www.sphinxsai.com

International Journal of PharmTech Research
CODEN (USA): IJPRIF, ISSN: 0974-4304
Vol.8, No.5, pp 964-973, 2015

Adaptive Chaotic Synchronization of Enzymes-Substrates System with Ferroelectric Behaviour in Brain Waves

Sundarapandian Vaidyanathan

R & D Centre, Vel Tech University, Avadi, Chennai, Tamil Nadu, India

Abstract: In the recent decades, there is significant interest in the literature in the application of chaos in physical, electrical, chemical and biological systems. This paper investigates research in the dynamic analysis and global chaos synchronization of enzymes-substrate reactions system with ferroelectric behaviour in brain waves which was studied by Enjieu Kadji, Chabi Orou, Yamapi and Woafo (2007). The enzymes-substrates system is a 2-D non-autonomous system with a cosinusoidal forcing term. This paper depicts the phase portraits of the 2-D enzymes-substrates system when the system undergoes chaotic behaviour. Next, this paper derives new adaptive control results for globally synchronizing the identical enzyme-substrates systems with uncertain parameters. Backstepping control is used to derive the main results for global synchronization of the enzyme-substrates systems. MATLAB plots have been shown in this paper to illustrate the main results for the enzyme-substrates system.
Keywords: Chaos, enzymes-substrate reactions, biology, synchronization, backstepping control, etc.

Introduction

Chaos theory is a modern research field which discusses the qualitative and numerical study of unstable aperiodic behaviour in deterministic nonlinear dynamical systems. A dynamical system is called chaotic if it satisfies the three properties: boundedness, infinite recurrence and sensitive dependence on initial conditions [1-2].

The first famous chaotic system was discovered by Lorenz, when he was developing a 3-D weather model for atmospheric convection in 1963 [3], and subsequently, Rössler discovered a 3-D chaotic system in 1976 [4]. The discovery of Lorenz and Rössler chaotic systems has ben followed by the discovery of many 3-D chaotic systems such as Arneodo system [5], Sprott systems [6], Chen system [7], Lü-Chen system [8], Cai system [9], Tigan system [10], etc. Many new chaotic systems have been also discovered in the recent years like Sundarapandian systems [11, 12], Vaidyanathan systems [13-37], Pehlivan system [38], Pham system [39], etc.

Coherent oscillations in biological systems are studied by Frohlich [40] and the following suggestions were made which are taken as a physical basis for theoretical investigation of enzymatic substrate reaction with ferroelectric behaviour in brain waves model [41].

1. When metabolic energy is available, long-wavelength electric vibrations are very strongly and coherently excited in active biological system.
2. Biological systems have metastable states with a very high electric polarization.

These long range interactions may lead to a selective transport of enzymes, and hence specific chemical reactions may become possible. Enjieu Kadji, Chabi Orou, Yamapi and Woafo (2007) derived enzymes-substrates reactions system with ferroelectric behaviour in brain waves [42]. Specifically, chaotic behaviour was noted for the 2-D enzyme-substrate reactions system. This paper discusses the chaotic properties of the enzyme-substrates reactions system, and MATLAB plots are shown for the phase portraits of the chaotic system.

Chaos and control theory have a manifold variety of applications in many fields of science and engineering such as oscillators [43], memristors [44-45], biology [46], chemical reactions [47-48], circuits [49-50], etc. Recently, there is significant result in the chaos literature in the synchronization of physical and chemical systems. A pair of systems called *master* and *slave* systems are considered for the synchronization process and the design goal is to device a feedback control mechanism so that the trajectories of the slave system asymptotically track the trajectories of the master system. Numerous effective methods have been designed for the synchronization of chaotic systems such as active control [51-60], adaptive control [61-74], sliding mode control [75-82], backstepping control [83-89], etc.

This paper also derives new results of adaptive backstepping controller design for the global chaos synchronization of enzymes-substrate systems, which are established using Lyapunov stability theory [90].

Enzymes-Substrates Reaction System

Enjieu Kadji, Chabi Orou, Yamapi and Woafo derived enzyme-substrate reactions system with ferroelectric behaviour in brain waves [29], which is given by the differential equation

$$\ddot{x} - \mu\left(1 - x^2 + ax^4 - bx^6\right)\dot{x} + x = E\cos(\omega t) \tag{1}$$

In (1), a, b are positive parameters, μ is the parameter of nonlinearity, while E and ω are the amplitude and the frequency of the external cosinusoidal excitation, respectively.

The enzymes-substrates reaction system (1) can be compactly put in system form as

$$\begin{cases} \dot{x} = y \\ \dot{y} = \mu\left(1 - x^2 + ax^4 - bx^6\right)y - x + E\cos(\omega t) \end{cases} \tag{2}$$

For the external excitation, we take the constants as

$$E = 8.27, \quad \omega = 3.465 \tag{3}$$

The biological system (2) is chaotic when the system parameters are chosen as

$$a = 2.55, \quad b = 1.70, \quad \mu = 2.001 \tag{4}$$

For numerical simulations, we take the initial conditions $x(0) = 0.1$ and $y(0) = 0.1$.

The 2-D phase portrait of the enzymes-substrates biological reaction system is depicted in Fig. 1.

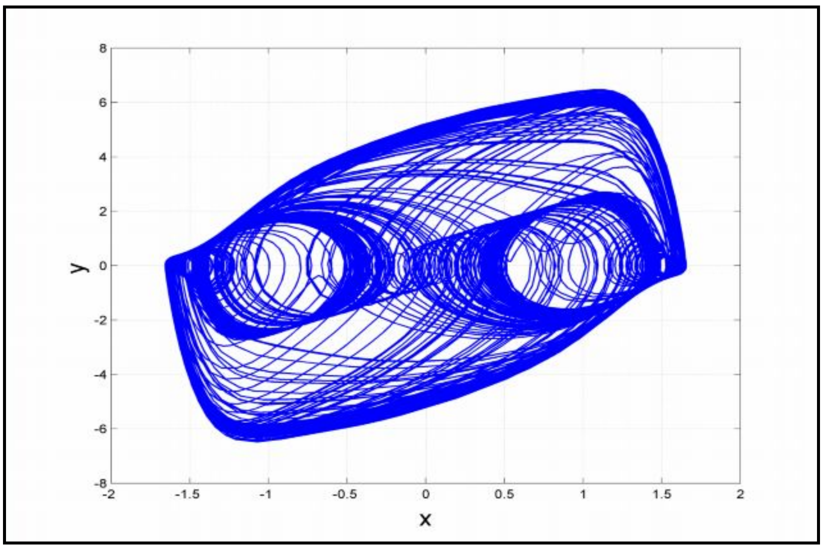

Figure 1. The 2-D phase portrait of the enzymes-substrates biological reaction system

Adaptive Chaos Synchronization of the Enzymes-Substrates Reaction Systems

In this section, we design an adaptive backstepping feedback control law for globally synchronizing the enzymes-substrates reaction system with uncertain parameters a and b. It is supposed that the constants E and ω associated with the external excitation $f(t) = E\cos(\omega t)$ are maintained at the constant values given in equation (3). It is also supposed that the nonlinear parameter μ is maintained at the constant value given in equation (4).

As the master system, we consider the controlled enzymes-substrates reaction system given by

$$\begin{cases} \dot{x}_1 = y_1 \\ \dot{y}_1 = \mu\left(1 - x_1^2 + a x_1^4 - b x_1^6\right) y_1 - x_1 + E\cos(\omega t) \end{cases} \tag{5}$$

As the slave system, we consider the controlled enzymes-substrates reaction system given by

$$\begin{cases} \dot{x}_2 = y_2 \\ \dot{y}_2 = \mu\left(1 - x_2^2 + a x_2^4 - b x_2^6\right) y_2 - x_2 + E\cos(\omega t) + u \end{cases} \tag{6}$$

Now, we define the complete synchronization errors as

$$\begin{cases} e_x = x_2 - x_1 \\ e_y = y_2 - y_1 \end{cases} \tag{7}$$

Then the error dynamics is obtained as

$$\begin{cases} \dot{e}_x = e_y \\ \dot{e}_y = \mu y_2\left(1 - x_2^2\right) - \mu y_1\left(1 - x_1^2\right) + a\mu\left(x_2^4 y_2 - x_1^4 y_1\right) - b\mu\left(x_2^6 y_2 - x_1^6 y_1\right) - e_x + u \end{cases} \tag{8}$$

Now, we define the parameter estimation errors as

$$\begin{cases} e_a = a - \hat{a}(t) \\ e_b = b - \hat{b}(t) \end{cases} \tag{9}$$

Differentiating (9) with respect to t, we get

$$\begin{cases} \dot{e}_a = -\dot{\hat{a}} \\ \dot{e}_b = -\dot{\hat{b}} \end{cases} \tag{10}$$

Theorem 1. The enzymes-substrates reaction systems (5) and (6) with uncertain system parameters a and b is globally and exponentially stabilized for all initial conditions by the adaptive control law

$$u = -e_x - 2e_y - \mu y_2\left(1 - x_2^2\right) + \mu y_1\left(1 - x_1^2\right) - \hat{a}(t)\mu\left(x_2^4 y_2 - x_1^4 y_1\right) + \hat{b}(t)\mu\left(x_2^6 y_2 - x_1^6 y_1\right) - k z_2 \tag{11}$$

where $k > 0$ is a gain constant,

$$z_2 = e_x + e_y, \tag{12}$$

and the update law for the parameter updates $\hat{a}(t), \hat{b}(t)$ is given by

$$\begin{cases} \dot{\hat{a}} = \mu z_2\left(x_2^4 y_2 - x_1^4 y_1\right) \\ \dot{\hat{b}} = -\mu z_2\left(x_2^6 y_2 - x_1^6 y_1\right) \end{cases} \tag{13}$$

Proof. We prove this result by applying backstepping control and Lyapunov stability theory.

First, we define a quadratic Lyapunov function

$$V_1(z_1) = \frac{1}{2} z_1^2, \tag{14}$$

where

$$z_1 = e_x \tag{15}$$

Differentiating V_1 along the dynamics (12), we get

$$\dot{V}_1 = z_1 \dot{z}_1 = -z_1^2 + z_1(e_x + e_y) \tag{16}$$

Now, we define

$$z_2 = e_x + e_y \tag{17}$$

Substituting (17) into (16), we obtain

$$\dot{V}_1 = -z_1^2 + z_1 z_2 \tag{18}$$

Next, we define a quadratic Lyapunov function

$$V_2(z_1, z_2, e_a, e_b) = V_1(z_1) + \frac{1}{2}e_a^2 + \frac{1}{2}e_b^2, \tag{19}$$

which is positive definite on R^4.

Differentiating (19) along the dynamics (8) and (10), we get

$$\dot{V}_2 = -z_1^2 - z_2^2 + z_2 S - e_a \dot{\hat{a}} - e_b \dot{\hat{b}} \tag{20}$$

where

$$S = z_1 + z_2 + \dot{z}_2 \tag{21}$$

A simple calculation gives

$$S = e_x + 2e_y + \mu y_2\left(1 - x_2^2\right) - \mu y_1\left(1 - x_1^2\right) + a\mu\left(x_2^4 y_2 - x_1^4 y_1\right) - b\mu\left(x_2^6 y_2 - x_1^6 y_1\right) + u \tag{22}$$

Substituting the feedback control law (11) into (22), we obtain

$$S = [a - \hat{a}(t)]\mu\left(x_2^4 y_2 - x_1^4 y_1\right) - \left[b - \hat{b}(t)\right]\mu\left(x_2^6 y_2 - x_1^6 y_1\right) - kz_2 \tag{23}$$

Using (9), the equation (23) can be simplified as

$$S = e_a \mu\left(x_2^4 y_2 - x_1^4 y_1\right) - e_b \mu\left(x_2^6 y_2 - x_1^6 y_1\right) - kz_2 \tag{24}$$

Substituting the value of S from (24) into (20), we get

$$\dot{V}_2 = -z_1^2 - (1+k)z_2^2 + e_a\left[\mu z_2\left(x_2^4 y_2 - x_1^4 y_1\right) - \dot{\hat{a}}\right] + e_b\left[-\mu z_2\left(x_2^6 y_2 - x_1^6 y_1\right) - \dot{\hat{b}}\right] \tag{25}$$

Substituting the parameter update law (13) into (25), we get

$$\dot{V}_2 = -z_1^2 - (1+k)z_2^2 \tag{26}$$

which is a negative semi-definite function on R^4.

By Barbalat's lemma in Lyapunov stability theory [90], it follows that the states $x(t), y(t)$ exponentially converge to zero as $t \to \infty$ for all initial conditions.

This completes the proof. ■

Numerical Simulations

We use classical fourth-order Runge-Kutta method in MATLAB with step-size $h = 10^{-8}$ for solving the systems of differential equations given by (5) and (10), when the backstepping control law (8) is applied.

We take the gain constant as $k = 20$. We take the initial conditions of the master system (5) as $x_1(0) = 0.4$ and $y_1(0) = 2.5$. We take the initial conditions of the slave system (6) as $x_2(0) = 3.1$ and $y_2(0) = 1.2$.

The parameter values are taken as in (3) and (4) for the chaotic case, viz.

$E = 8.27$, $\omega = 3.465$, $a = 2.55$, $b = 1.70$, $\mu = 2.001$

Also, we take $\hat{a}(0) = 1.8$ and $\hat{b}(0) = 2.4$.

Figs. 2-3 show the complete synchronization of the enzymes-substrates reaction systems (5) and (6). Fig. 4 shows the time-history of the chaos synchronization errors e_x, e_y. From Fig. 4, it is clear that the synchronization errors converge exponentially as time gets large.

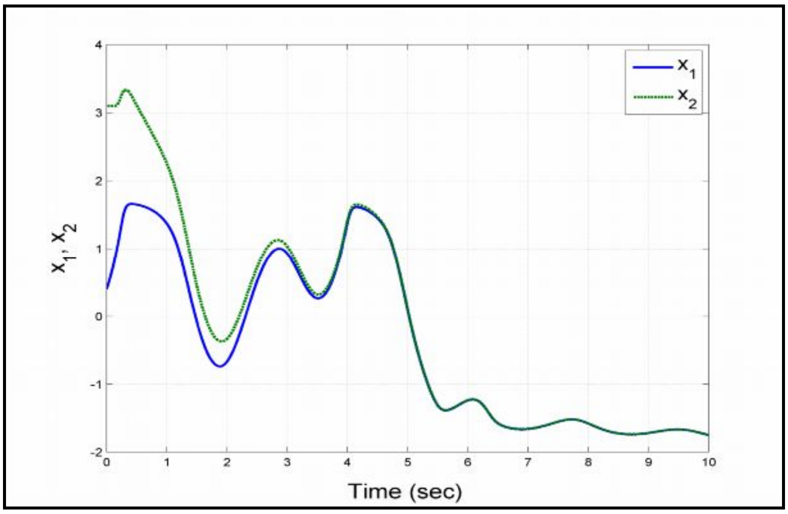

Figure 2. Complete synchronization of the states $x_1(t), x_2(t)$

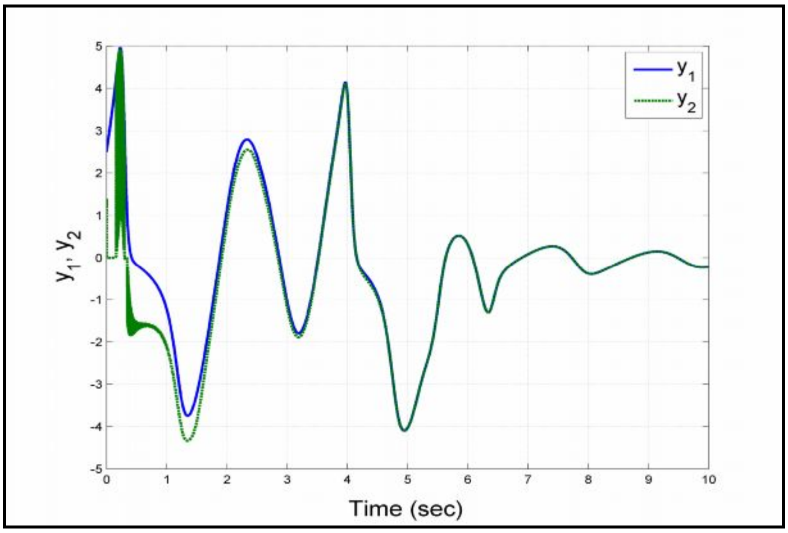

Figure 3. Complete synchronization of the states $y_1(t), y_2(t)$

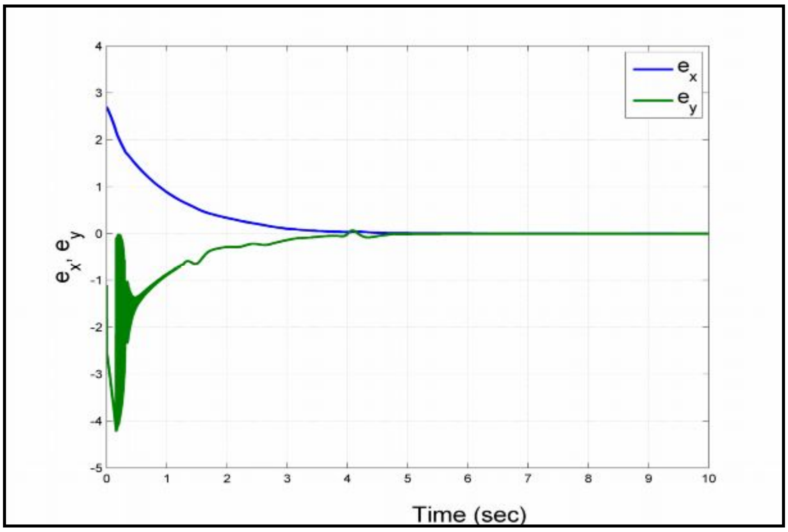

Figure 4. Time-history of the chaos synchronization errors $e_x(t), e_y(t)$

Conclusions

In this paper, new results have been derived for the enzymes-substrates reaction with ferroelectric behaviour in brain waves discovered by Enjieu Kadji, Chabi Orou, Yamapi and Woafo (2007). This paper presented adetailed description and dynamic analysis of the chaotic 2-D non-autonomous attractor describing the enzymes-substrates reaction system. Then this paper presented new results for the adaptive chaos synchronization of the identical enzymes-substrates reaction systems with uncertain parameters. The main results have been proved using backstepping control and Lyapunov stability theory. Also, numerical simulations using MATLAB were shown to elucidate the main results.

References

1. Azar, A. T., and Vaidyanathan, S., Chaos Modeling and Control Systems Design, Studies in Computational Intelligence, Vol. 581, Springer, New York, USA, 2015.
2. Azar, A. T., and Vaidyanathan, S., Computational Intelligence Applications in Modeling and Control, Studies in Computational Intelligence, Vol. 575, Springer, New York, USA, 2015.
3. Lorenz, E. N., Deterministic nonperiodic flow, Journal of the Atmospheric Sciences, 1963, 20, 130-141.
4. Rössler, O. E., An equation for continuous chaos, Physics Letters A, 1976, 57, 397-398.
5. Arneodo, A., Coullet, P., and Tresser, C., Possible new strange attractors with spiral structure, Communications in Mathematical Physics, 1981, 79, 573-579.
6. Sprott, J. C., Some simple chaotic flows, Physical Review E, 1994, 50, 647-650.
7. Chen, G., and Ueta, T., Yet another chaotic attractor, International Journal of Bifurcation and Chaos, 1999, 9, 1465-1466.
8. Lü, J., and Chen, G., A new chaotic attractor coined, International Journal of Bifurcation and Chaos, 2002, 12, 659-661.
9. Cai, G., and Tan, Z., Chaos synchronization of a new chaotic system via nonlinear control, Journal of Uncertain Systems, 2007, 1, 235-240.
10. Tigan, G., and Opris, D., Analysis of a 3D chaotic system, Chaos, Solitons and Fractals, 2008, 36, 1315-1319.
11. Sundarapandian, V., and Pehlivan, I., Analysis, control, synchronization and circuit design of a novel chaotic system, Mathematical and Computer Modelling, 2012, 55, 1904-1915.
12. Sundarapandian, V., Analysis and anti-synchronization of a novel chaotic system via active and adaptive controllers, Journal of Engineering Science and Technology Review, 2013, 6, 45-52.
13. Vaidyanathan, S., A new six-term 3-D chaotic system with an exponential nonlinearity, Far East Journal of Mathematical Sciences, 2013, 79, 135-143.
14. Vaidyanathan, S., Analysis and adaptive synchronization of two novel chaotic systems with hyperbolic sinusoidal and cosinusoidal nonlinearity and unknown parameters, Journal of Engineering Science and Technology Review, 2013, 6, 53-65.
15. Vaidyanathan, S., A new eight-term 3-D polynomial chaotic system with three quadratic nonlinearities, Far East Journal of Mathematical Sciences, 2014, 84, 219-226.
16. Vaidyanathan, S., Analysis, control and synchronisation of a six-term novel chaotic system with three quadratic nonlinearities, International Journal of Modelling, Identification and Control, 2014, 22, 41-53.
17. Vaidyanathan, S., and Madhavan, K., Analysis, adaptive control and synchronization of a seven-term novel 3-D chaotic system, International Journal of Control Theory and Applications, 2013, 6, 121-137.
18. Vaidyanathan, S., Analysis and adaptive synchronization of eight-term 3-D polynomial chaotic systems with three quadratic nonlinearities, European Physical Journal: Special Topics, 2014, 223, 1519-1529.
19. Vaidyanathan, S., Volos, C., Pham, V. T., Madhavan, K., and Idowu, B. A., Adaptive backstepping control, synchronization and circuit simulation of a 3-D novel jerk chaotic system with two hyperbolic sinusoidal nonlinearities, Archives of Control Sciences, 2014, 24, 257-285.
20. Vaidyanathan, S., Generalised projective synchronisation of novel 3-D chaotic systems with an exponential non-linearity via active and adaptive control, International Journal of Modelling, Identification and Control, 2014, 22, 207-217.
21. Vaidyanathan, S., and Azar, A.T., Analysis and control of a 4-D novel hyperchaotic system, Studies in

Computational Intelligence, 2015, 581, 3-17.

22. Vaidyanathan, S., Volos, C., Pham, V.T., and Madhavan, K., Analysis, adaptive control and synchronization of a novel 4-D hyperchaotic hyperjerk system and its SPICE implementation, Archives of Control Sciences, 2015, 25, 135-158.
23. Vaidyanathan, S., Volos, C., and Pham, V.T., Hyperchaos, adaptive control and synchronization of a novel 5-D hyperchaotic system with three positive Lyapunov exponents and its SPICE implementation, Archives of Control Sciences, 2014, 24, 409-446.
24. Vaidyanathan, S., A ten-term novel 4-D hyperchaotic system with three quadratic nonlinearities and its control, International Journal of Control Theory and Applications, 2013, 6, 97-109.
25. Vaidyanathan S., Qualitative analysis, adaptive control and synchronization of a seven-term novel 3-D chaotic system with a quartic nonlinearity, International Journal of Control Theory and Applications, 2014, 7, 1-20.
26. Vaidyanathan, S., Qualitative analysis and control of an eleven-term novel 4-D hyperchaotic system with two quadratic nonlinearities, International Journal of Control Theory and Applications, 2014, 7, 35-47.
27. Vaidyanathan, S., Analysis, properties and control of an eight-term 3-D chaotic system with an exponential nonlinearity, International Journal of Modelling, Identification and Control, 2015, 23, 164-172.
28. Vaidyanathan, S., Azar, A. T., Rajagopal, K., and Alexander, P., Design and SPICE implementation of a 12-term novel hyperchaotic system and its synchronisation via active control, International Journal of Modelling, Identification and Control, 2015, 23, 267-277.
29. 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, 380-392.
30. Vaidyanathan, S., Volos, C. K., and Pham, V.-T., Analysis, control, synchronization and SPICE implementation of a novel 4-D hyperchaotic Rikitake dynamo system without equilibrium, Journal of Engineering Science and Technology Review, 2015, 8, 232-244.
31. Vaidyanathan, S., A 3-D novel highly chaotic system with four quadratic nonlinearities, its adaptive control and anti-synchronization with unknown parameters, Journal of Engineering Science and Technology Review, 2015, 8, 106-115.
32. Vaidyanathan, S., Rajagopal, K., Volos, C. K., Kyprianidis, I. M., and Stouboulos, I. N., Analysis, adaptive control and synchronization of a seven-term novel 3-D chaotic system with three quadratic nonlinearities and its digital implementation in LabVIEW, Journal of Engineering Science and Technology Review, 2015, 8, 130-141.
33. Vaidyanathan, S., Volos, C. K., Rajagopal, K., Kyprianidis, I. M., and Stouboulos, I. N., Adaptive backstepping controller design for the anti-synchronization of identical WINDMI chaotic systems with unknown parameters and its SPICE implementation, Journal of Engineering Science and Technology Review, 2015, 8, 74-82.
34. Sampath, S., Vaidyanathan, S., Volos, C. K., and Pham, V.-T., An eight-term novel four-scroll chaotic system with cubic nonlinearity and its circuit simulation, Journal of Engineering Science and Technology Review, 2015, 8, 1-6.
35. Vaidyanathan, S., and Pakiriswamy, S., A 3-D novel conservative chaotic system and its generalized projective synchronization via adaptive control, Journal of Engineering Science and Technology Review, 2015, 8, 52-60.
36. Vaidyanathan, S., Volos, C. K., Kyprianidis, I. M., Stouboulos, I. N., and Pham, V.-T., Analysis, adaptive control and anti-synchronization of a six-term novel jerk chaotic system with two exponential nonlinearities and its circuit simulation, Journal of Engineering Science and Technology Review, 2015, 8, 24-36.
37. Vaidyanathan, S., Volos, C. K., and Pham, V.-T., Analysis, adaptive control and adaptive synchronization of a nine-term novel 3-D chaotic system with four quadratic nonlinearities and its circuit simulation, Journal of Engineering Science and Technology Review, 2015, 8, 174-184.
38. Pehlivan, I., Moroz, I. M., and Vaidyanathan, S., Analysis, synchronization and circuit design of a novel butterfly attractor, Journal of Sound and Vibration, 2014, 333, 5077-5096.
39. Pham, V. T., Volos, C., Jafari, S., Wang, X., and Vaidyanathan, S., Hidden hyperchaotic attractor in a novel simple memristic neural network, Optoelectronics and Advanced Materials–Rapid Communications, 2014, 8, 1157-1163.

40. Frohlich, H., Long range coherence and energy storage in biological systems, International Journal of Quantum Chemistry, 1968, 2, 641-649.
41. Kaiser, F., Coherent oscillations in biological systems, I. Bifurcation phenomena and phase transitions in an enzyme–substrate reaction with ferroelectric behavior, Z. Naturforsch A, 1978, 294, 304–333.
42. Enjieu Kadji, H.G., Chabi Orou, J.B., Yamapi, R., and Woafo, P., Nonlinear dynamics and strange attractors in the biological system, Chaos, Solitons and Fractals, 2007, 32, 862-882.
43. Shimizu, K., Sekikawa, M., and Inaba, N., Mixed-mode oscillations and chaos from a simple second-order oscillator under weak periodic perturbation, Physics Letters A, 2011, 375, 1566-1569.
44. Pham, V.-T., Volos, C. K., Vaidyanathan, S., Le, T. P., and Vu, V. Y., A memristor-based hyperchaotic system with hidden attractors: dynamics, synchronization and circuital emulating, Journal of Engineering Science and Technology Review, 2015, 8, 205-214.
45. Volos, C. K., Kyprianidis, I. M., Stouboulos, I. N., Tlelo-Cuautle, E., and Vaidyanathan, S., Memristor: A new concept in synchronization of coupled neuromorphic circuits, Journal of Engineering Science and Technology Review, 2015, 8, 157-173.
46. Vaidyanathan, S., Adaptive backstepping control of enzymes-substrates system with ferroelectric behaviour in brain waves, International Journal of PharmTech Research, 2015, 8, 256-261.
47. Vaidyanathan, S., Adaptive control of a chemical chaotic reactor, International Journal of PharmTech Research, 2015, 8, 377-382.
48. Vaidyanathan, S., Adaptive synchronization of chemical chaotic reactors, International Journal of ChemTech Research, 2015, 8, 612-621.
49. Volos, C. K., Pham, V.-T., Vaidyanathan, S., Kyprianidis, I. M., and Stouboulos, I. N., Synchronization phenomena in coupled Colpitts circuits, Journal of Engineering Science and Technology Review, 2015, 8, 142-151.
50. Elsonbaty, A., Elsaid, A., and Nour, H. M., Circuit realization, chaos synchronization and estimation of parameters of a hyperchaotic system with unknown parameters, Journal of the Egyptian Mathematical Society, 2014, 22, 550-557.
51. Vaidyanathan, S., and Rajagopal K., Anti-synchronization of Li and T chaotic systems by active nonlinear control, Communications in Computer and Information Science, 2011, 198, 175-184.
52. Vaidyanathan, S., and Rajagopal, K., Global chaos synchronization of hyperchaotic Pang and Wang systems by active nonlinear control, Communications in Computer and Information Science, 2011, 204, 84-93.
53. Sarasu, P., and Sundarapandian, V., Active controller design for generalized projective synchronization of four-scroll chaotic systems, International Journal of Systems Signal Control and Engineering Application, 2011, 4, 26-33.
54. Vaidyanathan, S., and Rasappan, S., Global chaos synchronization of hyperchaotic Bao and Xu systems by active nonlinear control, Communications in Computer and Information Science, 2011, 198, 10-17.
55. Vaidyanathan, S., and Rajagopal, K., Hybrid synchronization of hyperchaotic Wang-Chen and hyperchaotic Lorenz systems by active non-linear control, International Journal of Systems Signal Control and Engineering Applications, 2011, 4, 55-61.
56. Vaidyanathan, S., Hybrid chaos synchronization of Liu and Lü systems by active nonlinear control, Communications in Computer and Information Science, 2011, 204, 1-10.
57. Sarasu, P., and Sundarapandian, V., The generalized projective synchronization of hyperchaotic Lorenz and hyperchaotic Qi systems via active control, International Journal of Soft Computing, 2011, 6, 216-223.
58. Vaidyanathan, S., and Pakiriswamy, S., The design of active feedback controllers for the generalized projective synchronization of hyperchaotic Qi and hyperchaotic Lorenz systems, Communications in Computer and Information Science, 2011, 245, 231-238.
59. Sundarapandian, V., and Karthikeyan, R., Hybrid synchronization of hyperchaotic Lorenz and hyperchaotic Chen systems via active control, Journal of Engineering and Applied Sciences, 2012, 7, 254-264.
60. Karthikeyan, R., and Sundarapandian, V., Hybrid chaos synchronization of four-scroll systems via active control, Journal of Electrical Engineering, 2014, 65, 97-103.
61. Vaidyanathan, S., and Rajagopal, K., Global chaos synchronization of Lü and Pan systems by adaptive nonlinear control, Communications in Computer and Information Science, 2011, 205, 193-202.
62. Sundarapandian, V., and Karthikeyan, R., Anti-synchronization of hyperchaotic Lorenz and

hyperchaotic Chen systems by adaptive control, International Journal of Systems Signal Control and Engineering Application, 2011, 4, 18-25.
63. Sundarapandian, V., and Karthikeyan, R., Anti-synchronization of Lu and Pan chaotic systems by adaptive nonlinear control, International Journal of Soft Computing, 2011, 6, 111-118.
64. Sundarapandian, V., and Karthikeyan, R., Adaptive anti-synchronization of uncertain Tigan and Li systems, Journal of Engineering and Applied Sciences, 2012, 7, 45-52.
65. Sarasu, P., and Sundarapandian, V., Generalized projective synchronization of three-scroll chaotic systems via adaptive control, European Journal of Scientific Research, 2012, 72, 504-522.
66. Vaidyanathan, S., and Rajagopal, K., Global chaos synchronization of hyperchaotic Pang and hyperchaotic Wang systems via adaptive control, International Journal of Soft Computing, 2012, 7, 28-37.
67. Sarasu, P., and Sundarapandian, V., Generalized projective synchronization of two-scroll systems via adaptive control, International Journal of Soft Computing, 2012, 7, 146-156.
68. Sarasu, P., and Sundarapandian, V., Adaptive controller design for the generalized projective synchronization of 4-scroll systems, International Journal of Systems Signal Control and Engineering Application, 2012, 5, 21-30.
69. Vaidyanathan, S., Anti-synchronization of Sprott-L and Sprott-M chaotic systems via adaptive control, International Journal of Control Theory and Applications, 2012, 5, 41-59.
70. Vaidyanathan, S., Analysis, control and synchronization of hyperchaotic Zhou system via adaptive control, Advances in Intelligent Systems and Computing, 2013, 177, 1-10.
71. 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.
72. Sundarapandian, V., Adaptive control and synchronization design for the Lu-Xiao chaotic system, Lecture Notes in Electrical Engineering, 2013, 131, 319-327.
73. Pham, V.T., Volos, C., Jafari, S., Wang, X., and Vaidyanathan, S., Hidden hyperchaotic attractor in a novel simple memristive neural network, Optoelectronics and Advanced Materials: Rapid Communications, 2014, 8, 1157-1163.
74. Pham, V.T, Volos, C.K., and Vaidyanathan, S., Multi-scroll chaotic oscillator based on a first-order delay differential equation, Studies in Computational Intelligence, 2015, 581, 59-72.
75. Vaidyanathan, S., and Sampath, S., Global chaos synchronization of hyperchaotic Lorenz systems by sliding mode control, Communications in Computer and Information Science, 2011, 205, 156-164.
76. Sundarapandian, V., and Sivaperumal, S., Sliding controller design of hybrid synchronization of four-wing chaotic systems, International Journal of Soft Computing, 2011, 6, 224-231.
77. Vaidyanathan, S., and Sampath, S., Anti-synchronization of four-wing chaotic systems via sliding mode control, International Journal of Automation and Computing, 2012, 9, 274-279.
78. Vaidyanathan, S., Global chaos control of hyperchaotic Liu system via sliding control method, International Journal of Control Theory and Applications, 2012, 5, 117-123.
79. Vaidyanathan, S., Sliding mode control based global chaos control of Liu-Liu-Liu-Su chaotic system, International Journal of Control Theory and Applications, 2012, 5, 15-20.
80. Vaidyanathan, S., Global chaos synchronization of identical Li-Wu chaotic systems via sliding mode control, International Journal of Modelling, Identification and Control, 2014, 22, 170-177.
81. Vaidyanathan, S., and Azar, A.T., Anti-synchronization of identical chaotic systems using sliding mode control and an application to Vaidyanathan-Madhavan chaotic systems, Studies in Computational Intelligence, 2015, 576, 527-547.
82. Vaidyanathan, S., and Azar, A.T., Hybrid synchronization of identical chaotic systems using sliding mode control and an application to Vaidyanathan chaotic systems, Studies in Computational Intelligence, 2015, 576, 549-569.
83. Rasappan, S., and Vaidyanathan, S., Hybrid synchronization of n-scroll Chua and Lur'e chaotic systems via backstepping control with novel feedback, Archives of Control Sciences, 2012, 22, 343-365.
84. Suresh, R., and Sundarapandian, V., Global chaos synchronization of a family of n-scroll hyperchaotic Chua circuits using backstepping control with a recursive feedback, Far East Journal of Mathematical Sciences, 2013, 73, 73-95.
85. Vaidyanathan, S., Global chaos synchronization of Arneodo chaotic system via backstepping controller design, ACM International Conference Proceeding Series, 2012, 1-6.

86. Rasappan, S., and Vaidyanathan, S., Hybrid synchronization of n-scroll chaotic Chua circuits using adaptive backstepping control design with recursive feedback, Malaysian Journal of Mathematical Sciences, 2013, 7, 219-246.
87. Rasappan, S., and Vaidyanathan, S., Global chaos synchronization of WINDMI and Coullet chaotic systems using adaptive backstepping control design, Kyungpook Mathematical journal, 2014, 54, 293-320.
88. Vaidyanathan, S., and Rasappan, S., Global chaos synchronization of n-scroll Chua circuit and Lur'e system using backstepping control design with recursive feedback, Arabian Journal for Science and Engineering, 2014, 39, 3351-3364.
89. Vaidyanathan, S., Idowu, B.A., and Azar, A.T., Backstepping controller design for the global chaos synchronization of Sprott's jerk systems, Studies in Computational Intelligence, 2015, 581, 39-58.
90. Khalil, H.K., Nonlinear Systems, Prentice Hall, New Jersey, USA, 2001.

*****