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A Novel Chaos Application to Observe Performance of Asynchronous Machine Under Chaotic Load

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ABSTRACT In this study, a novel 4D chaos model is introduced to improve an existing chaotic system. Equations of the chaos model have been written. The dynamical analyses of the system have been executed by means of phase portraits, equilibrium points, eigenvalues, compound structure, and initial conditions. MATLAB/Simulink model has been designed to analyze load which is driven by an induction machine against chaos. Finally, the states of induction machine that is with and without chaotic load is compared.

KEYWORDS
Chaos theory,
Dynamical analysis,
Sensitivity,
Asynchronous machines,
Load performance.

INTRODUCTION

In the universe, most of systems do not linearly. Thus, we always need chaotic systems. Improving existing chaos systems is so important to introducing new models of chaos. In the literature, many chaos studies have been presented since Lorenz first introduced chaos (Lorenz 1963) . Lorenz improved notable parameters of chaos. Lorenz's chaos arises in science studies such as dynamos, chemical events and electric circuits (Knobloch 1981; Poland 1993; Cuomo and Oppenheim 1993). Chua used a simple circuit with a nonlinear resistor to show chaos (Kennedy 1993). Introducing new chaotic systems and analyzing them are executed in many studies such as (Sundarapandian and Pehlivan 2012; Vaidyanathan 2014, 2015; Wang *et al.* 2017b; Li *et al.* 2013; Wang *et al.* 2019; Liu 2009; Lü *et al.* 2004; Dadras and Momeni 2009). In recent studies, Wang *et al.* (2017a) presented an circuit implementation of chaos and showed sensitivity. In this study, a novel chaotic system is proposed by adding a new state variable to (Wang *et al.* 2017a) chaotic attractor.

Chaos studies on the specific fields of electricity and electrical machines also available in the literature. Singh and Sharma (2012) have realized sliding mode control on machines with chaotic system, relevant studies such as, electric power systems (Chiang *et al.* 1994), electric fields (Che *et al.* 2009; Wang *et al.* 2007), synchronization and load (Ge and Wu 2004), high power loads in transmission lines (O'Neill-Carrillo *et al.* 1999), chaotification on induction motors (Gao 2003), chaos control in the induction motor (Messadi and Mellit 2017; Ozer and Akin 2008).

This study presents the dynamical properties of the proposed chaos system in Section 2. The main purpose of this study is presented in Section 3.

Asynchronous motors are basically used to produce mechanical energy on loads. In this study, the circuit diagram and control structure were placed on the asynchronous machine. The load connected to the asynchronous motor is the chaotic load. It has been considered as chaotic loaded operation of the asynchronous motor. The performance and sensitivities of the asynchronous motor under the chaotic load were analyzed.

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PROPERTIES AND DYNAMICAL ANALYSES OF NOVEL CHAOS SYSTEM

The new chaos system is described by the following differential equations in Eq. 1:

$$
\begin{aligned}
\dot{x} &= y + yz \\
\dot{y} &= z \\
\dot{z} &= k_1 y^3 - xz - yz - k_2 \\
\dot{w} &= yz
\end{aligned} \tag{1}
$$

In Eq. 1, x, y, z and w are state variables and k_i $(i = 1,2)$ are constant parameters that can be improved. The system has eight terms and two parameters. The variables of proposed parameters are taken as $k_1 = 0.49$ and $k_2 = 50$. The initial conditions of system are taken as $x(0) = 0.3$, $y(0) = 0.3, z(0) = 3$ and $w(0)) = 0.3$. Novel chaos system can be described using proposed parameters by Eq. 2:

$$
\begin{aligned}
\dot{x} &= y + yz \\
\dot{y} &= z \\
\dot{z} &= 0.49y^3 - xz - yz - 50 \\
\dot{w} &= yz
\end{aligned} \tag{2}
$$

Phase portraits

The phase portraits of dynamical system were realized in MATLAB/Simulink. Ode45 method and 10^{-15} relative tolerance value are selected. Phase portraits were shown in Figure 1. The initial conditions are set as $(x(0), y(0), z(0), w(0)) = (0.3, 0.3, 3, 0.3)$

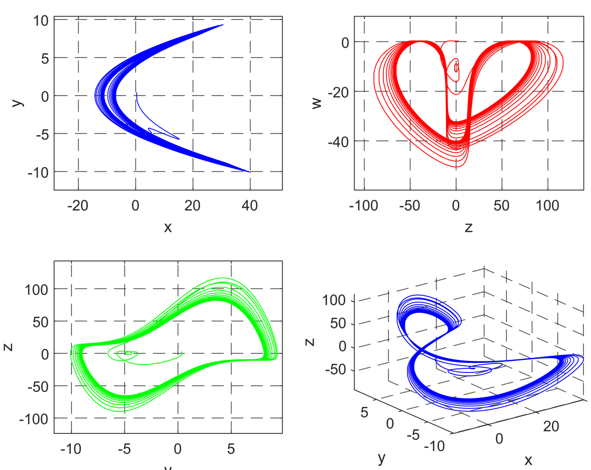

Figure 1 Phase portraits of the system (the x-y, z-w, y-z, and x-y-z)

System equilibria

Equilibrium points are a constant solution for a dynamical system that is transformed into a differentiation system. For this purpose, the differential equations are equalized to 0 as follows:

$$
\begin{aligned}
0 &= y + yz \\
0 &= z \\
0 &= 0.49y^3 - xz - yz - 50 \\
0 &= yz
\end{aligned} \tag{3}
$$

When the equation system is solved for x, y, z, w, $k_1 = 0.49$ and $k_2 = 50$, it is found that system has no equilibrium points.

The eigenvalues should be obtained to determine whether these equilibrium points are stable or unstable. The fact that at least two real values of the real part are positive indicates that chaos and the equilibrium point are unstable. The Jacobian matrix should be obtained to show eigenvalues.

$$
J = \begin{bmatrix} 0 & 1+z & y & 0 \\ 0 & 0 & 1 & 0 \\ -z & 1.47y^2 - z & -x-y & 0 \\ 0 & z & y & 0 \end{bmatrix} \tag{4}
$$

For finding eigenvalues, Equation 5 should be solved. In this equation, I is the unit matrix, and J is the Jacobian matrix.

$$
|\lambda I - J| = \begin{vmatrix} \lambda & -1-z & -y & 0 \\ 0 & \lambda & -1 & 0 \\ z & z - 1.47y^2 & \lambda + x + y & 0 \\ 0 & -z & -y & \lambda \end{vmatrix} = 0 \tag{5}
$$

After relevant determinant was found in MATLAB, the characteristic equation is obtained as follows:

$$
\lambda(\lambda^3 + (x+y)\lambda^2 + (-1.47y^2 + yz + z)\lambda + z^2 + z) = 0
$$

As it can be seen from the characteristic equation, one of the eigenvalues of the system is $\lambda = 0$. The Lyapunov exponents of the system are found as $\lambda_{L1} = 0.0263, \lambda_{L2} = 0, \lambda_{L3} = -0.0164, \lambda_{L4} = -1.686$ and they are depicted in Fig. 2. Lyapunov dimension of the proposed system is obtained in Eq. 6.

$$D_L = j + \frac{1}{|\lambda L_{j+1}|}\sum_{i=1}^{j}\lambda_{Li} = 2 + \frac{(\lambda_{L_1}+\lambda_{L_2})}{|\lambda_{L_3}|} = 3.60365 \quad (6)$$

Since $\lambda_{L_1} > 0$ and the Lyapunov dimension is fractal ($D_L = 3.60365$), the corresponding system exhibits chaotic behaviour.

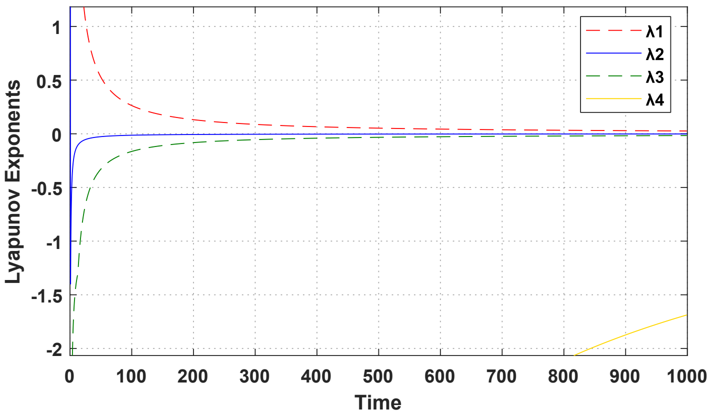

Figure 2 Lyapunov exponents of the system

Sensitivity to initial conditions

For systems which heavily depends on the initial conditions, even a small change in the initial conditions will lead to different chaotic behaviours. To show this property, difference between separate initial conditions should be chosen small enough. By using the ode45 function for x1(0) = 0 and x2(0) = 0.01, the time series were obtained as Fig. 3. It shows that trajectories of chaos system are not very sensitive to initial conditions.

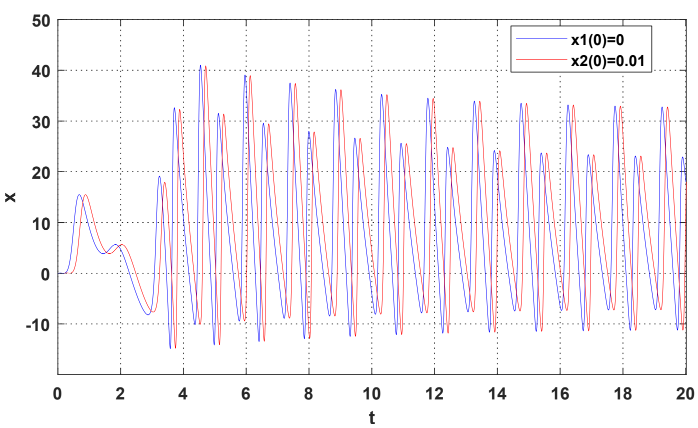

Figure 3 Time series for x1(0) = 0 and x2(0) = 0.01

Compound structure method

It is added that control parameter named as "u" to (y') in Eq. 2 for analyzing dynamical system. Control parameter "u" is a constant to observe unique dynamic behaviors of the system (Lü *et al.* 2002). The variation between the phase portraits can be seen in Figs. 1, 4, and 5. Obtained results show that for $5 \leq |u| \leq 20$, the chaos system has limit cycles. For $|u| \geq 100$, the chaos system has partial attractor that is bounded.

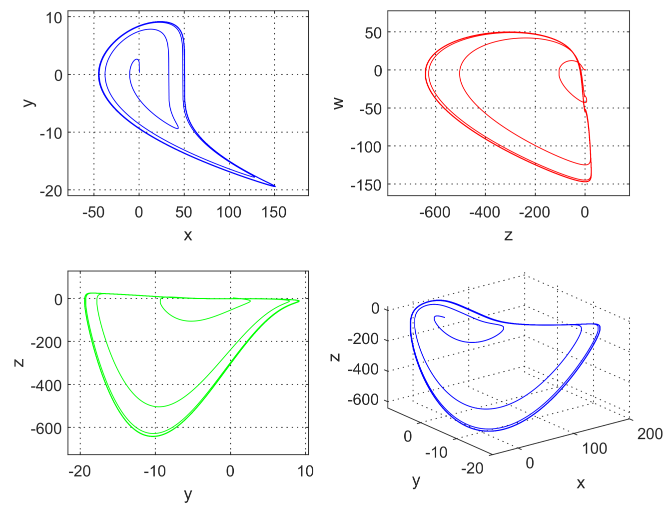

Figure 4 For u=12, the phase portraits of the system (the x-y, z-w, y-z, and x-y-z)

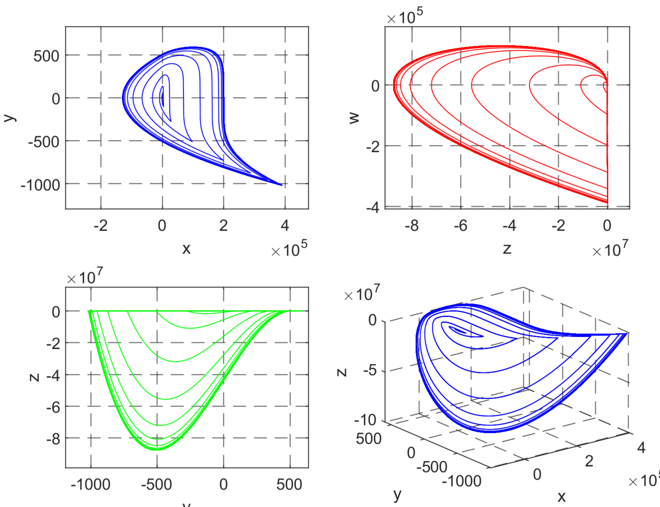

Figure 5 For u=1000, the phase portraits of the system (the x-y, z-w, y-z, and x-y-z)

DESIGNING CIRCUIT FOR USING CHAOS AS A LOAD

The control circuit of chaos was simulated in MATLAB/Simulink. The one of the compound structures of chaos system ($u = -50$) is taken for more chaotic load performance. In this study, high power asynchronous machine has been selected to show chaos effects. Its features can be seen in Table 1. Asynchronous machine has been loaded by chaos system. Whole performance analyses have been executed by rotor currents, stator currents, rotor angle, electromagnetic torque and rotor speed.

Table 1 Features of selected induction machine

Power	75 kW
Voltage	400 V
Frequence	50 Hz
Speed	1484 RPM

Simulink Results

The proposed system in Fig. 6 was performed in MATLAB/Simulink. By using nonadaptive algorithm, 10^{-15} tolerance value, and 5.10^{-6} time step, the system is solved for 10 seconds. It is aimed to observe chaos effects efficiently. For this purpose, results for without chaotic load are presented in Fig. 7, too. By comparing Fig. 7 and 8, the effects of chaotic load on the high power induction machine can be seen clearly.

According to the results obtained, in case of chaotic load, the rotor currents of the electric machine showed chaotic behavior at specific times. The currents are shown as 3 phases. The balances of the phases in the currents are disturbed. Each phase is affected separately. Asynchronous motor has returned to normal conditions after specific time intervals. Stator currents have increased and decreased over a certain period of time. Rotor angle is only slightly affected by the chaotic load. Rotor speed has shown short-lived and small amplitude chaotic oscillations. Electromagnetic torque is much more affected than rotor speed by the chaotic load. The amplitude of chaotic oscillations in electromagnetic torque is large enough to allow the electrical machine to collapse.

The effects of chaos on the asynchronous machine can be seen in the Table 2. The peak value of the effects of chaos is taken in the Table 2. As the chaotic load was changed, asynchronous machine sensitivities were observed to change. But the sensitivities and waveforms are similar.

Table 2 Variations between asynchronous machines

Parameter	Time	Normal Value	Chaos Value
Rotor Currents	9.276 s	-0.658 A 1.979 A -1.32 A	-218.9 A 1479 A -1260 A
Stator Currents	7.587 s	41.48 A -66.71 A 25.23 A	1526 A -641.4 A -884.2 A
Rotor Angle	5.563 s	844 rad	845.5 rad
Electromagnetic Torque	5.916 s	6.147 Nm	3028 Nm
Rotor Speed	4.306 s	157.1 wm	181 wm

Chaotic Loaded Working Results

Asynchronous motors or induction motors are AC electric motors, and they are widely used in many industrial fields to provide mechanical energy. The adjusted variable speed and frequency settings of asynchronous motors are realized by the drivers. Asynchronous motors are generally studied as they drive constant and variable loads (Kay *et al.* 2000). The corresponding loads are shown in Fig. 9. The variable loads can be linear or nonlinear. Control applications have been executed for linear and nonlinear loads such as fans (Yildirim and Bilgic 2008), conveyors (Kovalchuk and Baburin 2018), lifts (Cernys *et al.* 2003) on the asynchronous machine.

Unlike these cases, chaotic states have been recently discovered. In this study, it drives a chaotic load. Chaos is considered to be a very specific condition that occurs in load. It can be seen in Fig. 10. This study presented a novel load type that is mentioned as "Chaotic Load" for electrical machines. Asynchronous motor characteristics have been investigated under the chaotic loads. The asynchronous machine is affected by the state of the chaotic oscillator. Amongst chaotic oscillators, increasing the control parameter (u) caused the increase of the duration and effect of the instantaneous currents.

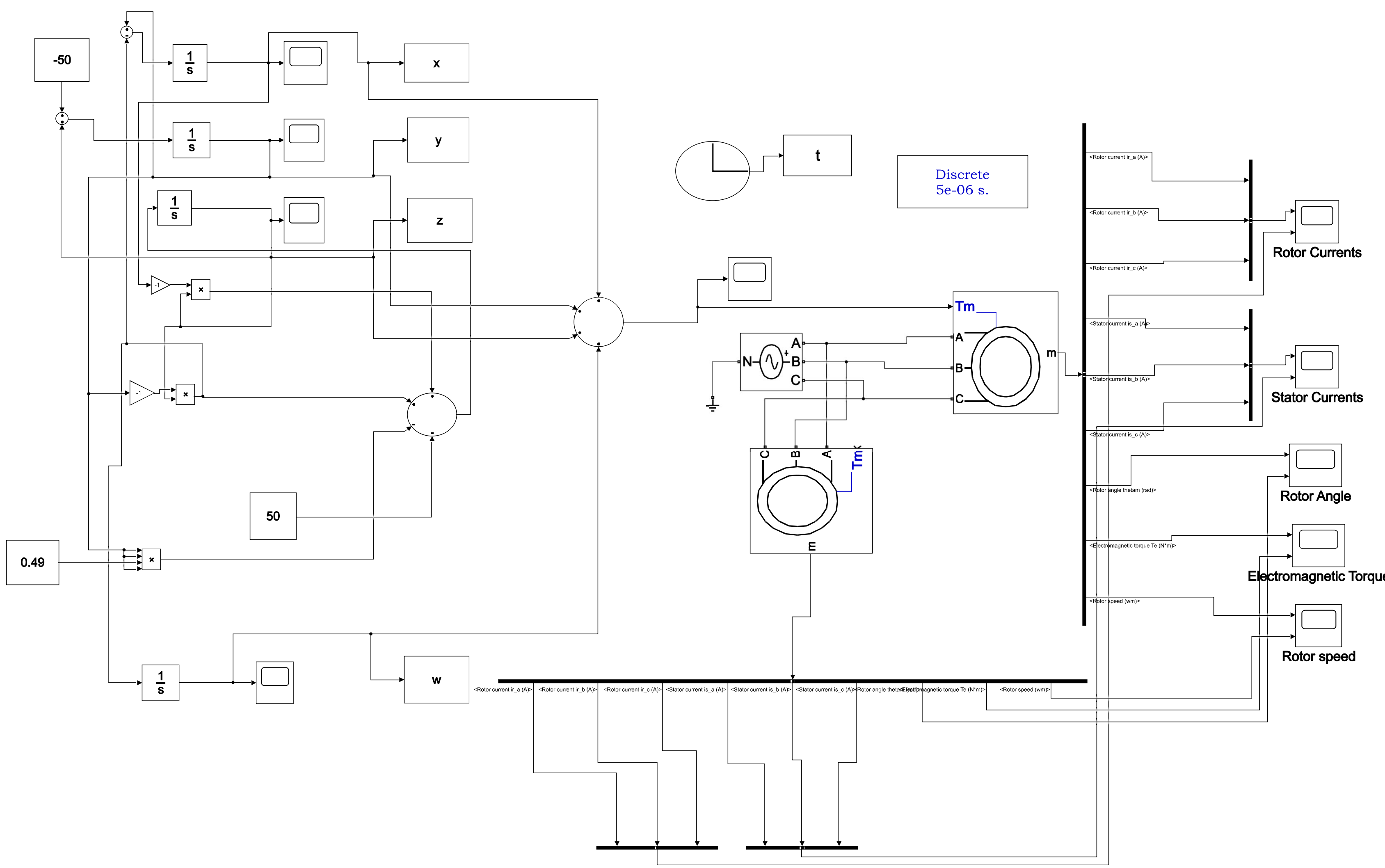

Figure 6 Proposed system for analyzing induction machine performance against chaos

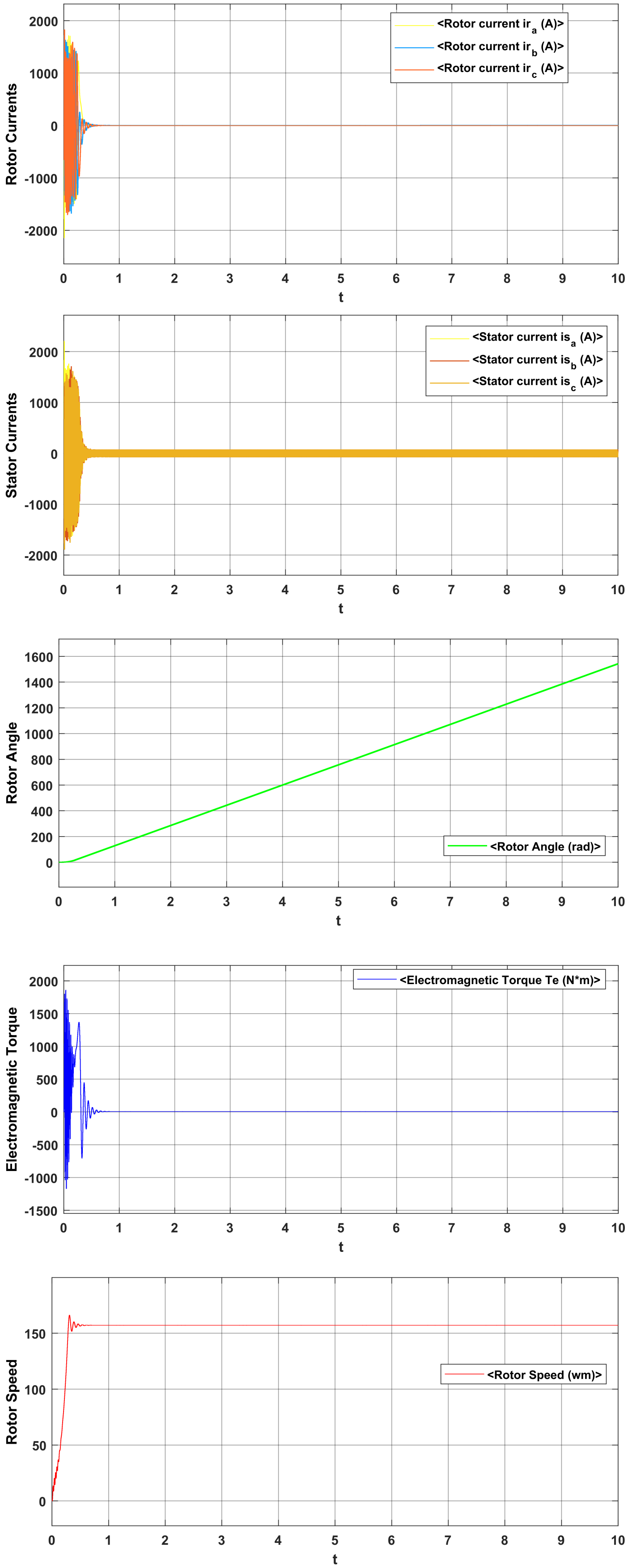

Figure 7 Asynchronous motor performance without the chaotic load

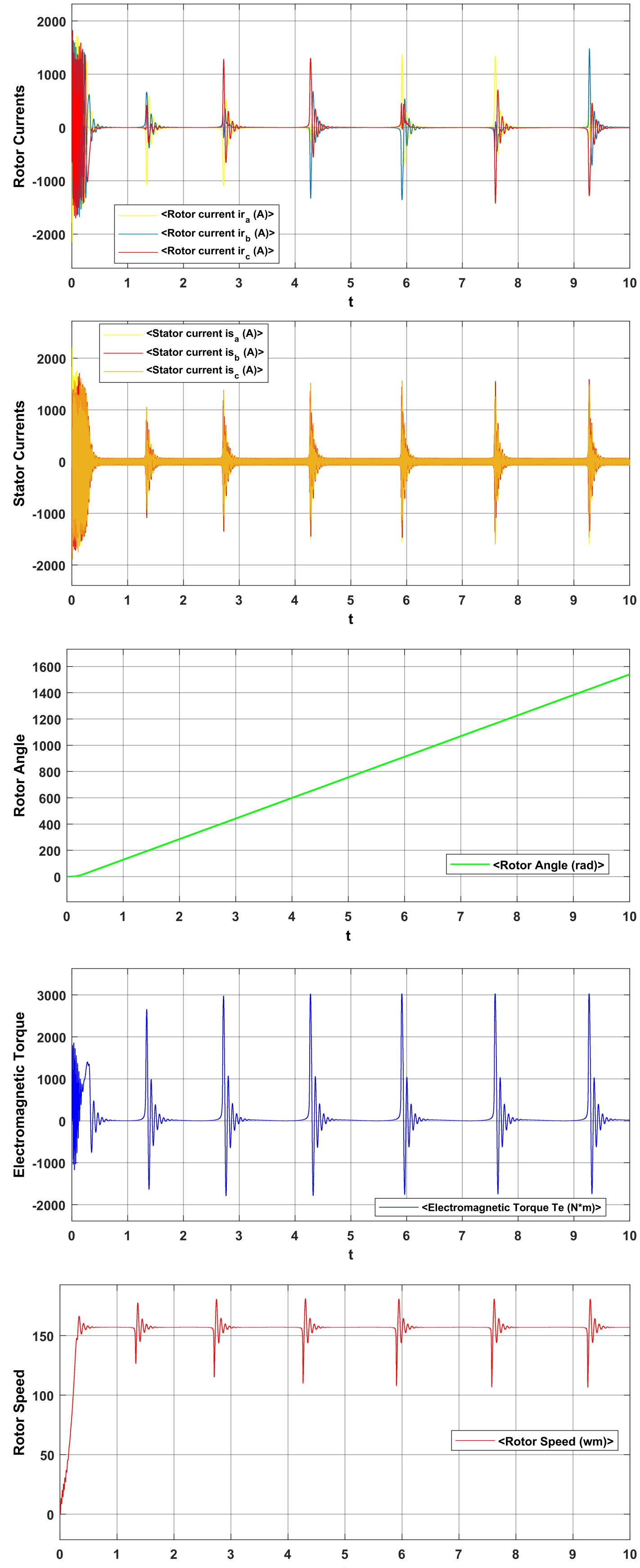

Figure 8 Asynchronous motor performance with the chaotic load

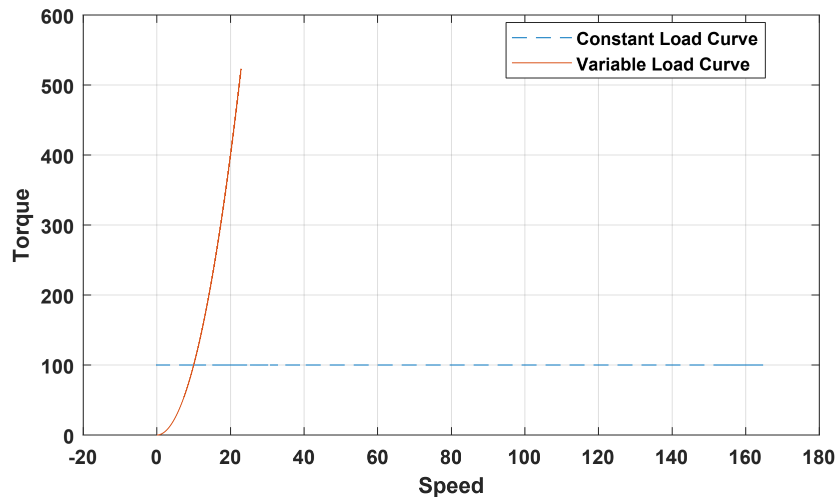

Figure 9 Illustration of the existing loads

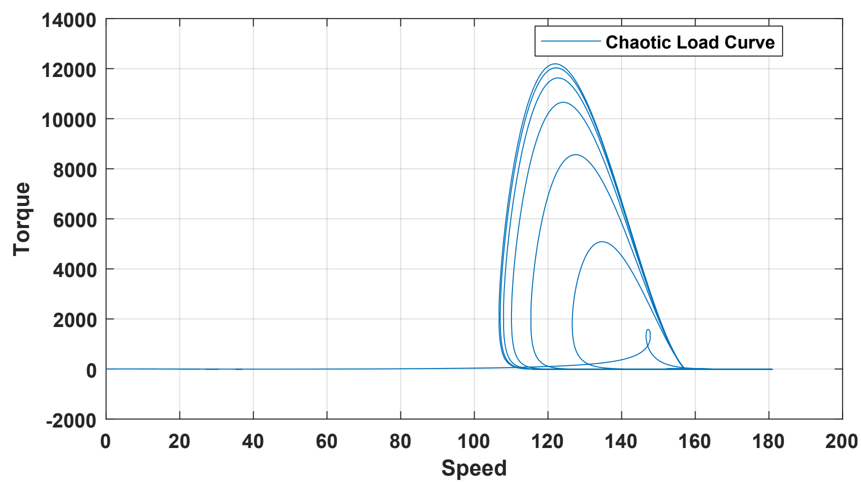

Figure 10 Illustration of the proposed chaotic load

CONCLUSION

In this paper, a novel 4D chaotic system has been obtained from an existing chaotic system. The corresponding dynamic analyses such as phase portraits and system equilibrium have been presented. The compound structure method was applied to determine various dynamic behaviors of the chaotic system. Sensitivity to initial conditions of the system was investigated. Simulink circuit implementation of the chaotic system has been designed with an electrical machine in MATLAB. Thus, the effects of chaos on loads and the performances of electrical machines in chaotic states have been commented.

Conflicts of interest

The author declares that there is no conflict of interest regarding the publication.

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