TELKOMNIKA, Vol.17, No.5, October 2019, pp.2465~2474
ISSN: 1693-6930, accredited First Grade by Kemenristekdikti, Decree No: 21/E/KPT/2018
DOI: 10.12928/TELKOMNIKA.v17i5.10650

A new two-scroll chaotic system with two nonlinearities: dynamical analysis and circuit simulation

Sundarapandian Vaidyanathan[1], Aceng Sambas*[2], Sen Zhang[3], Yicheng Zeng[4], Mohamad Afendee Mohamed[5], Mustafa Mamat[6]
[1]Research and Development Centre, Vel Tech University Avadi, Chennai, 600062, Tamil Nadu, India
[2]Department of Mechanical Engineering, Universitas Muhammadiyah Tasikmalaya,
29 Tamansari Gobras St., Tasikmalaya 46196, Indonesia
[3,4]School of Physics and Opotoelectric Engineering, Xiangtan University Xiangtan 411105, Hunan, China
[5,6]Faculty of Informatics and Computing, Universiti Sultan Zainal Abidin,
Gong Badak, Kuala Terengganu 21300, Malaysia
*Corresponding author, e-mail: acengs@umtas.ac.id

Abstract

Chaos theory has several applications in science and engineering. In this work, we announce a new two-scroll chaotic system with two nonlinearities. The dynamical properties of the system such as dissipativity, equilibrium points, Lyapunov exponents, Kaplan-Yorke dimension and bifurcation diagram are explored in detail. The presence of coexisting chaotic attractors, coexisting chaotic and periodic attractors in the system is also investigated. In addition, the offset boosting of a variable in the new chaotic system is achieved by adding a single controlled constant. It is shown that the new chaotic system has rotation symmetry about the z-axis. An electronic circuit simulation of the new two-scroll chaotic system is built using Multisim to check the feasibility of the theoretical model.

Keywords: *chaos, chaotic systems, circuit simulation, two-scroll system*

Copyright © 2019 Universitas Ahmad Dahlan. All rights reserved.

1. Introduction

In the last few decades, many advances applications of chaotic systems have been actively carried out in the literature [1-4]. Classical examples of 3-D chaotic systems include the Lorenz system [5], Rössler system [6], Chen system [7], Lü system [8], Liu system [9], Tigan system [10], Sprott systems [11], Arneodo system [12], etc. Chaotic systems arise in many applications of nonlinear oscillators [13-18]. Vaidyanathan [13] used active control method for the global chaos synchronization of the forced Van der Pol chaotic oscillators. Ghosh et al. [14] discussed the generation and control of chaos in a single loop optoelectronic oscillator with the variation of feedback loop delay. Vaidyanathan and Rasappan [15] applied nonlinear control for achieving hybrid synchronization of hyperchaotic Qi and Lü oscillators. Jin [16] presented a digitally programmable multi-direction fully integrated chaotic oscillator. Vaidyanathan [17] derived new results for the adaptive controller and synchronizer design for the Qi-Chen chaotic oscillator. Vaidyanathan [18] discussed the qualitative analysis, control and synchronization of a ten-term 4-D hyperchaotic system with an exponential nonlinearity and three quadratic nonlinearities.

Chaotic systems have applications in artificial and cellular neural networks [19, 20]. Akhmet and Fen [19] discussed the generation of cyclic and toroidal chaos by Hopfield neural networks. Vaidyanathan [20] derived new results for the synchronization of 3-cells cellular neural network (CNN) attractors via adaptive control method. Chaotic systems have applications in biology and medicine [21-24]. Akaishi et al. [21] presented a new theoretical model from a viewpoint of complex system with chaos model to reproduce and explain the non-linear clinical and pathological manifestations in multiple sclerosis. Vaidyanathan [22] presented new results for the adaptive control of the FitzHugh-Nagumo chaotic neuron model. Vaidyanathan [23] used backstepping control for the control and synchronization of a novel jerk system with two quadratic nonlinearities. Shepelev et al. [24] discussed the bifurcations of spatiotemporal structures in a medium of FitzHugh–Nagumo neurons with diffusive coupling.

Received July 23, 2018; Revised February 11, 2019; Accepted March 12, 2019

Multi-scroll chaotic systems have generated a lot of interest in chaos literature. Many works have been done on several types of multi-scroll chaotic systems such as two-scroll systems [25, 26], three-scroll systems [27, 28], four-scroll systems [29, 30], etc. Lien et al. [25] discussed the finding of a new two-scroll chaotic system with three quadratic nonlinearities. Vaidyanathan et al. [26] reported a new two-scroll chaotic system and gave a dynamic analysis. Vaidyanathan [27] announced a new ten-term three-scroll chaotic system with four quadratic nonlinearities. Pakiriswamy and Vaidyanathan [28] discussed the generalized projective synchronization of three-scroll chaotic systems via active feedback control. Zhang et al. [29] reported the finding of one to four-wing chaotic attractors coined from a novel 3-D fractional-order chaotic system with complex dynamics. Akgul et al. [30] derived a new four-scroll chaotic attractor and discussed its engineering applications.

For practical implementation of chaotic systems, it is important to design suitable electronic circuit design of chaotic systems [31-35]. Sambas et al. [31] discussed the circuit design of a six-term novel chaotic system with hidden attractor. Sambas et al. [32] derived a circuit design for a new 4-D chaotic system with hidden attractor. Sambas et al. [33] discussed the numerical simulation and circuit implementation for a Sprott chaotic system with one hyperbolic sinusoidal nonlinearity. Vaidyanathan et al. [34] presented a new 4-D chaotic hyperjerk system, and discussed its synchronization, circuit design and applications in RNG, image encryption and chaos-based steganography. Vaidyanathan et al. [35] reported a new chaotic attractor with two quadratic nonlinearities and discussed its synchronization via adaptive control and circuit implementation.

In this paper, we report the finding of a new two-scroll chaotic system with two nonlinearities. We study the dynamical properties of the system such as dissipativity, equilibrium points, Lyapunov exponents, Kaplan-Yorke dimension, etc. We show that the new chaotic system has rotation symmetry about the z-axis. Thus, this paper makes a valuable addition to existing multi-scroll chaotic systems. We also discuss an electronic circuit simulation of the new two-scroll chaotic system using Multisim to validate the feasibility of the theoretical model.

2. A New Two-scroll Chaotic System

In this paper, we report a new 3-D chaotic system given by:

$$\begin{cases} \dot{x} = a(y - x) \\ \dot{y} = xz \\ \dot{z} = c - by^4 \end{cases} \tag{1}$$

in the system (1), x, y, z are the states and a, b, c are positive parameters. In this work, we show that the system (1) exhibits a two-scroll chaotic attractor when we take the parameter values as:

$$a = 6, b = 1, c = 50 \tag{2}$$

for numerical simulations, we take the initial values as

$$x(0) = 0.2, y(0) = 0.2, z(0) = 0.2 \tag{3}$$

The Lyapunov exponents of the system (1) are obtained using MATLAB as:

$$L_1 = 1.2312, L_2 = 0,\ L_3 = -7.2312 \tag{4}$$

since $L_1 > 0$ and $L_1 + L_2 + L_3 < 0$, we conclude that the new 3-D system (1) is chaotic and dissipative. Thus, the system orbits of the new two-scroll chaotic system (1) are ultimately confined into a specific limit set of zero volume and the asymptotic motion settles onto a chaotic attractor. The Kaplan-Yorke dimension of the new two-scroll chaotic system (1) is obtained as:

$$D_{KY} = 2 + \frac{L_1 + L_2}{|L_3|} = 2.1703 \tag{5}$$

this shows the high complexity of the new two-scroll system (1).

The equilibrium points of the new chaotic system (1) are obtained by solving the following system:

$$a(y-x)=0 \tag{6a}$$

$$xz=0 \tag{6b}$$

$$c-by^4=0 \tag{6c}$$

From (6a), we see that *x*=*y*. From (6b), either *x*=0 or *z*=0. If *x*=0, then *y*=0, which contradicts (6c). Thus, *x* ≠0. From (6b), *z*=0. From (6c), since *b*=1 and *c*=50, we find that:

$$y=\pm(50)^{0.25}=\pm 2.6591 \tag{7}$$

This calculation shows that the new chaotic system (1) has two equilibrium points:

$$E_1=\begin{bmatrix}2.6591\\2.6591\\0\end{bmatrix} \text{ and } E_2=\begin{bmatrix}-2.6591\\-2.6591\\0\end{bmatrix} \tag{8}$$

We find that the new chaotic system (1) is invariant under the coordinates transformation

$$(x,y,z)\mapsto(-x,-y,z) \tag{9}$$

for all values of the parameters a, b, c. This shows that the new chaotic system (1) has rotation symmetry about z-axis. The Lyapunov exponents of the two-scroll chaotic system (1) are displayed in Figure 1. The phase portraits of the new two-scroll chaotic system (1) are displayed in Figure 2.

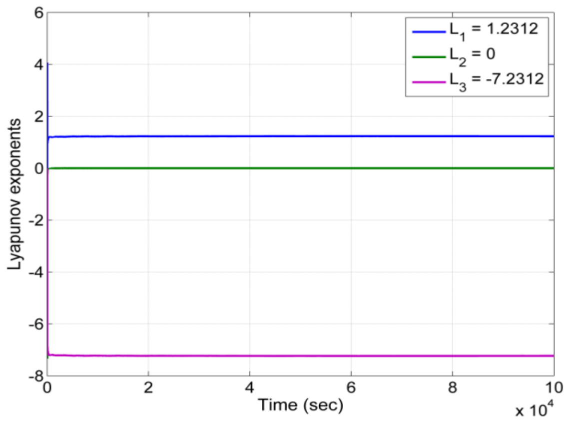


Figure 1. Lyapunov chaos exponents (LCE) of the new two-scroll chaotic system (1) for (*x*(0), *y*(0), *z*(0))=(0.2, 0.2, 0.2) and (*a*, *b*, *c*)=(6, 1, 50)

3. Dynamical Analysis
3.1. Route to Chaos

We study the dynamics of the new two-scroll chaotic system (1) by varying the value of the parameter *b*. Bifurcation diagram and Lyapunov exponents of the new two scroll chaotic system (1) are presented in Figures 3 (a) and 3 (b), respectively. The new two scroll chaotic system (1) displays a reverse period-doubling route to chaos. For example, period-1 state is derived for *a*=20 (Figure 4 (a)), period-2 state is derived for *a*=16.5 (Figure 4 (b)) and chaotic behavior is noted for *a*=15 (Figure 4 (c)). In addition, the bifurcation diagram and Lyapunov exponents of the system with respect to parameter *b* are shown in Figures 5 (a) and 5 (b). Here the maximum value of *b* can be very large. The system shows constant Lyapunov exponent behavior [36-38]. Figures 6 (a) and 6 (b) show the Lyapunov spectrum and bifurcation diagram, respectively, of the system with variation of parameter *c* in the range *c*=[4, 50]. It is seen from Figures 6 (a) and 6 (b) that system (1) has periodic, quasiperiodic and chaotic behaviors for the different values of parameter *c*.

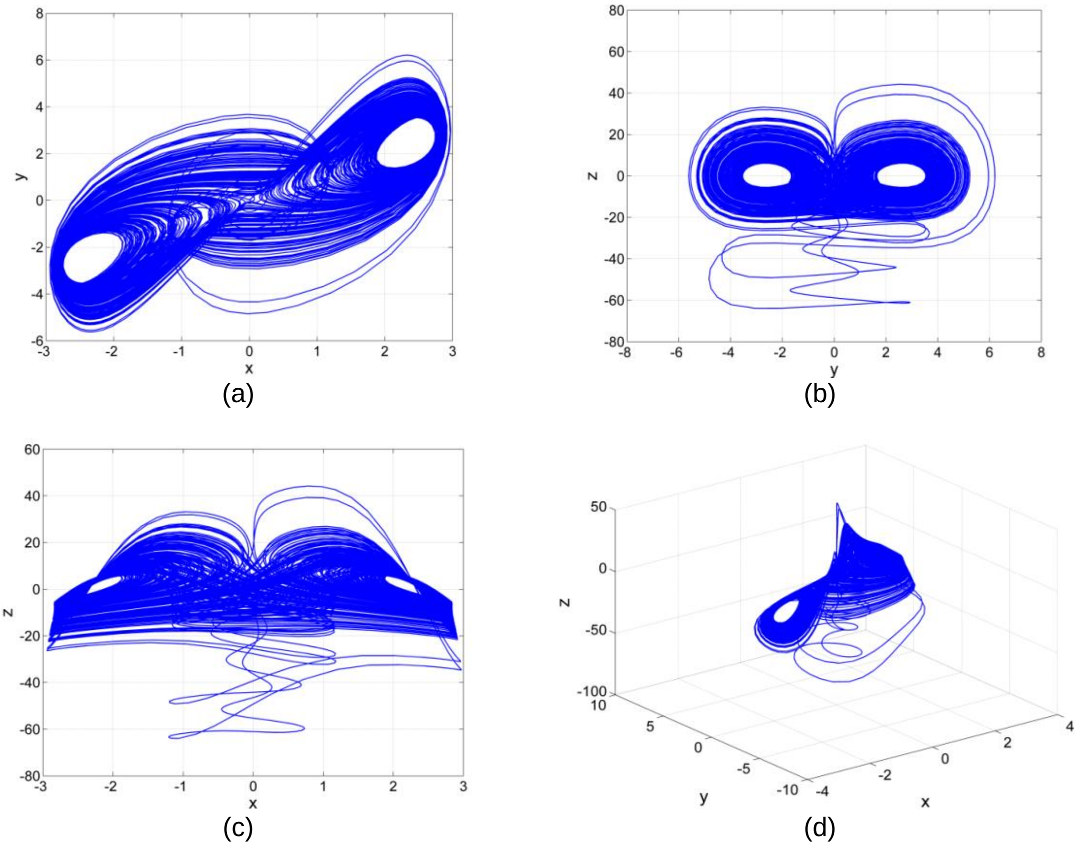


Figure 2. Numerical simulations of phase portraits of the new two-scroll chaotic system (1) for (*x*(0), *y*(0), *z*(0))=(0.2, 0.2, 0.2) and (*a*, *b*, *c*)=(6, 1, 50) (a) *x*-*y* plane, (b) *y*-*z* plane, (c) *x*-*z* plane, and (d) R^3

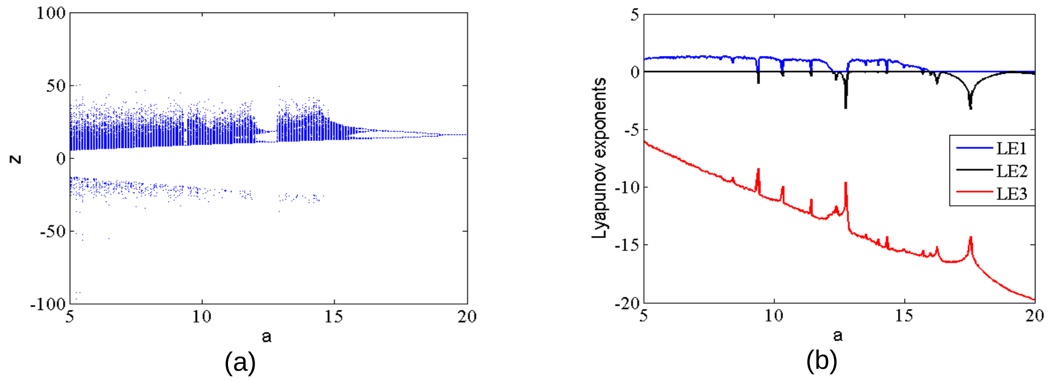
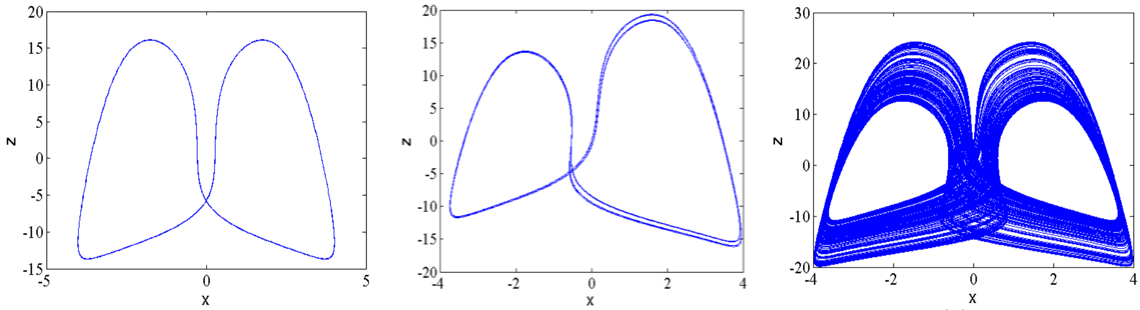
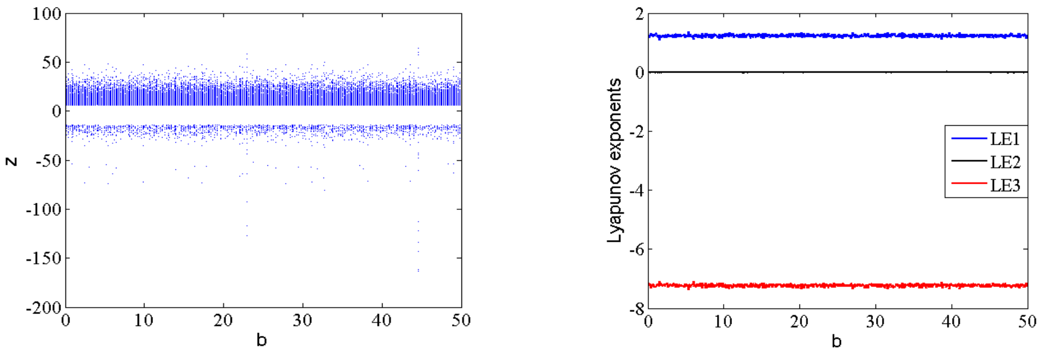


Figure 3. (a) Bifurcation diagram of system (1) versus the parameter *a* for *b*=1, *c*=50 and initial conditions (*x*(0), *y*(0), *z*(0))=(0.2, 0.2, 0.2); (b) Lyapunov spectrum of system (1) when varying the parameter *a* for *b*=1, *c*=50 and initial conditions (*x*(0), *y*(0), *z*(0))=(0.2, 0.2, 0.2)



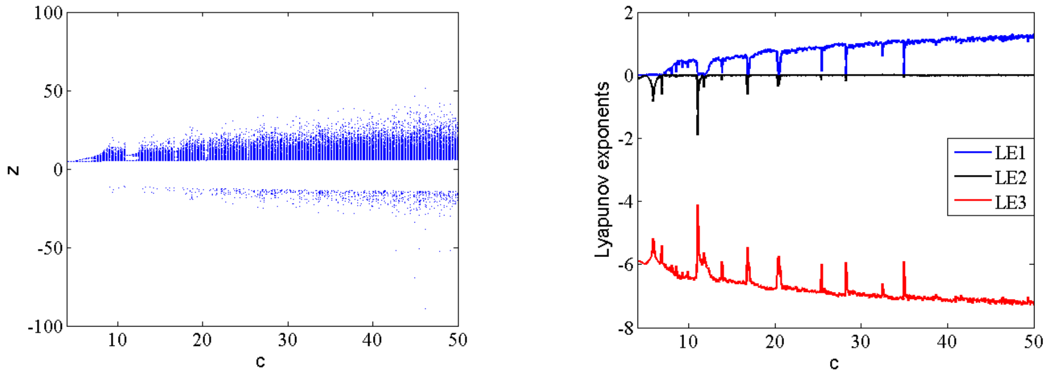
(a) (b) (c)

Figure 4. Phase portraits of system (1) displayed in the *x*–*z* plane when changing the value of parameter *a*: (a) *a*=20 (period-1 state), (b) *a*=16.5 (period-2 state) (c) *a*=15 (chaotic behavior) while keeping *b*=1, *c*=50 and initial conditions (*x*(0), *y*(0), *z*(0))=(0.2, 0.2, 0.2)



(a) (b)

Figure 5. (a) Bifurcation diagram of system (1) versus the parameter *b* for *a*=6, *c*=50 and initial conditions (*x*(0), *y*(0), *z*(0))=(0.2, 0.2, 0.2); (b) Lyapunov spectrum of system (1) when varying the parameter *b* for *a*=6, *c*=50 and initial conditions (*x*(0), *y*(0), *z*(0))=(0.2, 0.2, 0.2)



(a) (b)

Figure 6. (a) Bifurcation diagram of system (1) versus the parameter *c* for *a*=6, *b*=1 and initial conditions (*x*(0), *y*(0), *z*(0))=(0.2, 0.2, 0.2); (b) Lyapunov spectrum of system (1) when varying the parameter *c* for *a*=6, *b*=1 and initial conditions (*x*(0), *y*(0), *z*(0))=(0.2, 0.2, 0.2)

3.2. Coexistence of Attractors

In this study, the coexisting chaotic attractors, coexisting chaotic and periodic attractors of two scroll system (1) are theoretically and numerically investigated. If a=6.5, system (1) shows coexisting periodic attractors with respect to initial values (*x* (0), *y* (0), *z* (0))=(0.2, 0.2, 0.2) (blue color) and the initial conditions (*x* (0), *y* (0), *z* (0))=(-0.2, -0.2, 0.2) (red color) as shown in Figure 7 (a). If a=7.5, system (1) exhibits coexisting chaotic and periodic attractors corresponding to initial values (*x* (0), *y* (0), *z* (0))=(0.2, 0.2, 0.2) (blue color) and the initial conditions (*x* (0), *y* (0), *z* (0))=(-0.2, -0.2, 0.2) (red color) as shown in Figure 7 (b). Next, we fix *a*=6, *b*=1, and select *c* as a controlled parameter for over the range $4 \le c \le 10$. The coexisting bifurcation diagrams of the state variable *y* is illustrated in Figure 8, in which the orbit colored in blue starts from the initial values of (0.2, 0.2, 0.2) and the orbit colored in red starts from the initial values of (-0.2, −0.2, 0.2).

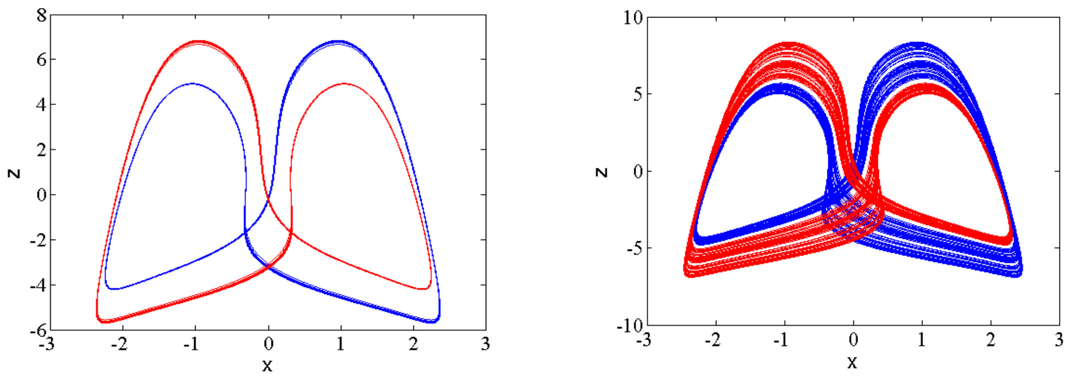


Figure 7. Phase portraits of various coexisting attractors in the *x*−*z* plane: (a) the coexisting periodic attractors for *a*=6.5, (b) the coexisting chaotic and periodic attractors for *a*=7.5

3.3. Offset Boosting Control

Clearly, the state variable *z* appears only once in the second equation of the system. Therefore, we can control the state variable *z* conveniently. The state variable *z* is offset-boosted by replacing *z* with *z* + *n*, in which *n* is a constant. The system can be rewritten as:

$$\begin{cases} \dot{x} = a(y-x) \\ \dot{y} = x(z+n) \\ \dot{z} = c - by^4 \end{cases} \tag{10}$$

consequently, the chaotic signal *z* can be transformed from a bipolar signal to a unipolar signal when varying the control parameter *n*. Figure 9 shows that with the variation of the offset boosting controller *n*, the signal *z* is effectively boosted from a bipolar signal to a unipolar signal. Interestingly, different locations of the phase portraits of chaotic attractors in the *x*–*z* and *y*-*z* plane are adjusted depending on different values of the offset boosting controller *n*, which are plotted in Figures 10 (a) and 10 (b), respectively.

4. Circuit Implementation of the New Chaotic System

In this section, the three state variables (*x*, *y*, *z*) of the system (1) have been rescaled as $X = \frac{1}{2}x,\ Y = \frac{1}{2}y,\ Z = \frac{1}{2}z$. The rescaled system reads:

$$\begin{cases} \dot{x} = a(y-x) \\ \dot{y} = 4xz \\ \dot{z} = \frac{c}{4} - 4by^4 \end{cases} \tag{11}$$

by applying Kirchhoff's circuit laws into the designed circuit, we can be derived:

$$\begin{cases} \dot{x} = \frac{1}{C_1 R_1} y - \frac{1}{C_1 R_2} x \\ \dot{y} = \frac{1}{C_2 R_3} xz \\ \dot{z} = \frac{V_1}{C_3 R_4} - \frac{1}{C_3 R_5} y^2 \end{cases} \tag{12}$$

In (12), the voltages of capacitors are denoted as *X, Y, Z.* the power supplies of all active devices are ±15 volt. We choose the values of the circuital elements as: R_1=R_2=66.67 kΩ, R_4=32 kΩ, R_3=R_5=R_6=R_7=R_8=R_9=100 kΩ, C_1=C_2=C_3=1nF. The designed circuit diagram of system (1) is shown in Figure 11 and Multisim results of the proposed system can be seen in Figure 12. It is easy to see that the oscilloscope results as shown in Figure 12 are consistent with the MATLAB simulations as shown in Figure 2.

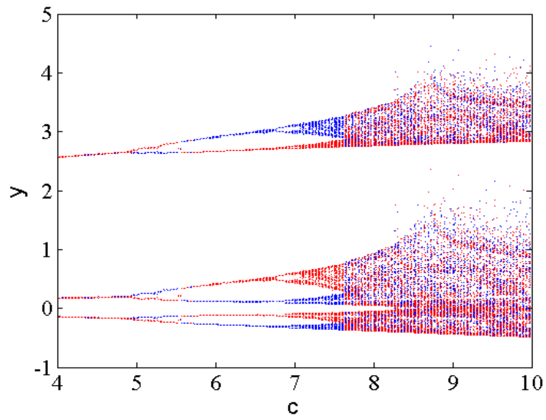


Figure 8. Continuations of system (1) when increasing the value of the parameter *c* from 4 to 10 for *a*=6 and *b*=1 starting with the initial condition; *x* (0), *y* (0), *z* (0))=(0.2, 0.2, 0.2) (blue color), (*x* (0), *y* (0), *z* (0))=(-0.2, -0.2, 0.2) (red color)

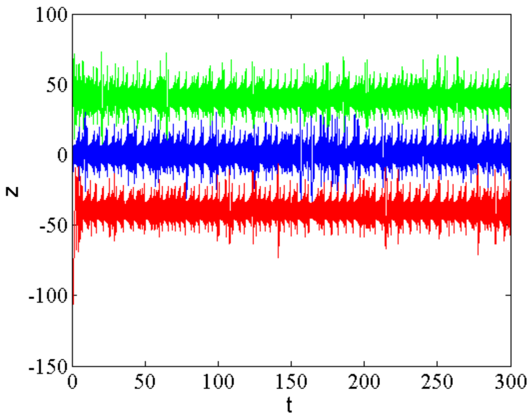


Figure 9. The signal *z* with different values of the offset boosting controller *n*: *n*=0 (blue color); *n*=40 (red color); *n*=-40 (green color)

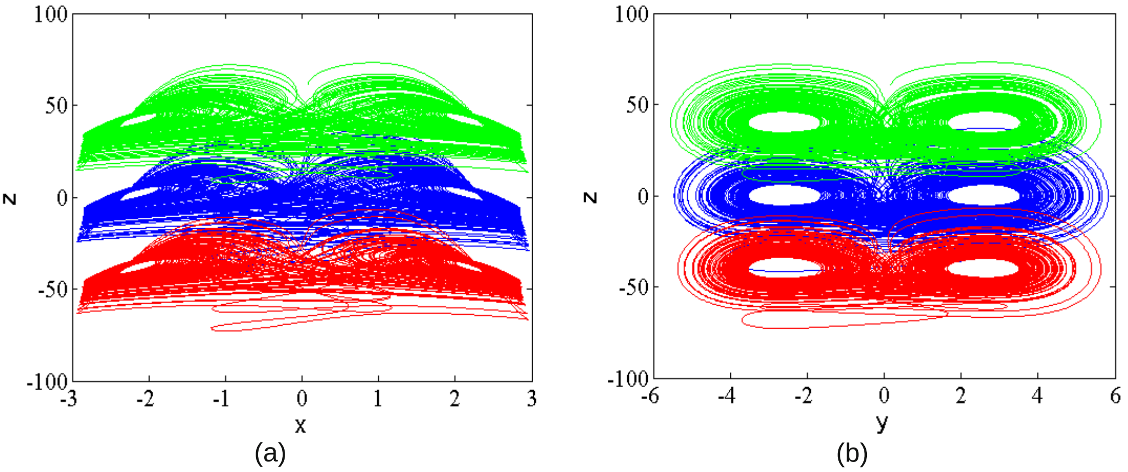


Figure 10. Phase portraits in different planes and different values of the offset boosting controller *n*: (a) *x*-*z* plane, (b) *y*-*z* plane *n*=0 (blue color), *n*=40 (red color), *n*=-40 (green color)

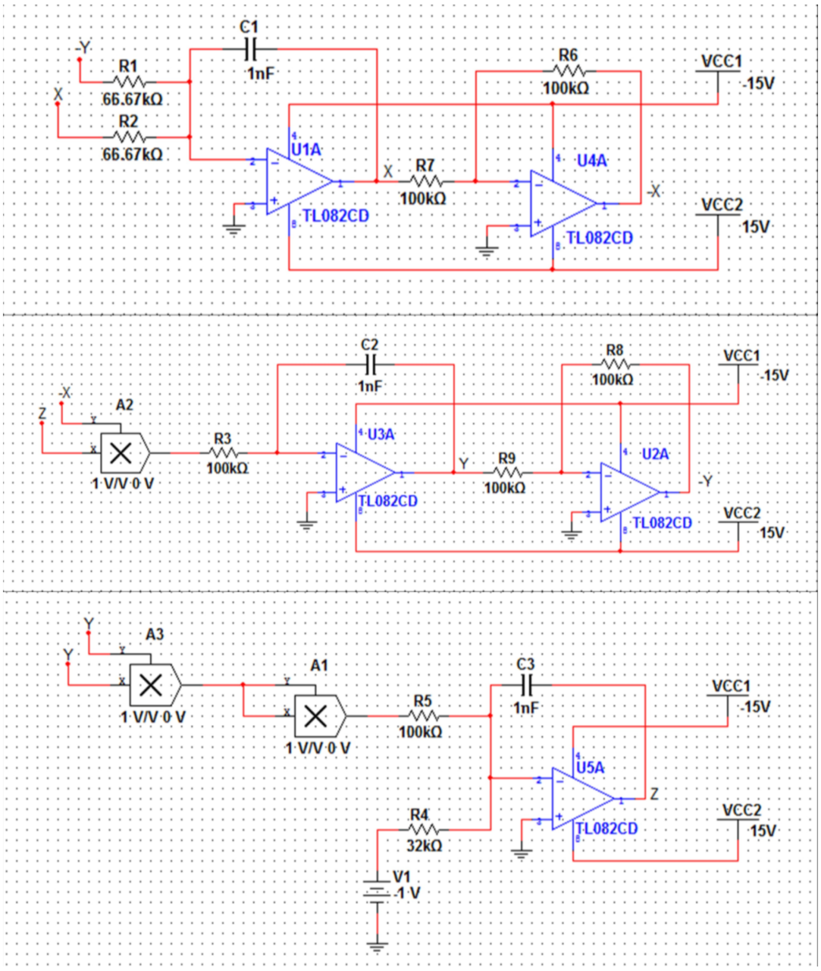
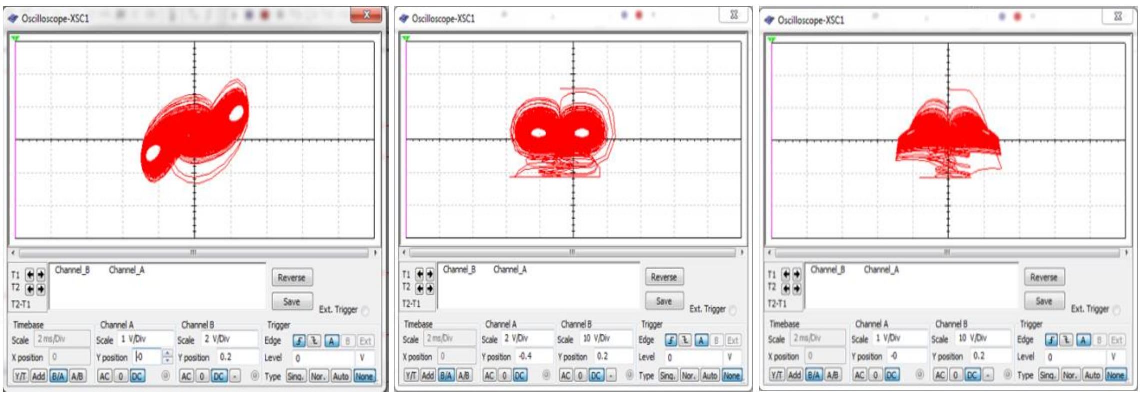


Figure 11. The electronic circuit schematic of the new two-scroll chaotic system (1)



(a) (b) (c)

Figure 12. Multisim outputs of the scaled new two-scroll chaotic system (12) in
(a) x-y plane, (b) y–z plane, (c) x–z plane

5. Conclusion

This paper reported a new two-scroll chaotic system with two nonlinearities (a quadratic nonlinearity and a quartic nonlinearity). We studied the properties of the new chaotic system such as dissipativity, symmetry, equilibrium points, Lyapunov exponents and Kaplan-Yorke dimension. In addition, we also studied the dynamic analysis of the new chaotic system and found multistability and coexisting chaotic attractors for the new chaotic system. An electronic circuit simulation of the new two-scroll chaotic system was designed using Multisim to check the feasibility of the theoretical chaotic model. As we have verified that the circuit simulations obtained using Multisim match with the numerical simulations obtained using MATLAB, the new chaotic system can be used for many engineering applications such as image encryption, speech encryption, steganography, etc.

Acknowledgement

The authors thank the Government of Malaysia for funding this research under the Fundamental Research Grant Scheme (FRGS/1/2018/ICT03/Unisza/02/2) and also Universiti Sultan Zainal Abidin, Terengganu, Malaysia.

References

[1] Azar AT, Vaidyanathan S. Chaos Modeling and Control Systems Design. Berlin: Springer. 2015.
[2] Vaidyanathan S, Sambas A, Mamat M. A new chaotic system with axe-shaped equilibrium, its circuit implementation and adaptive synchronization. *Archives of Control Sciences*. 2018; 28: 443-462.
[3] Mobayen S, Sambas A, Kaçar S, Çavuşoğlu Ü. A Novel Chaotic System with Boomerang-Shaped Equilibrium, Its Circuit Implementation and Application to Sound Encryption. *Iranian Journal of Science and Technology, Transactions of Electrical Engineering*. 2019; 43(1): 1-12.
[4] Sambas A, Vaidyanathan S, Mamat M, Mohamed MA, Sanjaya WSM. A new chaotic system with a pear-shaped equilibrium and its circuit simulation. *International Journal of Electrical and Computer Engineering*. 2018; 8(6): 4951-4958.
[5] Lorenz EN. Deterministic nonperiodic flow. *Journal of the Atmospheric Sciences*. 1963; 20(2): 130-141.
[6] Rössler OE. An equation for continuous chaos. *Physics Letters A*. 1976; 57(5): 397-398.
[7] Chen G, Ueta T. Yet another chaotic attractor. *International Journal of Bifurcation and Chaos*. 1999; 9(07): 1465-1466.
[8] Lu J, Chen G. A new chaotic attractor coined. *International Journal of Bifurcation and Chaos*. 2002; 12(5): 659-661.
[9] Liu C, Liu T, Liu L, Liu K. A new chaotic attractor. *Chaos, Solitions and Fractals*. 2004; 22(5): 1031-1038.
[10] Tigan G, Opriş D. Analysis of a 3D chaotic system. *Chaos, Solitons and Fractals*. 2008; 36(5): 1315-1319.
[11] Sprott J C. Some simple chaotic flows. *Physical Review E*. 1994; 50(2): 647-650.
[12] Arneodo A, Coullet P, Tresser C. Occurrence of strange attractors in three-dimensional Volterra equations. *Physics Letters A*. 1980; 79(4): 259-263.
[13] Vaidyanathan S. Global chaos synchronization of the forced Van der Pol chaotic oscillators via adaptive control method. *International Journal of PharmTech Research*. 2015; 8(6): 156-166.
[14] Ghosh D, Mukherjee, A, Das NR, Biswas BN. Generation & control of chaos in a single loop optoelectronic oscillator. *Optik*. 2018; 165: 275-287.
[15] Vaidyanathan S, Rasappan R. Hybrid synchronization of hyperchaotic Qi and Lü systems by nonlinear control. *Communications in Computer and Information Science*. 2011; 131: 585-593.
[16] Jin J. Programmable multi-direction fully integrated chaotic oscillator. *Microelectronics Journal*. 2018; 75: 27-34.
[17] Vaidyanathan S. Adaptive controller and synchronizer design for the Qi-Chen chaotic system. *Lecture Notes of the Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering*. 2012; 85: 124-133.
[18] Vaidyanathan S. Hyperchaos, qualitative analysis, control and synchronisation of a ten-term 4-D hyperchaotic system with an exponential nonlinearity and three quadratic nonlinearities. *International Journal of Modelling, Identification and Control*. 2015; 23(4): 380-392.
[19] Akhmet M, Fen MO. Generation of cyclic/toroidal chaos by Hopfield neural networks. *Neurocomputing*. 2014; 145: 230-239.
[20] Vaidyanathan S. Synchronization of 3-cells cellular neural network (CNN) attractors via adaptive control method. *International Journal of PharmTech Research*. 2015; 8(8): 946-955.
[21] Akaishi T, Takahashi T, Nakashima I. Chaos theory for clinical manifestations in multiple sclerosis. *Medical Hypotheses*. 2018; 115: 87-93.

[22] Vaidyanathan S. Adaptive control of the FitzHugh-Nagumo chaotic neuron model. *International Journal of PharmTech Research*. 2015; 8(6): 117-127.
[23] Vaidyanathan S. Analysis, control, and synchronization of a 3-D novel jerk chaotic system with two quadratic nonlinearities. *Kyungpook Mathematical Journal*. 2015; 55(3): 563-586.
[24] Shepelev IA, Shamshin DV, Strelkova GI, Vadivasova TE. Bifurcations of spatiotemporal structures in a medium of FitzHugh–Nagumo neurons with diffusive coupling. *Chaos, Solitons and Fractals*. 2017; 104: 153-160.
[25] Lien CH, Vaidyanathan S, Sambas A, Mamat M, Sanjaya WSM. *A new two-scroll chaotic attractor with three quadratic nonlinearities, its adaptive control and circuit design*. IOP Conference Series: Materials Science and Engineering. 2018; 332(1): 012010.
[26] Vaidyanathan S. Global chaos control and synchronization of a novel two-scroll chaotic system with three quadratic nonlinearities. In: Vaidyanathan S, Volos C. *Editors*. Advances and Applications in Chaotic Systems. Germany: *Springer*. 2016: 235-255.
[27] Vaidyanathan S. Mathematical analysis, adaptive control and synchronization of a ten-term novel three-scroll chaotic system with four quadratic nonlinearities. *International Journal Control Theory Appllication*. 2016; 9(1): 1-20.
[28] Pakiriswamy S, Vaidyanathan S. *Generalized projective synchronization of three-scroll chaotic systems via active control*. International Conference on Computer Science and Information Technology. 2012; 85: 146-155.
[29] Zhang S, Zeng Y, Li Z. One to four-wing chaotic attractors coined from a novel 3D fractional-order chaotic system with complex dynamics. *Chinese Journal of Physics*. 2018; 56(3): 793-806.
[30] Akgul A, Moroz I, Pehlivan I, Vaidyanathan S. A new four-scroll chaotic attractor and its engineering applications. *Optik-International Journal for Light and Electron Optics*. 2016; 127(13): 5491-5499.
[31] Sambas A, Vaidyanathan S, Mamat M, Sanjaya WSM. A six-term novel chaotic system with hidden attractor and its circuit design. In: Pham VT, Vaidyanathan S, Volos C, Kapitaniak T. Editors. Nonlinear Dynamical Systems with Self-Excited and Hidden Attractors. Germany: *Springer*. 2018: 365-373.
[32] Sambas A, Mamat M, Vaidyanathan S, Mohamed MA, Sanjaya WSM. A new 4-D chaotic system with hidden attractor and its circuit implementation. *International Journal of Engineering & Technology*. 2018; 7(3): 1245-1250.
[33] Sambas A, Mujiarto, Mamat M, Sanjaya WSM. Numerical simulation and circuit implementation for a Sprott chaotic system with one hyperbolic sinusoidal nonlinearity. *Far East Journal of Mathematical Sciences*. 2017; 102(6): 1165-1177.
[34] Vaidyanathan S, Akgul A, Kaçar S, Çavuşoğlu U. A new 4-D chaotic hyperjerk system, its synchronization, circuit design and applications in RNG, image encryption and chaos-based steganography. *The European Physical Journal Plus*. 2018; 133(2): 46.
[35] Vaidyanathan S, Sambas A, Mamat M, Gundara G, Sanjaya WSM. *A new chaotic attractor with two quadratic nonlinearities, its synchronization and circuit implementation*. IOP Conference Series: Materials Science and Engineering. 2018; 332(1): 012048.
[36] Munmuangsaen B, Srisuchinwong B. A minimum five-component five-term single-nonlinearity chaotic jerk circuit based on a twin-jerk single-op-amp technique. *International Journal of Circuit Theory and Applications*. 2018; 46(3): 656-670.
[37] Zhang S, Zeng YC, Li ZJ, Wang MJ, Xiong L. Generating one to four-wing hidden attractors in a novel 4D no-equilibrium chaotic system with extreme multistibility. *Chaos*. 2018; 28(1): 013113.
[38] Zhang S, Zeng Y, Li Z, Wang M, Zhang X, Chang D. A novel simple no-equilibrium chaotic system with complex hidden dynamics. *International Journal of Dynamics & Control*. 2018; 23: 1-12.