Comparative Study of Four Controllers Applied on Shunt-Excited DC Motor

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ABSTRACT

Engineering control problems include several types of nonlinear dynamics. This paper presents the stabilization design problem for the Single Input Single Output (SISO) nonlinear control system. A case study, which includes the stabilization problem of shunt-excited DC motor, is considered in this work by establishing the basic form of the nonlinear control law and applying four types of control techniques including diffeomorphisme and feedback linearization. The proposed controllers are two feedback controllers, zero dynamics controller and Lyapunov controller. Different initial conditions for each proposed controller are numerically simulated using MATLAB®\Simulink®. Consequently, the energy of each control signal and the corresponding energy of the state are computed and compared to evaluate each considered control technique. As a result, the zero dynamics controller has the advantage of being the simplest controller design and generate the minimum controller energy consumption relative to other proposed controllers. Moreover, the Lyapunov controller method leads to satisfactory behavior in means of minimum transient response of the dynamical system states comparing to other propose controllers.

Key words. Feedback linearization; SISO ; Nonlinear control ; Lyapunov controller ; Zero dynamics.

الخلاصة

تتضمن مشاكل التحكم الهندسي عدة أنواع من الانظمة الديناميكية غير الخطية. يقدم هذا البحث مشكلة تصميم استقرارية لنظام التحكم غير الخطي ذو المدخلات الفردية (SISO). يتضمن نموذج الدراسة مشكلة الاستقرارية لمحرك حثي من نوع التيار المستمر DC في هذا البحث من خلال إلصيغة الأساسية لقانون السيطرة غير الخطي وتطبيق أربعة أنواع من المسيطرات بما في ذلك استخدام التحويل الجبري والتغذية الخطية الراجعة. وحدات السيطرة المقترحة عبارة عن مسيطرين من نوع التغذية الخطية الراجعة ، وحدة سيطرة ديناميكية صفرية و مسيطر مبني على طريقة ليابانوف. يتم محاكاة الظروف الأولية المختلفة لكل وحدة تحكم مقترحة عدديًا باستخدام Simulink \ ®MATLAB®. وبالتالي ، تم حساب ومقارنة طاقة كل إشارة تحكم والطاقة المقابلة للحالة لتقييم كل تقنية سيطرة مدروسة. نتيجة لذلك ، تتميز وحدة التحكم في الديناميكيات الصفرية بأنها أبسط تصميم للسيطرة وتولد الحد الأدنى من استهلاك طاقة مقارنةً بوحدات التحكم الأخرى المقترحة. علاوة على ذلك ، تؤدي طريقة تحكم ليابانوف إلى سلوك مرضٍ من خلال الحد الأدنى من الاستجابة العابرة لحالات النظام الديناميكي مقارنةً بوحدات التحكم المقترحة الأخرى.

INTRODUCTION

In this paper Shunt DC motor with an output function $h(x)$ is adopted as a model of the study. The main theorem of this paper provides the nonlinear normal form for the shunt DC motor. Some numerical simulations are presented to demonstrate the behavior for the closed-loop system. In addition, some numerical results are computed to show the performance of the system with different controllers.

In [1], the parameter of a conventional PID controller was achieved by using the Ziegler–Nichols method. In [2], a PID controller with optimal parameters was obtained by using a novel algorithm called gravitational search algorithm. In [3], a PID controller with optimal characteristics was proposed to control the speed shunt DC motor by using simulated annealing. Other types of controllers, such as adaptive neuro-fuzzy [4], B-spline neural network-based adaptive [5], B-spline neural network [6], and Nonlinear Autoregressive Moving Average (NARMA) level-2 [7] controllers, were proposed in previous works. Several types of nonlinear controllers for nonlinear systems were also suggested. Examples of these methods include a fast integral terminal sliding mode control method [8], a neural-network-based adaptive gain scheduling back-stepping sliding mode control [9], generalization of the pointwise min-norm controller [10], and fuzzy logic controller [11], [12].

In this paper, we mainly depend on feedback linearization method some basic notions such as the gradient, Lie derivative, Lie bracket and relative degree can be found in [14]-[16] to develope the theortical part for the porposed controllers. Using these concepts we will state and prove our main theorem and its corresponding corrolaries where each corollary represent a different controller, finally we will compaire the performance of the control system under those controllers by figures and quadratic performance index function J. Comparative beween different controllers gives us the opportunity to have a deep look at the performance of the system with each controller.

The paper is organized as follows: in Section two a mathematical model of Shunt-Excited DC Motor has been constructed. In Section three the design of different types of control signals based on different techniques presented in many corollaries. The numerical simulations of different initial conditions of the shunt DC motor model and their controllers are presented in section four supported by concluding remarks. Section five is the conclusions of the study.

SYSTEM MODELING

In this paper, to present the statement of the problem consider the shunt-excited DC motor model [7] and [13]

$$\dot{z} = \begin{bmatrix} -a_1 z_1 - a_2 z_2 z_3 \\ -a_4 z_2 \\ -a_6 z_3 + a_7 z_1 z_2 \end{bmatrix} + \begin{bmatrix} a_3 \\ a_5 \\ 0 \end{bmatrix} u$$

(1)

$$y = z_3,$$

where $z = \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix}$ is the state vector, and the parameters $a_i \in R$, $\forall i = 1, \cdots, 7$ are defined in Table 1.

.

TABLE 1. Model parameters

Parameter	**Value**
a_1	50
a_2	100
a_3	83.3
a_4	2
a_5	0.01
a_6	0.01
a_7	1.2

The linearization of the system (1) is as follows:

$$\dot{z} = \begin{bmatrix} -a_1 & 0 & 0 \\ 0 & -a_4 & 0 \\ 0 & 0 & -a_6 \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix} + \begin{bmatrix} a_3 \\ a_5 \\ 0 \end{bmatrix} u.$$

The system in the nonlinear form of the system will be stabilized in this work.

THE PROPOSED CONTROLLERS

This subsection contain the most important part of the work, which represents the theorems related to the porposed controllers, theorem (1), followed by three corrolaries and a proposition each one gives us a different controller which able us to stabilize the system in different approach. The following theorem and related coroleries are stated and proved to be our main work to design different types of controller.

Theorem (1):

Recall system (1)

where $z = \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix}$ is the state vector, and the parameters $a_i \in R$, $\forall i = 1, \cdots ,7$ are defined in Table 1.

If a scalar function is available, then $\omega(z)$ satisfies the following conditions:

$$z_1 \frac{\partial \omega(z)}{\partial z_1} \neq z_2 \frac{\partial \omega(z)}{\partial z_2}$$

(2)

$$\nabla \omega(z) \cdot g(z) = 0.$$

(3)

Then, the nonlinear controller of the original system is defined as follows:

$$u = \frac{v - \left(a_6^2 z_3 - a_7(a_1 + a_4 + a_6) z_1 z_2 - a_2 a_7 z_2^2 z_3\right)}{(a_5 a_7 z_1 + a_3 a_7 z_2)}$$

(4)

Proof:

Given that the output function $h(z) = z_3$, if the derivative of y w.r.t. time is taken as

$$\dot{y} = L_f h(X) + L_g h(X) u$$

because $L_g h(X) = 0$, then

$$\dot{y} = L_f h(X) = \dot{z}_3 = -a_6 z_3 + a_7 z_1 z_2.$$

(5)

Considering that the input armature voltage $u = v_a$ does not appear in (5), then the derivative is repeated to obtain the following:

$$\ddot{y} = L_f^2 h(X) + L_g L_f h(X) \cdot u$$

$$= a_6^2 z_3 - a_6 a_7 z_1 z_2 - a_4 a_7 z_1 z_2 - a_1 a_7 z_1 z_2 - a_2 a_7 z_2^2 z_3 + (a_5 a_7 z_1 + a_3 a_7 z_2) u$$

$= v$,

(6)

where $L_g L_f h(X) \neq 0$.

If the definition of the nonlinear diffeomorphism $T(z) = \xi$

$$T = \begin{pmatrix} y \\ \dot{y} \\ \omega(z) \end{pmatrix} = \begin{pmatrix} \xi_1 \\ \xi_2 \\ \xi_3 \end{pmatrix},$$

(7)

then one should define the scalar function $\omega(z)$. T must satisfy the diffeomorphism condition such that the Jacobian of the vector T is linearly independent because $\omega(z)$ should be represented in terms of z. Thus, $|\nabla T| \neq 0$. This finding implies the following:

$$\begin{vmatrix} 0 & 0 & 1 \\ a_7 z_2 & a_7 z_1 & -a_6 \\ \frac{\partial \omega(z)}{\partial z_1} & \frac{\partial \omega(z)}{\partial z_2} & \frac{\partial \omega(z)}{\partial z_3} \end{vmatrix} = a_7 \left(z_2 \frac{\partial \omega(z)}{\partial z_2} - z_1 \frac{\partial \omega(z)}{\partial z_1} \right)$$

$\neq 0$ …by condition. (2)

Meanwhile, the time derivative of $\omega(z)$ is

$$\frac{d\omega(z)}{dt} = \nabla \omega \cdot \dot{z}$$

$$= \nabla \omega f(z) + \nabla \omega g(z) u.$$

By condition (3),

$$\dot{\omega} = \nabla \omega f(z).$$

(8)

The last condition generates a partial differential equation. Checking the condition presented below is easy.

$$\omega(z) = a_5 z_1 - a_3 z_2$$

(9)

is a solution of (8) and serves (7) as a diffeomorphism, where

$$\begin{pmatrix} \xi_1 \\ \xi_2 \\ \xi_3 \end{pmatrix} = \begin{pmatrix} z_3 \\ -a_6 z_3 + a_7 z_1 z_2 \\ a_5 z_1 - a_3 z_2 \end{pmatrix}$$

(10)

With the inverse transformation $z = T^{-1}(\xi)$ defined as

$$\begin{pmatrix} z_1 \\ z_2 \\ z_3 \end{pmatrix} = \begin{pmatrix} \frac{1}{2a_5}\xi_3 \mp \sqrt{\left(\frac{a_5a_6}{a_3a_7}\right)\xi_1 - \left(\frac{a_5}{a_3a_7}\right)\xi_2 + \left(\frac{1}{a_5}\right)\xi_3 + \left(\frac{\xi_3}{2a_3}\right)^2} \\ -\frac{1}{2a_3}\xi_3 \mp \sqrt{\left(\frac{a_5a_6}{a_3a_7}\right)\xi_1 - \left(\frac{a_5}{a_3a_7}\right)\xi_2 + \left(\frac{1}{a_5}\right)\xi_3 + \left(\frac{\xi_3}{2a_3}\right)^2} \\ \xi_1 \end{pmatrix},$$

(11)

the nonlinear transforms the original system (1) into the following form:

$$\begin{pmatrix} \dot{\xi}_1 \\ \dot{\xi}_2 \\ \dot{\xi}_3 \end{pmatrix} = \begin{pmatrix} \xi_2 \\ v \\ -\left(\frac{a_1+a_4}{2}\right)\xi_3 + N(\xi; a_1, \cdots, a_7) \end{pmatrix},$$

(12)

where $N(\xi; a_1, \cdots, a_7)$ is purely nonlinear term based on ξ and the parameters. Equation (6) provides the relationship between u and v defined as:

$$u = \frac{v-(a_6^2z_3-a_7(a_1+a_4+a_6)z_1z_2-a_2a_7z_2^2z_3)}{(a_5a_7z_1+a_3a_7z_2)},$$

and this completes the proof. ■

The signal v in Equation (4) must be defined to design a control signal u for the original system. Therefore, some corollaries of theorem (1), which will completely design the signal u, are introduced. Moreover, an additional controller based on Lyapunov function will be designed.

Corollary (1) (Feedback Linearization controller 1 (FLC1)): Under the hypothesis theorem (1), system (1) could have the control law

$$u_1 = \frac{(a_6k_2 - k_1 - a_6^2)z_3 + a_7(a_1 + a_4 + a_6 - k_2)z_1z_2 + a_2a_7z_2^2z_3}{(a_5a_7z_1 + a_3a_7z_2)}$$

(13)

such that k_1 and k_2 satisfies the condition

$$0 < k_1 \leq \left(\frac{k_2}{2}\right)^2.$$

(14)

Proof.

Owing to the almost linear [17] system (12), then the approximate linearization of $\dot{\xi}_3$ is defined as follows:

$$\dot{\xi}_3 = -\left(\frac{a_1 + a_4}{2}\right)\xi_3 \qquad ,$$

(15)

where a_1 and a_4 are both positive. Thus, the third branch in Equation (15) is stable and can be defined as follows:

$$v = -K \cdot \xi \qquad ,$$

(16)

where K is the gain vector $K = [k_1 \quad k_2 \quad 0]$, and the other branches in (12) form a 2-dim Bronovsky form

$$\begin{pmatrix} \dot{\xi}_1 \\ \dot{\xi}_2 \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} \xi_1 \\ \xi_2 \end{pmatrix} + \begin{pmatrix} 0 \\ 1 \end{pmatrix} v.$$

The feedback form using (16) becomes

$$\begin{pmatrix} \dot{\xi}_1 \\ \dot{\xi}_2 \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ -k_1 & -k_2 \end{pmatrix} \cdot \begin{pmatrix} \xi_1 \\ \xi_2 \end{pmatrix}.$$

Considering that the matrix $\begin{pmatrix} 0 & 1 \\ -k_1 & -k_2 \end{pmatrix}$ has a negative real part by condition (14), then system (12) is stable; thus, system (1) is. ■

Corollary (2) (Zero dynamics controller (ZDC)): Under the hypothesis theorem (1), system (1) could have the controller

$$u_2 = \frac{-a_6^2 z_3 + a_7(a_1 + a_4 + a_6) z_1 z_2 + a_2 a_7 z_2^2 z_3}{(a_5 a_7 z_1 + a_3 a_7 z_2)} \quad . \qquad (17)$$

Proof.

The output function can be defined as

$$h(z_0) = 0 \quad , \qquad (18)$$

where $z_0 = \begin{pmatrix} z_1(0) \\ z_2(0) \\ z_3(0) \end{pmatrix}$.

Then,

$$\ddot{y} = v = 0 \quad . \qquad (19)$$

Substituting Equation (19) in (4) implies (17). ■

Remark on corollary (2):

The output in Equation (18) is chosen because the voltage V(t) is maintained at the voltage reference VREF when the dynamical system started. Therefore, one can choose the output function as

$$y(t) = h(z(t)) = \mathrm{V(t)} - V_{REF} = 0 \ , \forall t > 0.$$

Initially, the satisfaction of the previous equation in practice is unknown. However, the assumption that the condition required to stabilize the output is also necessary to generate a small as possible quadratic performance index functional J is reasonable. This assumption provides two advantages: the dynamical system is asymptotically stable, and the system output has optimal control characteristics.

Corollary (3) (Feedback Linearization controller 3 (FLC2)): Using the feedback linearization concept, the controller can be defined as follows:

$$u_3 = \frac{-\lambda_1 z_1 - \lambda_2 z_2 - (\lambda_3 + a_6^2) z_3 + a_7 (a_1 + a_4 + a_6) z_1 z_2 + a_2 a_7 z_2^2 z_3}{(a_5 a_7) z_1 + (a_3 a_7) z_2}$$

(20)

for system (1).

Proof.

The essential concept of FL is to achieve a linear relationship between the suggested input v and the output y [18]–[20] by respectively recalling Equations (5) and (6):

$\dot{y} = \dot{z}_3 = -a_6 z_3 + a_7 z_1 z_2$

and

$\ddot{y} = a_6^2 z_3 - a_6 a_7 z_1 z_2 - a_4 a_7 z_1 z_2 - a_1 a_7 z_1 z_2 - a_2 a_7 z_2^2 z_3 + (a_5 a_7 z_1 + a_3 a_7 z_2) u$.

Using a PID controller, this relationship can be expressed as

$\ddot{y} = v = -\lambda_1 z_1 - \lambda_2 z_2 - \lambda_3 z_3.$

(21)

Substituting Equation (21) in (4) yields (20). ■

Proposition (1) (Lyapunov controller (LC)) : Recall system (1)

$$\dot{z} = \begin{bmatrix} -a_1 z_1 - a_2 z_2 z_3 \\ -a_4 z_2 \\ -a_6 z_3 + a_7 z_1 z_2 \end{bmatrix} + \begin{bmatrix} a_3 \\ a_5 \\ 0 \end{bmatrix} u$$

$y = z_3,$

where $z = \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix}$ is the state vector, and the parameters $a_i \in R$, $\forall i = 1, \cdots, 7$ are defined in Table 1.

If the control signal

$u_4 = \frac{-k_1 z_1^2 - k_2 z_2^2 - k_3 z_3^2 + (a_2 - a_7) z_1 z_2 z_3}{a_3 z_1 + a_5 z_2}$

(22)

then function $V(z) = \frac{1}{2} Z^T \cdot Z$ defines a Lyapunov function for system (1)

Proof:

as

$V(z) = \frac{1}{2} Z^T \cdot Z$

$= \frac{1}{2}(z_1^2 + z_2^2 + z_3^2).$

(23)

If the derivative of $V(z)$ w.r.t. time is taken, the following is obtained:

$\dot{V}(z) = z_1 \dot{z}_1 + z_2 \dot{z}_2 + z_3 \dot{z}_3$

$\dot{V}(z) = z_1(-a_1 z_1 - a_2 z_2 z_3 + a_3 u) + z_2(-a_4 z_2 + a_5 u) + z_3(-a_6 z_3 + a_7 z_1 z_2)$

$\dot{V}(z) = -a_1 z_1^2 - a_4 z_2^2 - a_6 z_3^2 + (a_7 - a_2) z_1 z_2 z_3 + (a_3 z_1 + +a_5 z_2) u.$ (24)

If $u = \frac{(a_2 - a_7) z_1 z_2 z_3 - k_1 z_1^2 - k_2 z_2^2 - k_3 z_3^2}{a_3 z_1 + a_5 z_2}$ is set,

then (24) becomes

$\dot{V}(z) = -(a_1 + k_1) z_1^2 - (a_4 + k_2) z_2^2 - (a_6 + k_3) z_3^2 < 0.$

(25)

Therefore, the controller (22) stabilizes the system in terms of Lyapunov function.

NUMERICAL SIMLUATION RESULTS

This study aims to analyze the shunt DC motor system as a nonlinear dynamical control system. The main theorem in the paper, which establishes the basic form of the nonlinear control law, is then presented and proven in subsection 3.1. Then a numerical simulations would be given in 3.2. to illustrate the performance well.

All the numerical simulations are achieved using MATLAB®\Simulink® 2018b. in figure 1 , the block diagram of the shunt excieted DC motor is presented. Moreover, the block diagram of the proposed controllers is illustrated in figure 2.

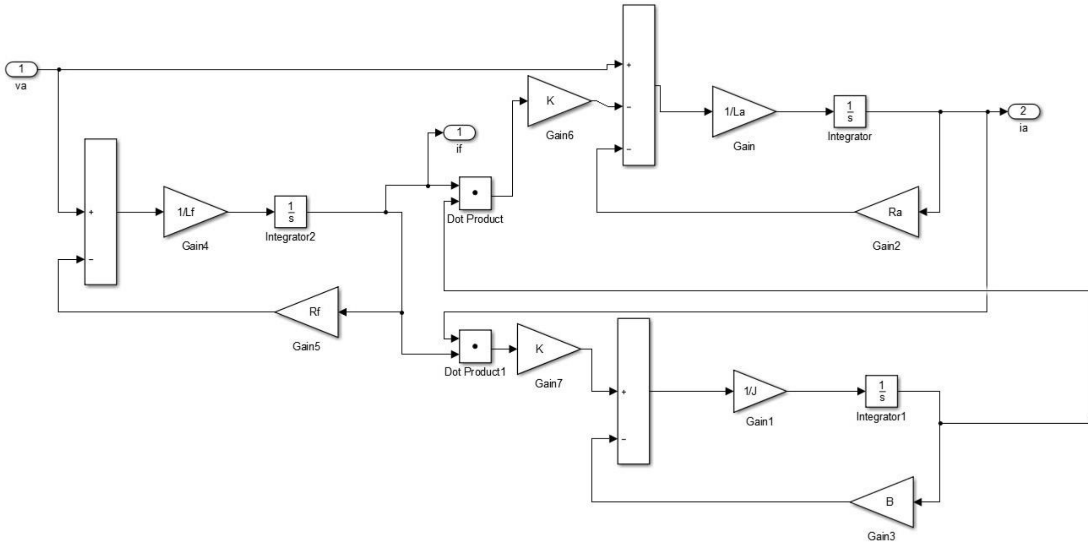


FIGURE 1. The block diagram of the shunt excieted DC motor

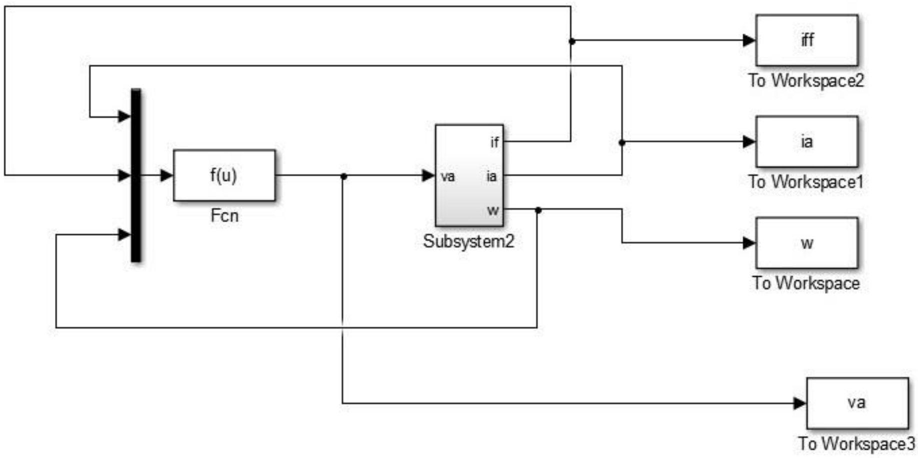
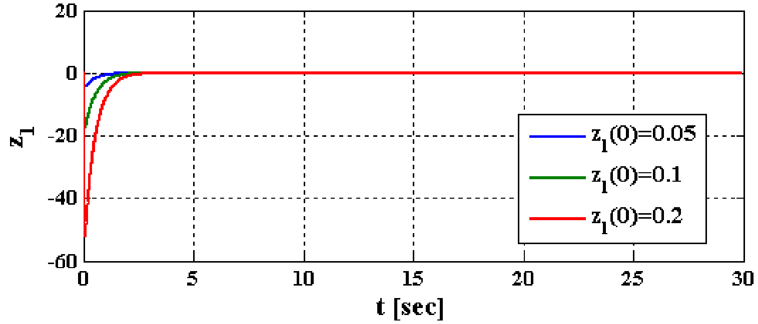
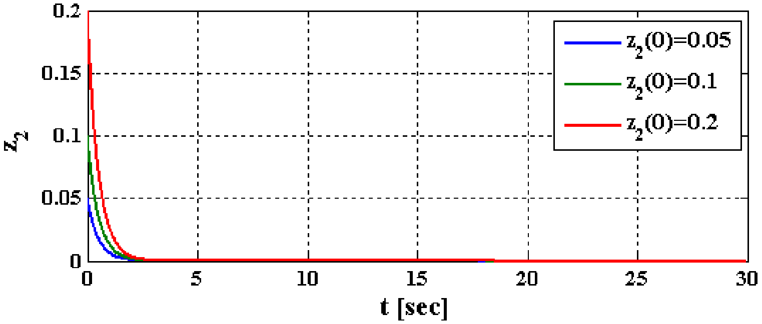


FIGURE 2. The block diagram of the proposed controllers

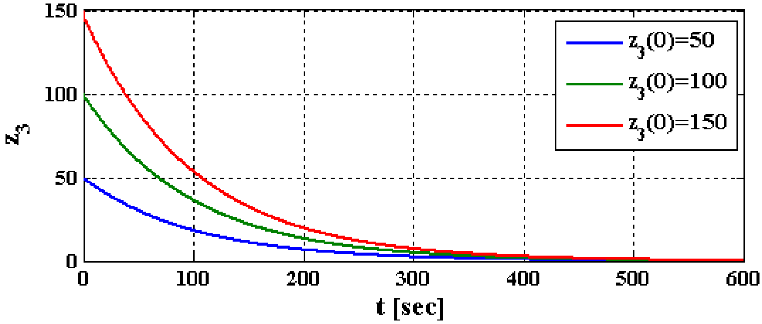
The following are the numerical simulations that illustrate the behavior of the uncontrolled $(u = 0)$ (Figure 3) and the controlled shunt DC motor system by obtaining the parameters in Table 1 with a set of the following initial conditions: $z_1(0) = 0.05$, $z_2(0) = 0.05$, and $z_3(0) = 50$; $z_1(0) = 0.1$, $z_2(0) = 0.1$, and $z_3(0) = 100$; and $z_1(0) = 0.2$, $z_2(0) = 0.2$, and $z_3(0) = 150$. The plot of z_1-, z_2-, and z_3-state versus time is computed based on the controllers in Equations (13), (17), (20), and (22) and shown in Figures 4, 5, 6, and 7, respectively.



(a)



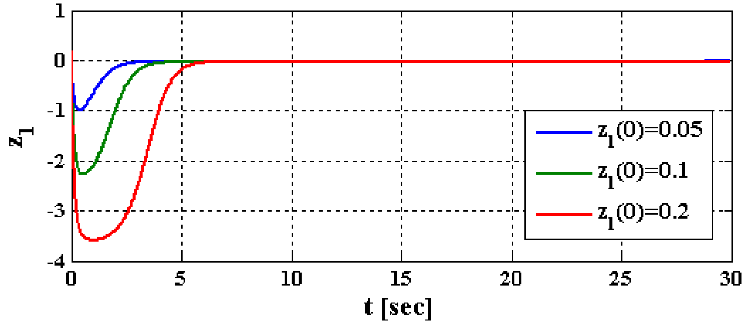
(b)



(c)

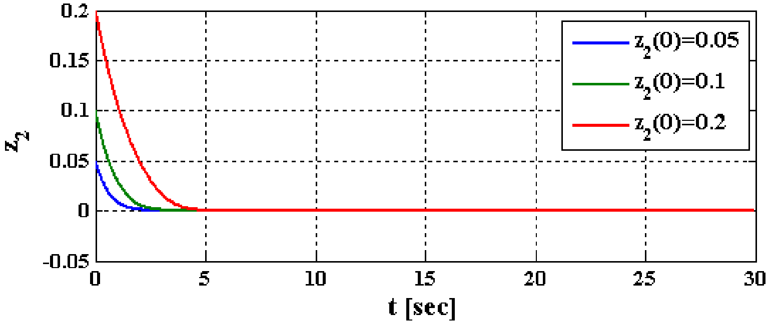
FIGURE 3. Response curves to the uncontrolled shunt DC motor system (u = 0)

(a) $z_1$vs. time, (b) z_2 vs. time, and (c) z_3 vs. time



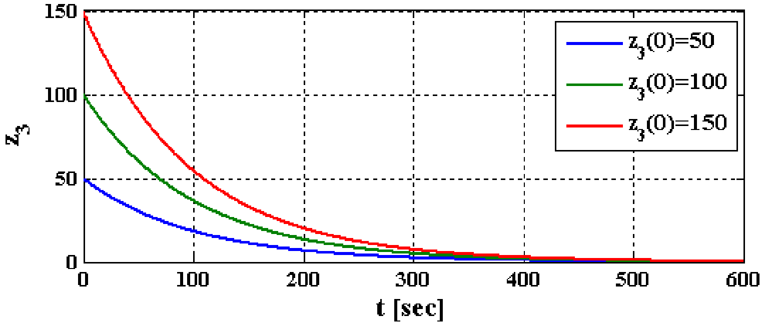
1
0
-1
-2
-3
-4
z1
0
5
10
15
20
25
30
t [sec]
z1(0)=0.05
z1(0)=0.1
z1(0)=0.2

(a)



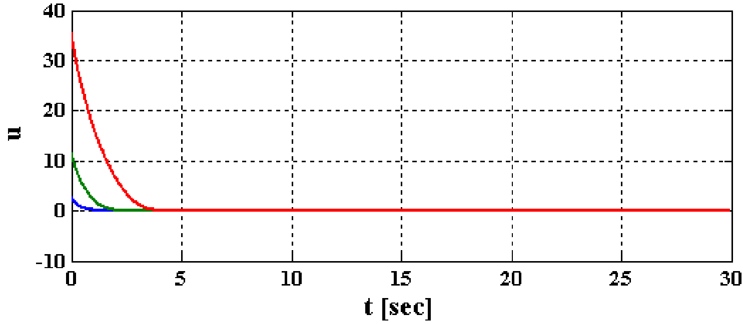
0.2
0.15
0.1
0.05
0
-0.05
z2
0
5
10
15
20
25
30
t [sec]
z2(0)=0.05
z2(0)=0.1
z2(0)=0.2

(b)



150
100
50
0
z3
0
100
200
300
400
500
600
t [sec]
z3(0)=50
z3(0)=100
z3(0)=150

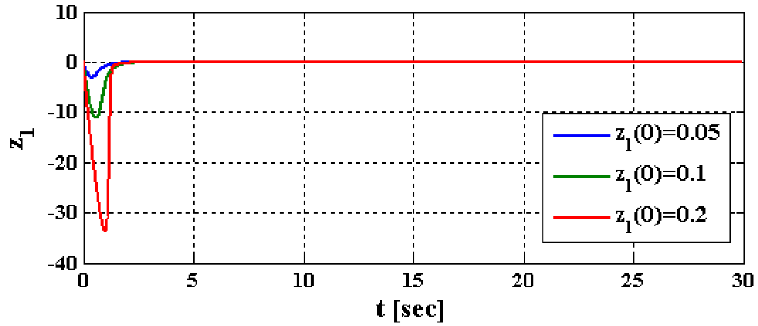
(c)



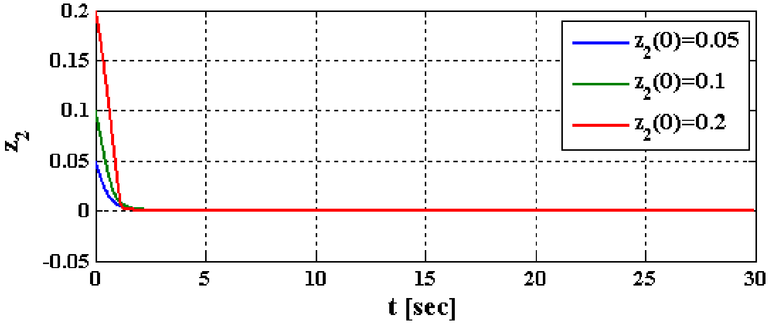
(d)

FIGURE 4. Response curves to the shunt DC motor system with FLC1 (u_1)

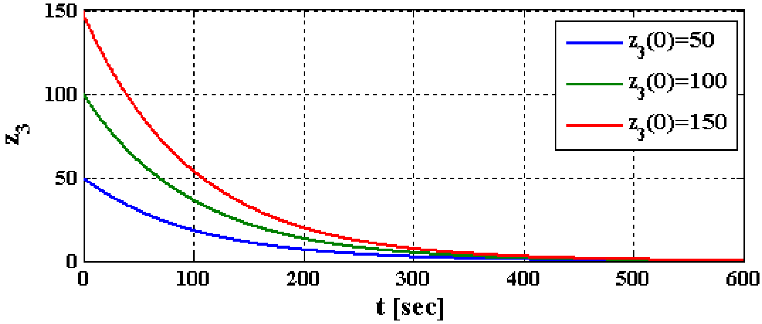
(a) $z_1$vs. time, (b) z_2 vs. time, (c) z_3 vs. time, and (d) u_1 vs. time



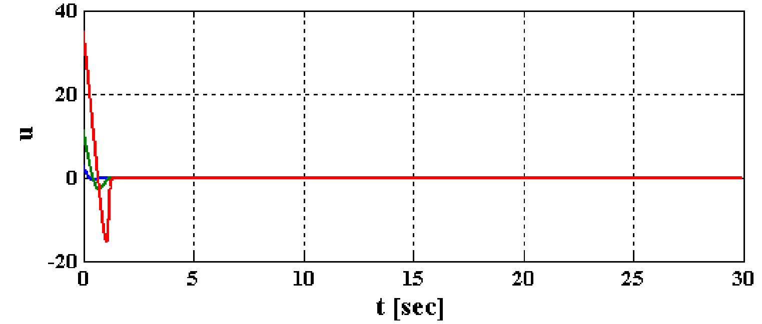
(a)



(b)



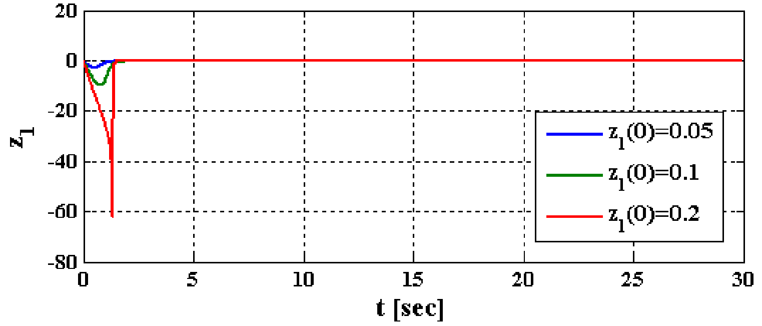
(c)



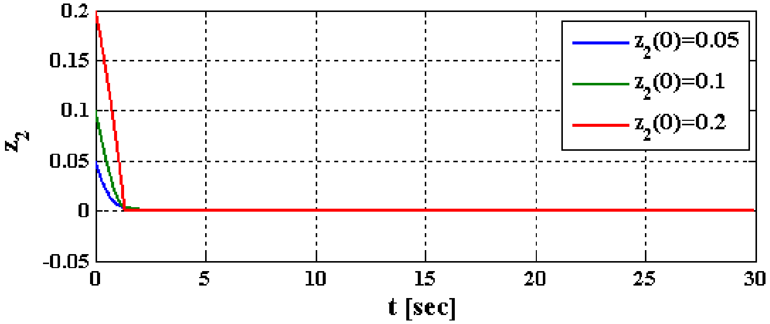
(d)

FIGURE 5. Response curves to the shunt DC motor system with **ZDC** (u_2)

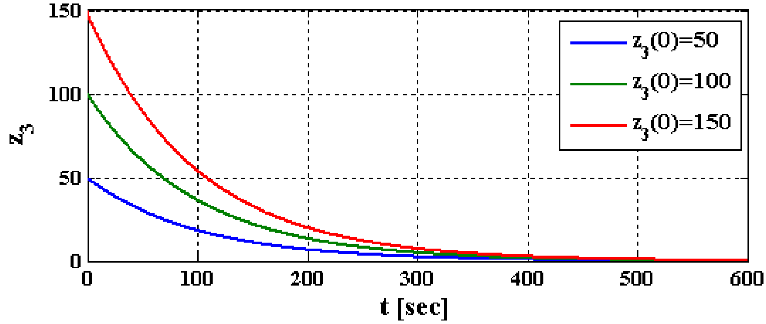
(a) $z_1$vs. time, (b) z_2 vs. time, (c) z_3 vs. time, and (d) u_2 vs. time



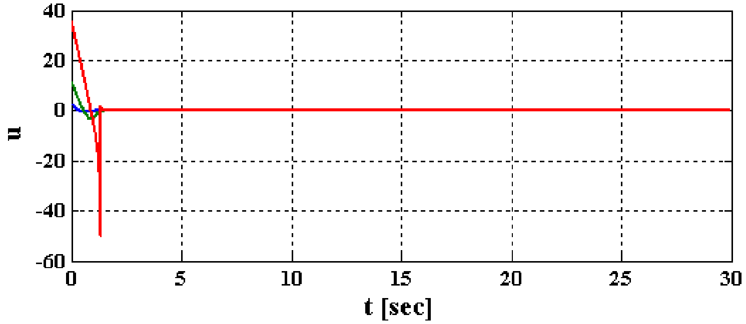
(a)



(b)



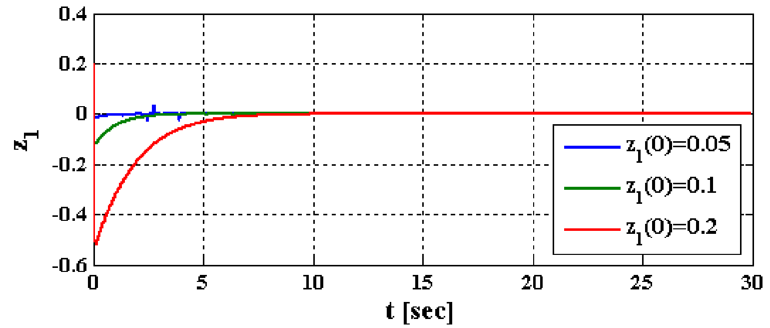
(c)



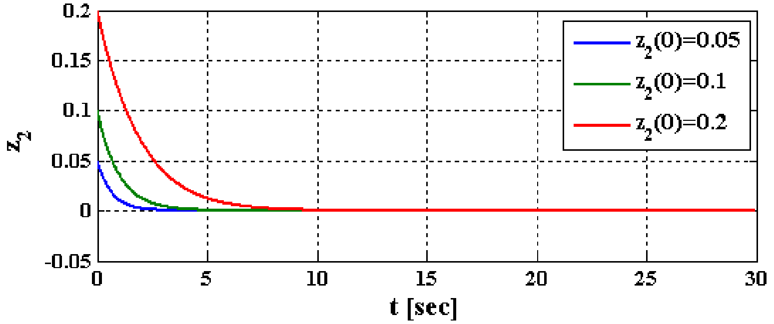
(d)

FIGURE 6. Response curves to the shunt DC motor system with FLC2 (u_3)

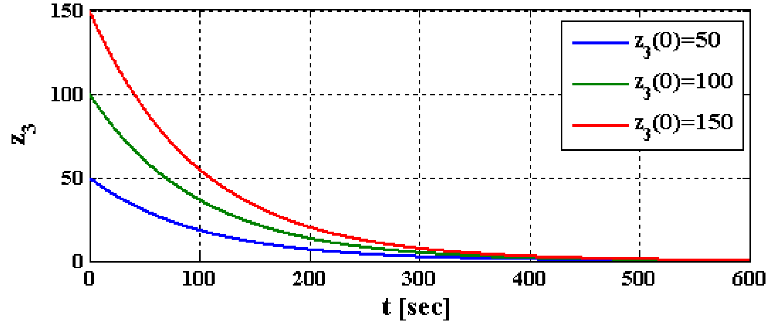
(a) $z_1$vs. time, (b) z_2 vs. time, (c) z_3 vs. time, and (d) u_3 vs. time


z1
t [sec]
z1(0)=0.05
z1(0)=0.1
z1(0)=0.2

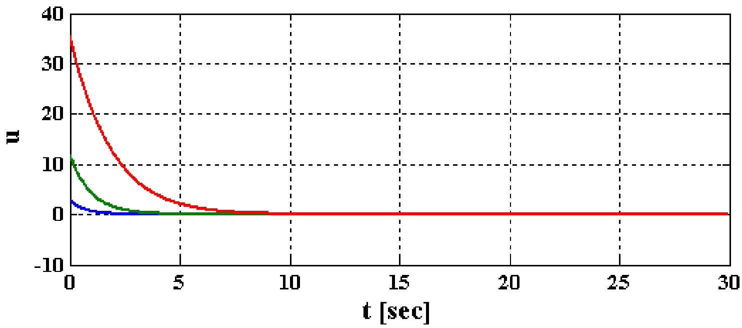
(a)


z2
t [sec]
z2(0)=0.05
z2(0)=0.1
z2(0)=0.2

(b)


z3
t [sec]
z3(0)=50
z3(0)=100
z3(0)=150

(c)



(d)

FIGURE 7. Response curves to the shunt DC motor system with LC (u_4)

(a) $z_1$vs. time, (b) z_2 vs. time, (c) z_3 vs. time, and (d) u_4 vs. time

Remark: The zero initial condition may show a disturbance-like behavior in z_1-state due to the existence of near-zero values in the denominator. Figure 7 shows that the controllers dealt well with this phenomenon and regulated the state before 10 s for any given initial condition seconds.

TABLE 2. Results of the numerical simulations

$\boldsymbol{u_i}$	$\int_0^\infty \boldsymbol{u_i^2 dt}$	$\int_0^\infty \boldsymbol{z_1^2 dt}$	$\int_0^\infty \boldsymbol{z_2^2 dt}$	$\int_0^\infty \boldsymbol{z_3^2 dt}$	$\boldsymbol{J}$
$u = 0$	0.0000	95.0875	0.0025	494291.5588	494386.6487
u_1	42.1986	7.2203	0.00426	498328.2408	498377.6640
u_2	**19.4102**	70.1368	0.0032	495909.3775	495998.9277

u_3	26.5930	55.7777	0.0035	496569.3750	496651.7492
u_4	68.7994	**0.00777**	0.0049	499920.3326	499989.1447

Energy of each control signal and the corresponding energy of the state variables with the quadratic performance index

$$J = \int_0^\infty u^T \cdot u \; + Z^T \cdot Z \, dt.$$

The ZDC u_2 produces the minimum controller energy consumption relative to other proposed controllers u_1 , u_3 and u_4 . Moreover, it has the benefit of being the simplest controller design. However, the LC approach has a trial-and-error flavor but may actually lead to satisfactory behavior as presented in this research. This behavior is reflected on the value of z_1 transient response of the LC controller with respect to other propose controllers.

Remark. All values in Table 2 are computed using the numerical integration method and approximated to four decimal places.

CONCLUSION

Numerous forms of dynamics with nonlinearities are established in industrial control problems. The stabilization problem of shunt-excited DC motor as a SISO nonlinear control system is considered by establishing the control law in the nonlinear form with four types of control techniques, including diffeomorphism and feedback linearization. Consequently, different situations are numerically simulated with a set of initial conditions, and the energy of each signal of the state is computed. In the second control technique, the third state, which represents the speed of the DC motor, is reduced to an exponentially stable state and need not be included in the linear control law. This condition reduces the energy of the control law. By contrast, the fourth control technique, a Lyapunov controller, is considered by all the states, including the control law and the absence of a reduction in the model. This condition leads to high energy in the control law.

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