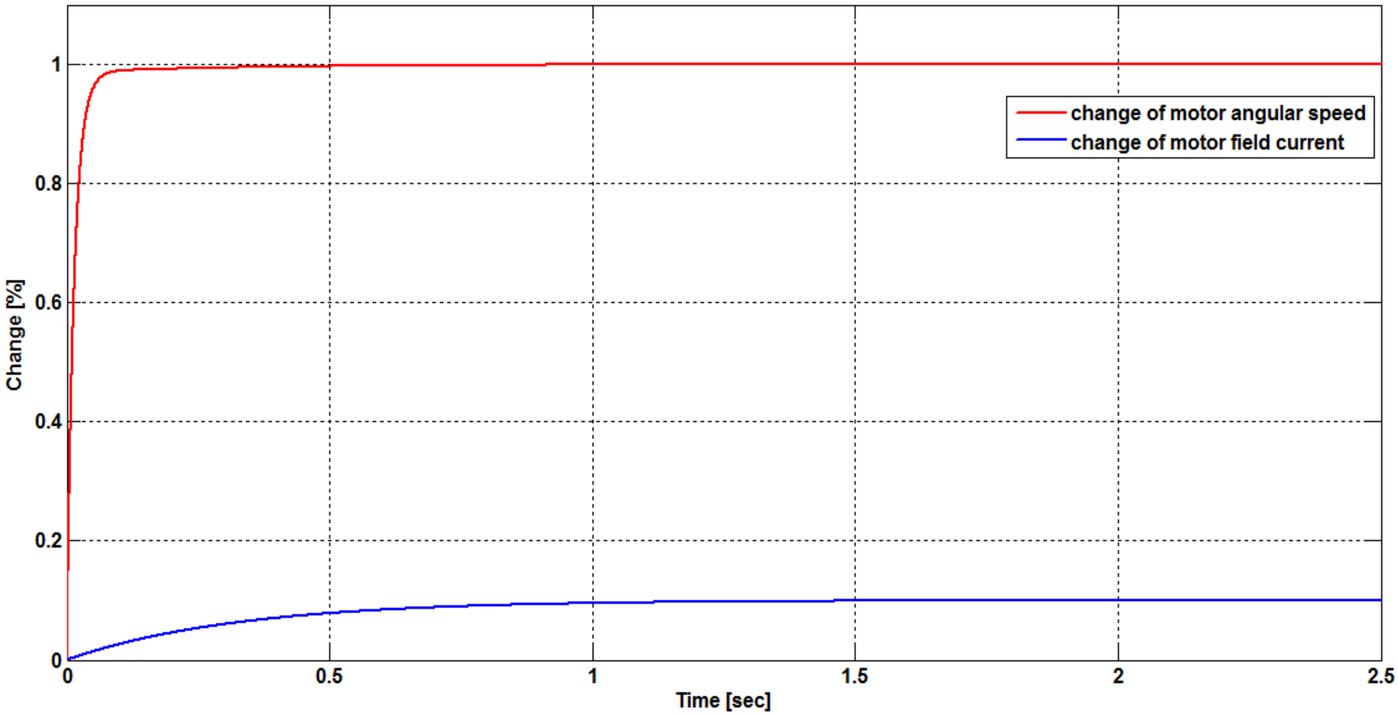

Figure.8. Closed-loop response caused by a unit step change on $r_1(t)$, with $r_2(t) = 0$.

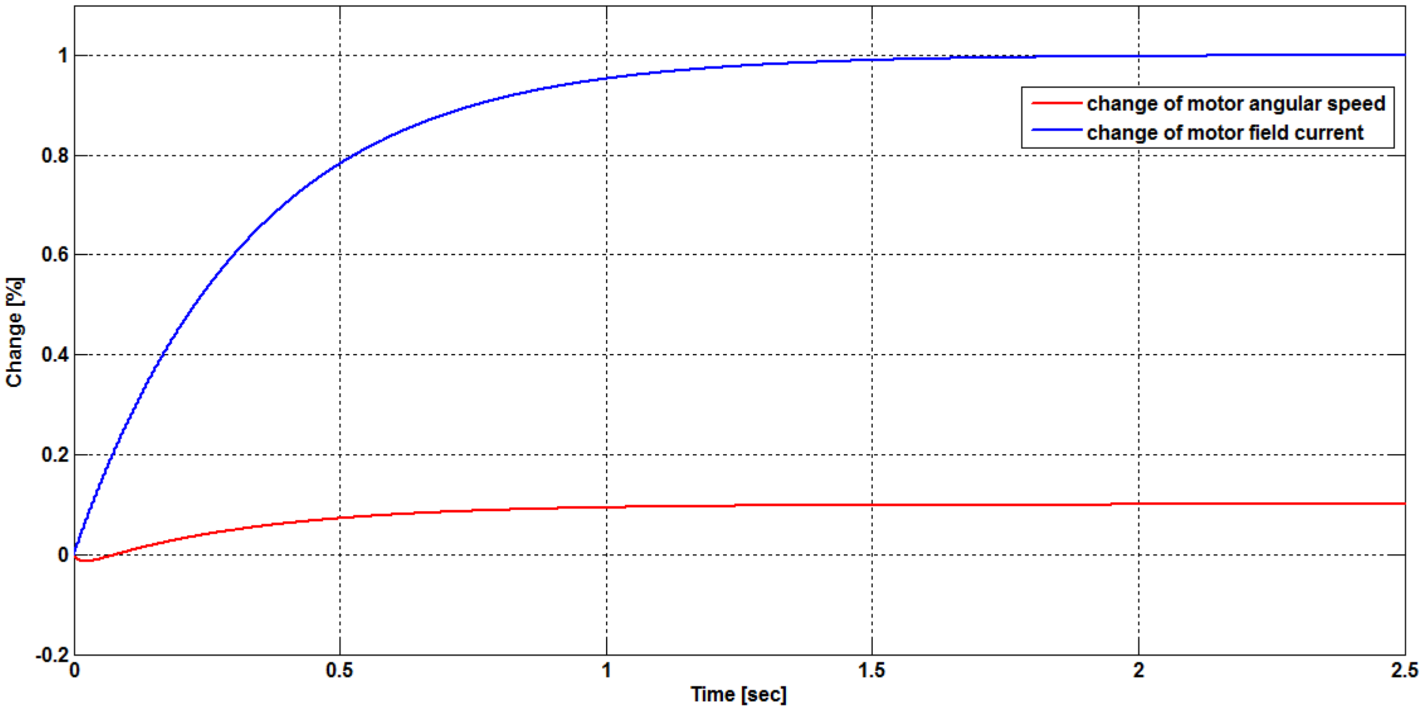

Figure. 9. Closed-loop response caused by a unit step change on $r_2(t)$, with $r_1(t) = 0$.

Figure.8 shows that, a unit step change on the first reference input causes the first output (the motor angular speed) to change by a unit step, or no steady state error exists. At the same time, the motor field current changes by 0.1% , which means that a 10% coupling is existing between the two outputs.

In the same way, figure. 9 shows that, following a unit step change on the second reference input, the second output, which is the motor field current, changes by a unit step, which means that also no steady state error exists. While, the first output, which is the motor angular speed, changes by 0.1%, which means that a coupling of 10% is also existing between the two system outputs.

These simulation results prove that the designed controller causes the steady-state error and the cross-coupling between the system outputs to be reduced very much while the over-damped character of the system is kept.

VI. RESULTS AND CONCLUSIONS

In this contribution the optimal state feedback controller for the separately excited DC motor was investigated. To compare the performance of the closed-loop system with that of the open-loop system, models of the two systems were built and simulated using MATLAB®/SIMULINK®. The results show an excellent performance of the closed loop system in terms of the steady-state error, cross-coupling between the system outputs and general system behavior.

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