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Modelling and MultiSim Simulation of a New Hyperchaos System with No Equilibrium Point

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Abstract: Crypto-devices and encryption applications make good use of nonlinear dynamical systems with hyperchaotic attractors due to their inherent complexity. Using four quadratic nonlinearities, a new 12-term hyperchaos system with hidden attractor is proposed in this research paper. It is established that the new hyperchaos system has no balance point and a hidden attractor exists for the system. Coexisting attractors and multistability are also proven to exist for the new system. The Kaplan-Yorke fractal dimension is determined for the new hyperchaos system with hidden attractor. MultiSim circuit design and simulation are carried out for the validation and real-world applications of the new hyperchaos system with hidden attractor. Finally, the chaos control results based on feedback control are also derived for the new 4D hyperchaotic system with no equilibrium point.

Keywords: *hidden attractor; hyperchaotic systems; MultiSim design; chaos control.*

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1 Introduction

Chaos applications of dynamical models arise in various engineering domains such as nonlinear oscillatory systems [1, 2], biological models [3, 4], circuit devices [5, 6], ANN models [7,8], chemical models [9,10], finance models [11,12], robotics [13,14], mechanical systems [15, 16] etc.

Dynamical systems with positive Lyapunov index numbers are addressed as hyperchaotic systems [17] which possess diverse engineering applications such as secure devices [18,19], crypto-devices [20,21], memristor devices [22–24], neural networks [25,26], etc. The hyperchaotic attractor extends in two or more directions concurrently as compared to a chaotic attractor with a singularly positive Lyapunov exponent. It implies that the hyperchaotic attractor performs significantly better in many real-world applications such as secure communication and encryption because it has a topological structure that is highly complex.

Hyperchaotic models are broadly divided as hyperchaos systems exhibiting self-excited or hidden attractors. The hyperchaos models with no balance point belong to the class of systems exhibiting hidden attractors [27, 28]. Li et al. [29] proposed an optical image encryption scheme based on the fractional Fourier transform and five-dimensional host-induced nonlinearity fractional-order laser hyperchaotic system. Erkan et al. [30] studied a novel two-dimensional (2D) chaotic system depending on the Schaffer function and the recursive 2D discrete model of the Schaffer function has superior chaotic behavior. Yu et al. [31] introduced two-dimensional logistic-adjusted-sine map (2D-LASM) and four-dimensional quadratic autonomous hyperchaotic system (4D-QAHS). Also, the experimental results demonstrate that the encryption approach is secure, with an average information entropy of 7.9972. Hosny et al. [32] proposed a novel utilization of fractional-order chaotic systems in color image encryption using the 4D hyperchaotic Chen system of fractional-order combined with the Fibonacci Q-matrix. Pavithran et al. [33] proposed a novel encryption process based on Deoxyribonucleic Acid (DNA) cryptography, a hyperchaotic system and a Moore machine. Alkhayyat et al. [34] studied a novel four-dimensional continuous-time dynamical system with the features of hyperchaotic phenomenon, dissipativity, rich dynamics, unstable equilibrium point, multistability and cryptographic S-box application.

In this work, we report a new 4-D nonlinear dynamical system with a hyperchaotic attractor. We show that the proposed nonlinear dynamical system has no balance point and it displays a hidden hyperchaotic attractor. We illustrate the qualitative properties of the proposed nonlinear dynamical system with a hyperchaotic attractor via MATLAB signal plots, balance points, multi-stability, coexisting hyperchaotic attractors, etc. The proposed nonlinear dynamical system with a hyperchaotic attractor has good applications in cryptosystems [35, 36] and secure communications [37].

For practical implementation of the hyperchaos systems, designs carried out via electronic circuits [38–40] or FPGA [41, 42] are immensely useful. In this research work, we exhibit MultiSim circuit design of the proposed new hyperchaos system in the four-dimensional space with no balance point.

This paper is organised as follows. Section 2 describes the dynamics and basic properties of the new 4D hyperchaotic system. Electronic circuit using MultiSim (Version 14.0) of the new 4D hyperchaotic system is given in Section 3. Section 4 presents control results using feedback control for the new 4D hyperchaotic system. Section 5 contains the conclusions of this work.

2 A Four-Dimensional Hyperchaos Systems with No Balance Point

A novel four-dimensional dynamical system is described in this work as follows:

$$\begin{cases} \dot{\xi} = \alpha(\eta - \xi) - \eta\zeta + \omega, \\ \dot{\eta} = -\gamma\xi\zeta + \beta\eta - \varepsilon\zeta^2 + \omega, \\ \dot{\zeta} = \xi\eta - \vartheta, \\ \dot{\omega} = -\xi - \eta. \end{cases} \tag{1}$$

The four-dimensional vector $K = (\xi, \eta, \zeta, \omega)$ designates the state of the system (1). It is remarked that there are four quadratic nonlinearities (in the first, second and third differential equations). It will be established using the Lyapunov Index (LI) values spectrum analysis in MATLAB that there is hyperchaos in the system (1) when the parameters assume the values

$$\alpha = 18,\ \beta = 6,\ \gamma = 14,\ \vartheta = 10,\ \varepsilon = 0.2. \tag{2}$$

For the time-series analysis of the state K of the system (1), we assume the initial state as

$$\xi(0) = 0.2,\ \eta(0),\ \zeta(0) = 0.4,\ \omega(0) = 0.2. \tag{3}$$

Using Wolf's procedure [43], the Lyapunov Index (LI) values of the 4-D model (1) are numerically found in seconds (see Figure 1) as follows:

$$\mu_1 = 2.8033,\ \mu_2 = 0.0535,\ \mu_3 = 0,\ \mu_4 = -14.8266. \tag{4}$$

The existence of two positive LI values ($viz.\ \mu_1, \mu_2$) summarily signifies that the model (1) has hyperchaos nature. As the total of all LI values in the LI spectrum is seen to be negative, the model (1) has also dissipative motion of all its trajectories converging to the hyperchaotic attractor. The Kaplan-Yorke dimension of the hyperchaotic system (1) is computed as follows:

$$D_{KY} = 3 + \frac{\mu_1 + \mu_2 + \mu_3}{\mu_4} = 3.1927. \tag{5}$$

Figures 1 and 2 show the LI values and signal plots of the model (1) simulated in MATLAB for the parameter set $(\alpha, \beta, \gamma, \vartheta, \varepsilon) = (18, 6, 14, 10, 0.2)$. The MATLAB plots show the high complexity of the hyperchaos system (1).

Multistability means two or more attractors coexist together with different initial conditions and has been found in many nonlinear systems. Let the parameters be fixed as $\alpha = 18,\ \beta = 6,\ \gamma = 14,\ \vartheta = 10,\ \varepsilon = 0.2$ and we suppose that the initial states of the system (1) are picked as $K_0 = (0.2, 0.4, 0.4, 0.2)$ and $\Lambda_0 = (-0.8, 0.8, -0.8, 0.8)$. Figure 3 shows the multistability of the hyperchaotic system (1) with two coexisting hyperchaotic attractors emanating from K_0 (blue color) and Λ_0 (red color), respectively.

3 Multisim Simulation of the Novel Hyperchaos System with Hidden Attractor

This study will consider the analog circuit implementation of the new double-scroll hyperchaos system described in (1). Figure 4 shows a four channels electronic circuit scheme

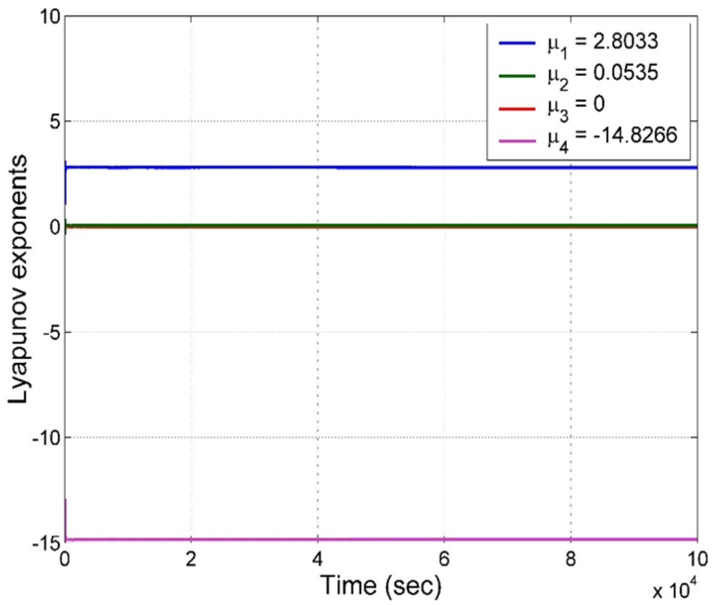


Figure 1: Lyapunov index values spectrum for the new hyperchaos system (1).

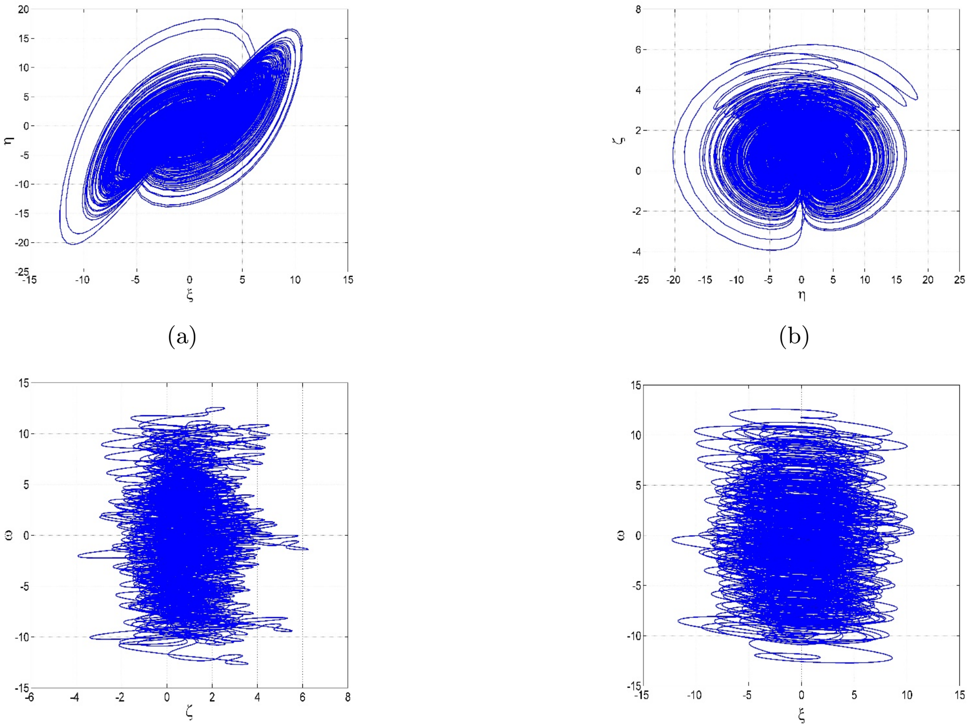
with variables ξ, η, ζ, ω from the system (1). For circuit implementation, we rescale the state variables of the new chaotic system (1) as follows: $\xi = \frac{1}{2}\xi, \eta = \frac{1}{2}\eta, \zeta = \frac{1}{2}\zeta$ and $\omega = \frac{1}{2}\omega$. In the new coordinates $(\xi, \eta, \zeta, \omega)$, the chaotic system (1) becomes

$$\begin{cases} \dot{\xi} = \alpha(\eta - \xi) - 2\eta\zeta + \omega, \\ \dot{\eta} = -2\gamma\xi\zeta + \beta\eta - 2\varepsilon\zeta^2 + \omega, \\ \dot{\zeta} = 2\xi\eta - \frac{1}{2}\vartheta, \\ \dot{\omega} = -\xi - \eta. \end{cases} \tag{6}$$

By applying Kirchhoff's laws to the designed electronic circuit, its nonlinear equations can be derived in the following form:

$$\begin{cases} \dot{\xi} = \dfrac{1}{C_1R_1}\eta - \dfrac{1}{C_1R_2}\xi - \dfrac{1}{10C_1R_3}\eta\zeta + \dfrac{1}{C_1R_4}\omega, \\ \\ \dot{\eta} = -\dfrac{1}{10C_2R_5}\xi\zeta + \dfrac{1}{C_2R_6}\eta - \dfrac{1}{10C_2R_7}\zeta^2 + \dfrac{1}{C_2R_8}\omega, \\ \\ \dot{\zeta} = \dfrac{1}{10C_3R_9}\xi\eta - \dfrac{1}{C_3R_{10}}V_1, \\ \\ \dot{\omega} = -\dfrac{1}{C_4R_{11}}\xi - \dfrac{1}{C_4R_{12}}\eta. \end{cases}$$

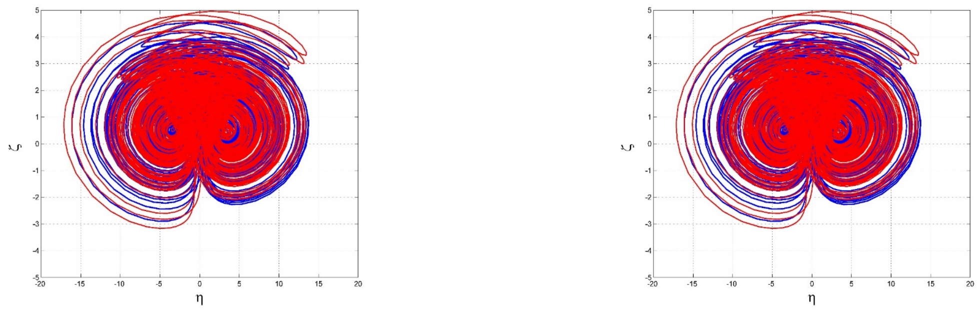
Here, ξ, η, ζ, ω are the voltages across the capacitors C_1, C_2, C_3 and C_4, respectively.



(a) (b)

(c) (d)

Figure 2: Signal plots of the new hyperchaos system (1) simulated in MATLAB.



(a) (b)

Figure 3: Phase portraits of the coexisting hyperchaotic attractors (1) for the initial states $K_0 = (0.2, 0.4, 0.4, 0.2)$ and $\Lambda_0 = (-0.8, 0.8, -0.8, 0.8,)$.

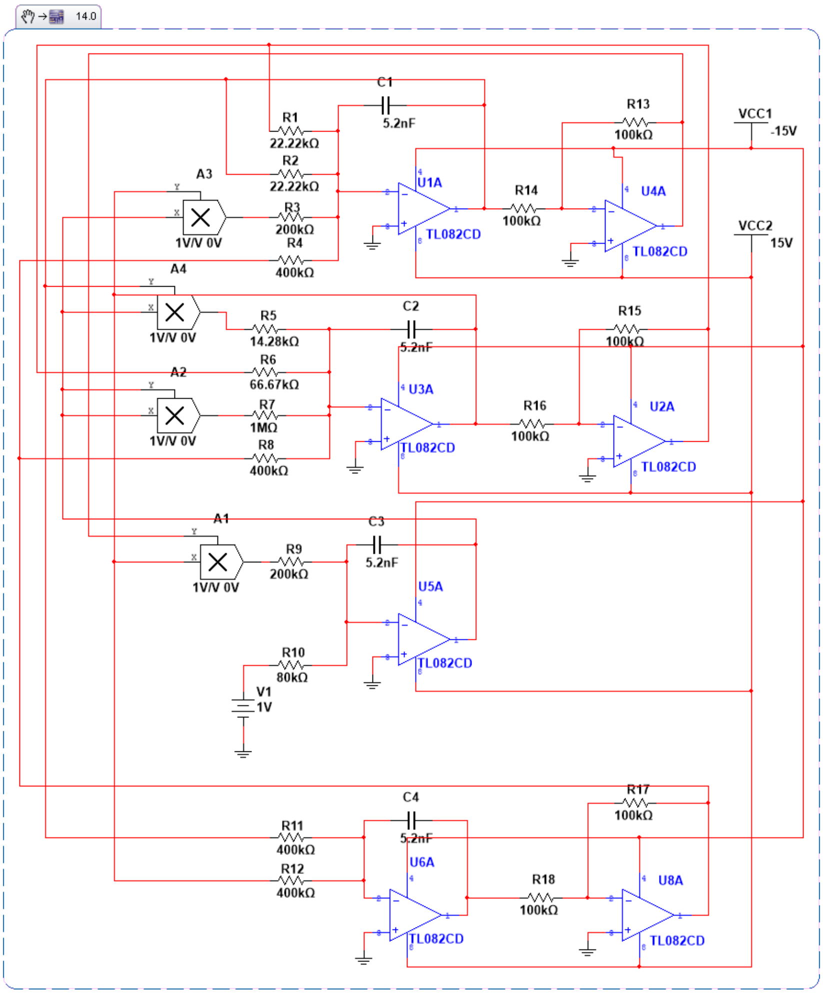


Figure 4: Circuit design for the new hyperchaotic two-scroll system.

We choose the values of the circuital elements as $R_1 = R_2 = 22.22$ k$\Omega, R_3 = R_9 = 200$ k$\Omega, R_4 = R_8 = R_{11} = R_{12} = 400$ k$\Omega, R_5 = 14.28$ k$\Omega, R_6 = 66.67$ k$\Omega, R_7 = 1$ M$\Omega, R_{10} = 80$ k$\Omega, R_{13} = R_{14} = R_{15} = R_{16} = R_{17} = R_{18} = 100$ k$\Omega, C_1 = C_2 = C_3 = C_4 = 5.2$ nF. The corresponding phase portraits on the oscilloscope are shown in Figure 5. The agreement between the Multisim results (Figure 5) and the MATLAB plots (Figure 2) shows the feasibility of the proposed hyperchaotic system.

4 Chaos Control

The system (1) is modified by introducing feedback controllers $U = [u_1, u_2, u_3,\ u_4]^T$ and is expressed as

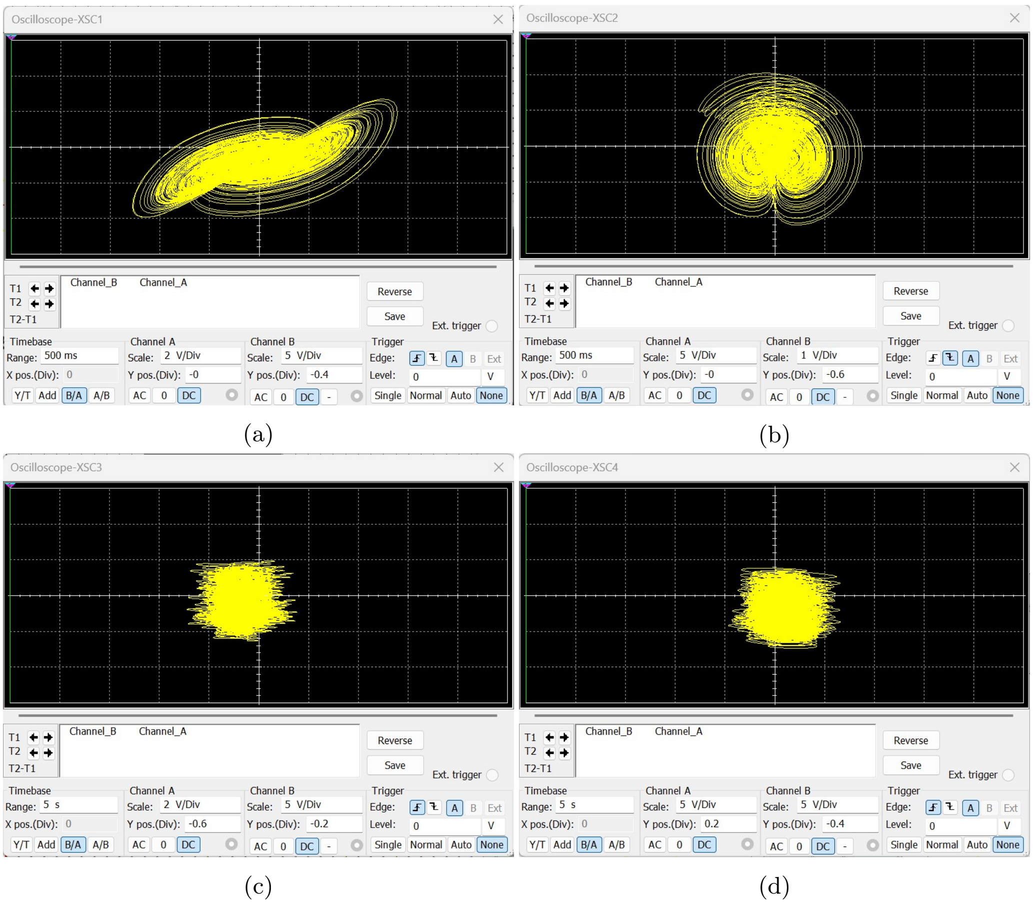


Figure 5: MultiSIM chaotic attractors of the new hyperchaotic two-scroll system (a) ξ–η plane, $(b)\eta$–ζ plane, $(c)\zeta - \omega$ plane and $(d)\xi$–ω plane.

$$\begin{cases} \dot{\xi} = \alpha(\eta - \xi) - \eta\zeta + \omega + u_1, \\ \dot{\eta} = -\gamma\xi\zeta + \beta\eta - \varepsilon\zeta^2 + \omega + u_2, \\ \dot{\zeta} = \xi\eta - \vartheta + u_3, \\ \dot{\omega} = -\xi - \eta + u_4. \end{cases} \tag{7}$$

Consider the nonlinear control strategy [44,45] and assume the parameters $\alpha, \beta, \gamma, \vartheta$ and ε are unknown, while $u_i,\ i = 1, 2, 3, 4$, is a feedback controller to be designed.

Theorem 1. *If the controller designed in (8) is implemented using a nonlinear control strategy, the system (1) will be suppressed.*

$$\begin{cases} u_1 = 0, \\ u_2 = -\alpha\xi - 2\beta\eta, \\ u_3 = \gamma\xi\eta + (\varepsilon\eta - 1)\zeta + \vartheta, \\ u_4 = -\omega. \end{cases} \tag{8}$$

Proof. Substituting the controllers (8) into the system (7), we have

$$\begin{cases} \dot{\xi} = \alpha(\eta - \xi) - \eta\zeta + \omega, \\ \dot{\eta} = -\gamma\xi\zeta + \beta\eta - \varepsilon\zeta^2 + \omega - \alpha\xi, \\ \dot{\zeta} = \zeta\eta + \gamma\xi\eta + (\varepsilon\eta - 1)\zeta, \\ \dot{\omega} = -\xi - \eta - \omega. \end{cases} \tag{9}$$

Construct the Lyapunov candidate function as

$$v = \tfrac{1}{2}[\ \xi^2 +\ \eta^2 + \zeta^2 + \omega^2]$$

and

$$\begin{gathered} \dot{v} =\ \xi\dot{\xi} + \eta\dot{\eta} + \zeta\dot{\zeta} + \omega\dot{\omega}, \\ \dot{v} =\ \xi(\alpha\,(\eta - \xi) - \eta\zeta + \omega) \\ +\eta(-\gamma\xi\zeta - \beta\eta - \varepsilon\zeta^2 + \omega - \alpha\xi) \\ +\zeta\,(\xi\eta + \gamma\xi\eta + (\varepsilon\eta - 1)\,\zeta) \\ +\omega(-\xi - \eta - \omega), \\ \Rightarrow \dot{v} =\ -\alpha\xi^2 - \beta\eta^2 - \zeta^2 - \omega^2. \end{gathered}$$

By using a theoretical method (the Lyapunov stability theorem), the system (1) was suppressed, and the accuracy of the analytical results was validated by the numerical simulations via Figure 6.

5 Conclusions

The main novelty of this work is the modelling of a new 4-D hyperchaos system with no balance point. We remark that the proposed hyperchaos system displays a hidden attractor as it has no balance point. In this research paper, invoking the use of four quadratic nonlinearities, a new nonlinear dynamical system with a hidden hyperchaotic attractor was proposed and illustrated with MATLAB signal plots. For nonlinear dynamical systems with chaotic or hyperchaotic attractors, multistability is a special property

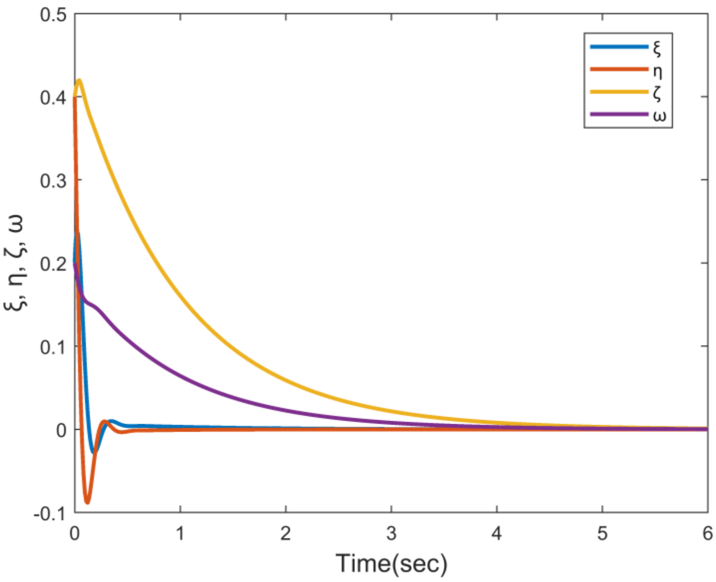


Figure 6: Convergence of attractors to zero by controller (8).

which refers to the existence of chaotic or hyperchaotic attractors for the fixed set of parameters but different choices of initial states. In this research work, we showed the existence of multistability with coexisting hyperchaotic attractors for the proposed hyperchaos system. MultiSim circuit simulation of the new hyperchaos system was designed for the validation of the new hyperchaos system with a hidden attractor, which has many practical applications in secure communication devices. Finally, the chaos control results based on feedback control are also derived for the new 4D hyperchaotic system with no equilibrium point.

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