

FRACTIONAL-ORDER HYPERCHAOTIC MULTI-SWITCHING SYNCHRONIZATION FOR SECURE SIGNAL TRANSMISSIONS IN RENEWABLE ENERGY MICROGRIDS

¹Makarios A. Emmanuel, ²Adamu Z. Ngari, ²Oyono S. Job, ²Jamilu A. Zarma, ³Jamilu M. Garba, ¹Yakubu H. Ngadda, ⁴Olasunkanmi I. Olusola

¹Department of Physics, University of Maiduguri, Maiduguri, Nigeria

²Department of Physics, Nigerian Army University, Biu, Borno State, Nigeria

³Department of Science Laboratory Technology, Nigerian Building and Road Research Institute, Kano Zonal Office, Nigeria

⁴Department of Physics, Lagos State University, Nigeria

*Corresponding Author Email Address: adamuzngari886@gmail.com

ABSTRACT

Renewable energy microgrids have emerged as key platforms for decentralised electricity generation, intelligent energy management, and sustainable power delivery. However, integrating solar photovoltaic systems, wind energy conversion systems, battery energy storage, power electronic converters, sensors, and communication networks introduces highly nonlinear dynamics, intermittent power fluctuations, communication uncertainties, and cyber-physical security vulnerabilities. These challenges intensify when communication channels transmit sensitive monitoring, protection, and control signals and are exposed to disturbances and malicious attacks. This paper proposes a fractional-order hyperchaotic multi-switching synchronization framework for secure signal transmission in renewable energy microgrids. The proposed approach integrates fractional-order calculus, hyperchaotic dynamics, nonlinear control, multi-switching synchronization, Lyapunov stability theory, renewable microgrid disturbance modelling, and hyperchaotic signal masking to enhance communication security and system reliability. We formulate three fractional-order hyperchaotic drive systems and one controlled response system to represent secure communication dynamics. We construct a novel multi-switching synchronization error structure to synchronise the response states with selected combinations of the drive-system states. We systematically derive nonlinear control laws and incorporate them into the error dynamics to guarantee asymptotic convergence of the synchronization errors. We rigorously establish the stability of the resulting closed-loop system using Lyapunov stability theory. MATLAB simulations validate the effectiveness of the proposed framework through state-variable responses, synchronization error convergence, Lyapunov function convergence, approximate Lyapunov exponent analysis, phase portraits, drive-response synchronization comparisons, renewable microgrid power fluctuation, encrypted hyperchaotic signal behaviour, and original-recovered signal reconstruction. The simulation results demonstrate robust synchronization performance, effective nonlinear signal masking, enhanced communication security, and reliable secure signal transmission for renewable energy microgrid networks.

Keywords: Fractional-order systems; hyperchaotic synchronization; multi-switching synchronization; renewable energy microgrids; secure signal transmission; nonlinear control; Lyapunov stability; solar-wind systems.

INTRODUCTION

The global transition from conventional fossil-fuel-based power generation to renewable energy systems has increased the importance of microgrid technologies. Renewable energy microgrids integrate distributed energy resources such as solar photovoltaic arrays, wind turbines, battery energy storage systems, intelligent controllers, and local loads into flexible power networks. These systems can improve energy access, reduce carbon emissions, support decentralised generation, and increase energy resilience. However, renewable microgrids also face intermittency, nonlinear converter dynamics, low inertia, uncertain load variation, and communication-dependent operation (Ackermann, 2012; Kundur, 1994; Ojo et al., 2025).

Modern microgrids require reliable communication infrastructures for real-time monitoring, supervisory control, energy management, protection coordination, and distributed decision-making. As microgrids become increasingly digital and networked, they become vulnerable to cyberattacks, false data injection, signal interception, communication delay, replay attacks, and unauthorised manipulation of control signals. These threats may affect voltage stability, frequency regulation, power sharing, and overall operational security (Aghmadi et al., 2023; Ayele et al., 2024).

Chaos and hyperchaos provide useful mechanisms for secure communication because of their sensitivity to initial conditions, nonlinear complexity, broadband-like behaviour, and apparent randomness. Pioneering work by Pecora and Carroll (1990) established the possibility of synchronizing chaotic systems and opened a major research direction in chaos-based communication. Hyperchaotic systems extend ordinary chaotic systems by having more than one positive Lyapunov exponent, increasing dynamic complexity and improving signal-masking strength.

Fractional-order calculus offers an additional modelling advantage because it captures memory and hereditary characteristics in physical systems. Unlike integer-order models, fractional-order systems describe dynamics whose current behaviour depends partly on past states. This is important for renewable energy systems, where storage, power conversion, environmental variation, and control responses may exhibit memory-dependent behaviour. Podlubny (1999) provides a well-established mathematical basis for fractional differential

equations.

Although microgrid control has been widely studied, many conventional control and communication schemes do not adequately address the combined effects of nonlinear renewable disturbances, fractional-order memory, cyber vulnerability, and synchronization-based secure signal transmission. Hierarchical microgrid control strategies provide an important foundation for power sharing and system regulation (Guerrero et al., 2011), but cyber-resilient renewable microgrid networks also require additional secure communication mechanisms.

This study therefore develops a nonlinear fractional-order hyperchaotic multi-switching synchronization framework for secure signal transmission in renewable energy microgrids. The framework integrates fractional-order hyperchaotic drive systems, a response system, nonlinear controllers, Lyapunov stability analysis, renewable microgrid disturbance modelling, and secure signal masking. This research highlights that renewable energy microgrids depend on communication networks for real-time data exchange, control coordination, and monitoring. However, these communication channels may be exposed to signal interception, data manipulation, and cyberattacks. Conventional encryption and control methods may become inadequate when nonlinear renewable fluctuations, parameter uncertainty, variable load demand, and converter-induced dynamics affect the microgrid. Existing synchronization-based secure communication schemes often focus on ordinary chaotic systems, single drive-response structures, or integer-order models. Few integrate fractional-order modelling, hyperchaotic dynamics, nonlinear control, multi-switching synchronization, renewable microgrid disturbances, and secure signal recovery into a single framework. This creates a research gap in designing robust and secure signal transmission methods for renewable energy microgrid communication networks. This study's novelty lies in integrating fractional-order hyperchaotic multi-switching synchronization with secure signal transmission in renewable energy microgrids. The proposed framework differs from conventional synchronization structures by combining multiple drive systems, a multi-switching error configuration, nonlinear controllers, fractional-order memory effects, renewable microgrid operating conditions, and synchronization-based signal masking within a unified framework.

The major contributions are (a) development of a fractional-order hyperchaotic synchronization model for renewable microgrid communication; (b) formulation of a multi-switching synchronization structure involving three drive systems and one response system; (c) derivation of nonlinear control laws for synchronization error cancellation; (d) Lyapunov-based establishment of synchronization stability.

Renewable Energy Microgrids

Renewable energy microgrids are decentralised power systems that combine distributed generation, energy storage, local loads, and control infrastructure. They may operate in grid-connected or islanded modes. Their increasing adoption is motivated by the need for resilient, sustainable, and locally managed power systems. However, variable solar irradiance and wind speed introduce intermittency and nonlinear operating behaviour (Ackermann, 2012; Ojo et al., 2025).

Microgrid control is commonly organised into hierarchical levels: primary, secondary, and tertiary control. Guerrero et al. (2011) presented a standardised hierarchical control approach for droop-controlled AC and DC microgrids. While this provides a foundation for power sharing and voltage-frequency control, modern networked microgrids require secure communication and cyber-resilient operation.

Recent studies show that networked microgrids face cybersecurity challenges because they depend on communication technologies and digital infrastructure (Aghmadi et al., 2023; Ayele et al., 2024). These challenges justify the need for secure signal-transmission frameworks that can operate under nonlinear and uncertain renewable-energy conditions.

Chaos, Hyperchaos, and Secure Communication

Chaotic systems are nonlinear deterministic systems that exhibit sensitive dependence on initial conditions and irregular bounded behaviour. Pecora and Carroll (1990) demonstrated that chaotic systems can be synchronized, thereby establishing a theoretical basis for chaos-based secure communication. Hyperchaotic systems have more than one positive Lyapunov exponent, making them more complex and better suited for secure information masking.

Recent studies have applied fractional-order chaotic systems to image encryption and secure communication. Lin et al. (2023) proposed an encryption algorithm based on fractional-order chaotic systems combined with adaptive predefined-time synchronization. Nail et al. (2024) investigated real-time synchronization of multiple fractional-order chaotic systems for secure communication. Li et al. (2025) also applied finite-time synchronization of fractional-order chaotic systems to image encryption. These works show that fractional-order chaotic synchronization remains an active and relevant area of secure communication research.

Fractional-Order Systems

Fractional-order calculus extends ordinary differentiation and integration to non-integer orders. It is useful in modelling systems with memory, heredity, and nonlocal behaviour. Podlubny (1999) provided a foundational treatment of fractional differential equations and their engineering applications. Fractional-order chaotic systems are especially useful in secure communication because the fractional order adds a design parameter and increases system complexity.

Multi-Switching Synchronization

Synchronization is the process by which two or more dynamical systems adjust their trajectories to satisfy a desired relationship. Multi-switching synchronization is more complex than complete synchronization because the response states synchronize with switched combinations of different drive-system states. This increases the complexity of the synchronization structure and enhances security, since an interceptor cannot easily determine the correspondence between transmitted and recovered.

METHODOLOGY

Fractional-Order Calculus Framework

The Caputo fractional derivative is used because it allows initial conditions to be represented in classical physical form. For a

function $x(t)$, the Caputo derivative of order q , where $0 < q < 1$, is defined as:

$${}^C D_t^q x(t) = \frac{1}{\Gamma(1-q)} \int_0^t \frac{\dot{x}(\tau)}{(t-\tau)^q} d\tau, \quad (1)$$

where $\Gamma(\cdot)$ is the Gamma function, and q denotes the fractional order.

Renewable Energy Microgrid Model

The renewable energy microgrid consists of solar photovoltaic generation, wind turbine generation, battery energy storage, and local load demand. The net microgrid power is expressed as:

$$PMG = PPV + PWT + PBESS - PLoad. \quad (2)$$

The photovoltaic output can be modelled as:

$$PPV = \eta_{PV} A_{PV} G(t), \quad (3)$$

Where η_{PV} is the photovoltaic efficiency, A_{PV} is the panel area, and $G(t)$ is solar irradiance.

The wind turbine output can be expressed as:

$$P_{WT} = \frac{1}{2} \rho A_{WT} C_p v^3(t) \quad (4)$$

where ρ is air density, A_{WT} is the swept area, C_p is the power coefficient, and $v(t)$ is wind speed.

Fractional-Order Hyperchaotic Drive Systems

We consider three fractional-order hyperchaotic drive systems.

Drive System 1

$$D^q x_1 = f_1(x_1, x_2, x_3, x_4), \quad (5)$$

$$D^q x_2 = f_2(x_1, x_2, x_3, x_4), \quad (6)$$

$$D^q x_3 = f_3(x_1, x_2, x_3, x_4), \quad (7)$$

$$D^q x_4 = f_4(x_1, x_2, x_3, x_4). \quad (8)$$

Drive System 2

$${}^q y_1 = g_1(y_1, y_2, y_3, y_4), \quad (9)$$

$$D^q y_2 = g_2(y_1, y_2, y_3, y_4), \quad (10)$$

$$D^q y_3 = g_3(y_1, y_2, y_3, y_4), \quad (11)$$

$$D^q y_4 = g_4(y_1, y_2, y_3, y_4). \quad (12)$$

Drive System 3

$$D^q z_1 = h_1(z_1, z_2, z_3, z_4), \quad (13)$$

$$D^q z_2 = h_2(z_1, z_2, z_3, z_4), \quad (14)$$

$$D^q z_3 = h_3(z_1, z_2, z_3, z_4), \quad (15)$$

$$D^q z_4 = h_4(z_1, z_2, z_3, z_4). \quad (16)$$

Response System

The controlled response system is:

$$D^q w_1 = p_1(w_1, w_2, w_3, w_4) + u_1, \quad (17)$$

$$D^q w_2 = p_2(w_1, w_2, w_3, w_4) + u_2, \quad (18)$$

$$D^q w_3 = p_3(w_1, w_2, w_3, w_4) + u_3, \quad (19)$$

$$D^q w_4 = p_4(w_1, w_2, w_3, w_4) + u_4, \quad (20)$$

where u_1, u_2, u_3, u_4 are nonlinear control inputs.

Multi-Switching Synchronization Error Functions. The synchronization error functions are defined as:

$$e_1 = w_1 - (a_1 x_2 + b_1 y_3 + c_1 z_4), \quad (21)$$

$$e_2 = w_2 - (a_2 x_3 + b_2 y_4 + c_2 z_1), \quad (22)$$

$$e_3 = w_3 - (a_3 x_4 + b_3 y_1 + c_3 z_2), \quad (23)$$

$$e_4 = w_4 - (a_4 x_1 + b_4 y_2 + c_4 z_3). \quad (24)$$

Derivation of the Error Dynamics and Nonlinear Controllers

From the multi-switching synchronization errors defined above as :

$$e_1 = w_1 - (a_1 x_2 + b_1 y_3 + c_1 z_4), \quad (33)$$

$$e_2 = w_2 - (a_2 x_3 + b_2 y_4 + c_2 z_1), \quad (34)$$

$$e_3 = w_3 - (a_3 x_4 + b_3 y_1 + c_3 z_2), \quad (35)$$

$$e_4 = w_4 - (a_4 x_1 + b_4 y_2 + c_4 z_3). \quad (36)$$

Taking the fractional derivative of e_1 gives:

$$D^q e_1 = D^q w_1 - D^q (a_1 x_2 + b_1 y_3 + c_1 z_4) \quad (37)$$

$$= D^q w_1 - a_1 D^q x_2 - b_1 D^q y_3 - c_1 D^q z_4. \quad (38)$$

$$\text{Using}$$

$$D^q w_1 = p_1(w) + u_1, \quad D^q x_2 = f_2(x), \quad D^q y_3 = g_3(y), \quad D^q z_4 = h_4(z), \quad (39)$$

We obtain:

$$D^q e_1 = p_1(w) + u_1 - a_1 f_2(x) - b_1 g_3(y) - c_1 h_4(z).$$

To make $D^q e_1 = -k_1 e_1$, choose:

(41)

$$u_1 = -p_1(w) + a_1f_2(x) + b_1g_3(y) + c_1h_4(z) - k_1e_1.$$

Substituting u_1 into $D^q e_1$ gives:

$$D^q e_1 = p_1(w) + [-p_1(w) + a_1f_2(x) + b_1g_3(y) + c_1h_4(z) - k_1e_1]$$

$$- a_1f_2(x) - b_1g_3(y) - c_1h_4(z) \quad (42)$$

$$= p_1(w) - p_1(w) + a_1f_2(x) - a_1f_2(x) + b_1g_3(y) - b_1g_3(y)$$

$$+ c_1h_4(z) - c_1h_4(z) - k_1e_1 \quad (43)$$

$$= -k_1e_1. \quad (44)$$

For the second error function:

$$Dq e_2 = Dq w_2 - Dq(a_2x_3 + b_2y_4 + c_2z_1) \quad (45)$$

$$(46)$$

$$= Dq w_2 - a_2Dq x_3 - b_2Dq y_4 - c_2Dq z_1.$$

Using

$$D^q w_2 = p_2(w) + u_2, \quad D^q x_3 = f_3(x), \quad D^q y_4 = g_4(y), \quad D^q z_1 = h_1(z), \quad (47)$$

We obtain:

$$D^q e_2 = p_2(w) + u_2 - a_2f_3(x) - b_2g_4(y) - c_2h_1(z). \quad (48)$$

To make $D^q e_2 = -k_2e_2$, choose:

(49)

$$u_2 = -p_2(w) + a_2f_3(x) + b_2g_4(y) + c_2h_1(z) - k_2e_2.$$

Substituting u_2 into $D^q e_2$ gives:

$$D^q e_2 = p_2(w) + [-p_2(w) + a_2f_3(x) + b_2g_4(y) + c_2h_1(z) - k_2e_2]$$

$$- a_2f_3(x) - b_2g_4(y) - c_2h_1(z) \quad (50)$$

$$= p_2(w) - p_2(w) + a_2f_3(x) - a_2f_3(x) + b_2g_4(y) - b_2g_4(y)$$

$$+ c_2h_1(z) - c_2h_1(z) - k_2e_2 \quad (51)$$

$$= -k_2e_2. \quad (52)$$

For the third error function:

$$Dq e_3 = Dq w_3 - Dq(a_3x_4 + b_3y_1 + c_3z_2) \quad (53)$$

$$(54)$$

$$= Dq w_3 - a_3Dq x_4 - b_3Dq y_1 - c_3Dq z_2.$$

Using

$$D^q w_3 = p_3(w) + u_3, \quad D^q x_4 = f_4(x), \quad D^q y_1 = g_1(y), \quad D^q z_2 = h_2(z), \quad (55)$$

we obtain:

$$D^q e_3 = p_3(w) + u_3 - a_3f_4(x) - b_3g_1(y) - c_3h_2(z). \quad (56)$$

$$(44)$$

To make $D^q e_3 = -k_3e_3$, choose:

(57)

$$u_3 = -p_3(w) + a_3f_4(x) + b_3g_1(y) + c_3h_2(z) - k_3e_3.$$

Substituting u_3 into $D^q e_3$ gives:

$$D^q e_3 = p_3(w) + [-p_3(w) + a_3f_4(x) + b_3g_1(y) + c_3h_2(z) - k_3e_3]$$

$$- a_3f_4(x) - b_3g_1(y) - c_3h_2(z) \quad (58)$$

$$= p_3(w) - p_3(w) + a_3f_4(x) - a_3f_4(x) + b_3g_1(y) - b_3g_1(y)$$

$$+ c_3h_2(z) - c_3h_2(z) - k_3e_3 \quad (59)$$

$$= -k_3e_3. \quad (60)$$

For the fourth error function:

$$Dq e_4 = Dq w_4 - Dq(a_4x_1 + b_4y_2 + c_4z_3) \quad (61)$$

$$(62)$$

$$= Dq w_4 - a_4Dq x_1 - b_4Dq y_2 - c_4Dq z_3.$$

Using

$$D^q w_4 = p_4(w) + u_4, \quad D^q x_1 = f_1(x), \quad D^q y_2 = g_2(y), \quad D^q z_3 = h_3(z), \quad (63)$$

we obtain:

$$(64)$$

$$D^q e_4 = p_4(w) + u_4 - a_4f_1(x) - b_4g_2(y) - c_4h_3(z).$$

To make $D^q e_4 = -k_4e_4$, choose:

(65)

$$\begin{aligned}
 u_4 &= -p_4(w) + a_4f_1(x) + b_4g_2(y) + c_4h_3(z) - k_4e_4. \\
 \text{Substituting } u_4 \text{ into } D^q e_4 \text{ gives:} \\
 D^q e_4 &= p_4(w) + [-p_4(w) + a_4f_1(x) + b_4g_2(y) + \\
 &\quad c_4h_3(z) - k_4e_4] \\
 &\quad - a_4f_1(x) - b_4g_2(y) - c_4h_3(z) \quad (66) \\
 &= p_4(w) - p_4(w) + a_4f_1(x) - a_4f_1(x) + b_4g_2(y) - \\
 &\quad b_4g_2(y) + c_4h_3(z) - c_4h_3(z) - k_4e_4 \quad (67) \\
 &= -k_4e_4. \quad (68)
 \end{aligned}$$

Hence, the complete controller set is:

$$\begin{aligned}
 u_1 &= -p_1(w) + a_1f_2(x) + b_1g_3(y) + c_1h_4(z) - k_1e_1, \quad (69) \\
 u_2 &= -p_2(w) + a_2f_3(x) + b_2g_4(y) + c_2h_1(z) - k_2e_2, \quad (70) \\
 u_3 &= -p_3(w) + a_3f_4(x) + b_3g_1(y) + c_3h_2(z) - k_3e_3, \quad (71) \\
 u_4 &= -p_4(w) + a_4f_1(x) + b_4g_2(y) + c_4h_3(z) - k_4e_4. \quad (72)
 \end{aligned}$$

Therefore, the closed-loop error dynamics become:

$$\begin{aligned}
 D^q e_1 &= -k_1e_1, & D^q e_2 &= -k_2e_2, & D^q e_3 &= -k_3e_3, \\
 D^q e_4 &= -k_4e_4. \quad (73)
 \end{aligned}$$

Since $k_1, k_2, k_3, k_4 > 0$, the synchronization errors decay to zero. Thus, the response system synchronizes with the selected multi-switching combinations of the three drive systems.

To establish the stability of the synchronization error system, consider the positive Lyapunov function.

$$V(e) = \frac{1}{2} \sum_{i=1}^4 1 e_i^2$$

(74)

For $0 < q < 1$, the Caputo fractional derivative of the Lyapunov function satisfies

$$\{1\}^C D_t^q V(e) \leq \sum_{i=1}^4 1 e_i \{1\}^C D_t^q e_i$$

(75)

From the closed-loop synchronization error dynamics,

$$\{1\}^C D_t^q e_i = -k_i e_i, \quad i = 1, 2, 3, 4$$

(76)

where $k_i > 0$. Therefore,

$$\{1\}^C D_t^q V(e) \leq -k_{\min} \sum_{i=1}^4 1 e_i^2$$

(77)

Let

$$k_{\min} = \min\{k_1, k_2, k_3, k_4\}$$

(78)

Then

$$\{1\}^C D_t^q V(e) \leq -k_{\min} \sum_{i=1}^4 1 e_i^2 = -2k_{\min} V(e)$$

(79)

Since $k_{\min} > 0$, the fractional derivative of the Lyapunov function is negative definite for all e , not equal to zero. Hence, the synchronization error system is Mittag-Leffler stable, and

$$\lim_{(t \rightarrow \infty) e_i(t)} = 0, \quad i = 1, 2, 3, 4$$

(80)

Secure Signal Transmission Model

The encrypted signal is defined as:

$$c_{T(t)} = a_1 x_{2(t)} + b_1 y_{3(t)} + c_1 z_{4(t)} \quad (81)$$

The information signal $m(t)$ is masked using the hyperchaotic carrier according to

$$S_{enc(t)} = m(t) + \alpha c_{T(t)} \quad (82)$$

At the receiver, the message is recovered using the synchronized response state $w_1(t)$ as

$$m_{r(t)} = S_{enc(t)} - \alpha w_1(t) \quad (83)$$

Lyapunov Stability Analysis

As synchronization is achieved, $w_1(t)$ approaches $c_T(t)$ and consequently the recovered signal $m_r(t)$ approaches the original information signal $m(t)$.

Numerical Simulation Procedure

MATLAB simulations were used to validate the proposed framework. The simulation outputs include drive-system state variables, response-system state variables, multi-switching synchronization errors, individual error functions, error norm, Lyapunov function, approximate Lyapunov exponent, phase portraits, drive-response synchronization comparisons, renewable energy microgrid fluctuation, encrypted hyperchaotic

signal, and original–recovered signal comparison.

RESULTS AND DISCUSSION

4.1 Dynamic Behaviour of the Hyperchaotic Drive Systems

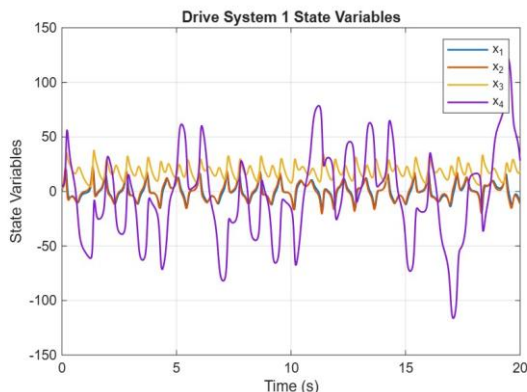


Figure 1: State variables of Drive System 1.

Figure 1 shows the state variables of Drive System 1. The trajectories exhibit bounded but irregular oscillations, which confirms nonlinear hyperchaotic behaviour.

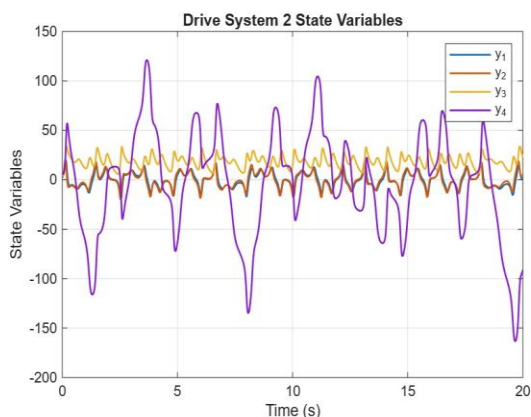


Figure 2: State variables of Drive System 2.

Figure 2 presents the state variables of Drive System 2. The irregular behaviour of the system confirms sensitivity to initial conditions and suitability for secure signal masking.

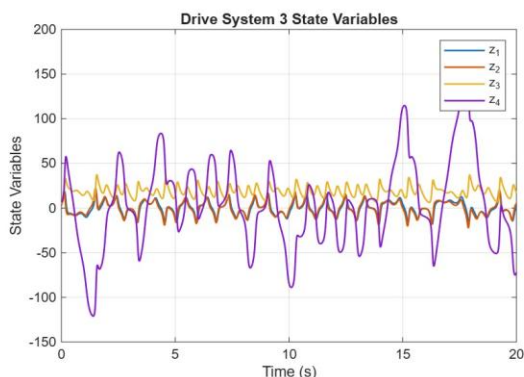


Figure 3: State variables of Drive System 3.

Figure 3 shows the state variables of Drive System 3. The bounded

oscillations confirm that the third drive system maintains complex nonlinear dynamics.

4.1 Response System Dynamics

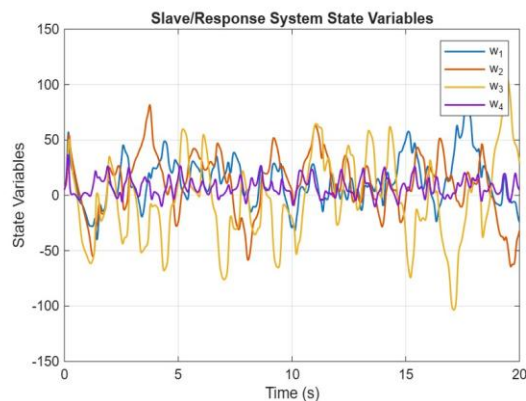


Figure 4: State variables of the slave/response system.

Figure 4 shows the response-system state variables under nonlinear control. The response system remains bounded while responding to the selected drive-system combinations.

4.2 Synchronization Error Analysis

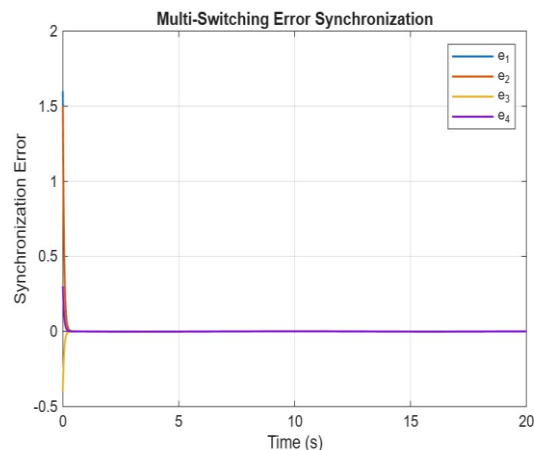


Figure 5: Multi-switching synchronization error convergence.

Figure 5 shows that the multi-switching synchronization errors converge rapidly towards zero, demonstrating the effectiveness of the proposed nonlinear controllers and supporting the theoretical convergence established by the stability analysis.

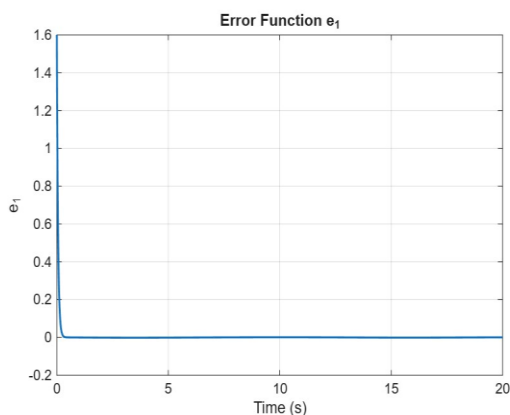


Figure 6: Error function e_1 .

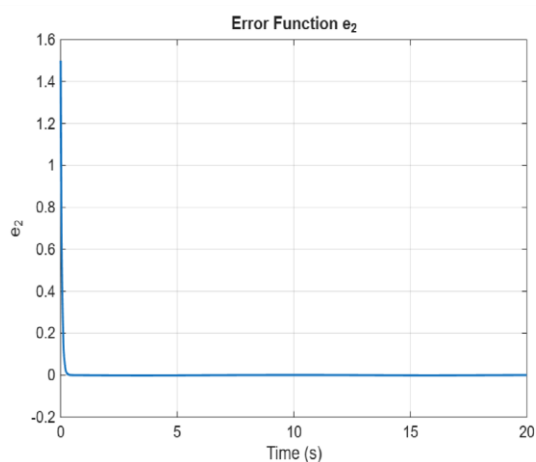


Figure 7: Error function e_2 .

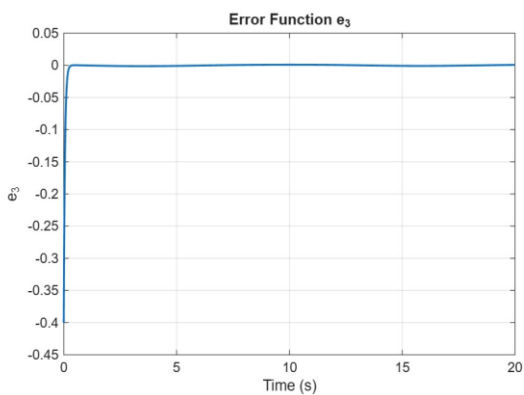


Figure 8: Error function e_3 .

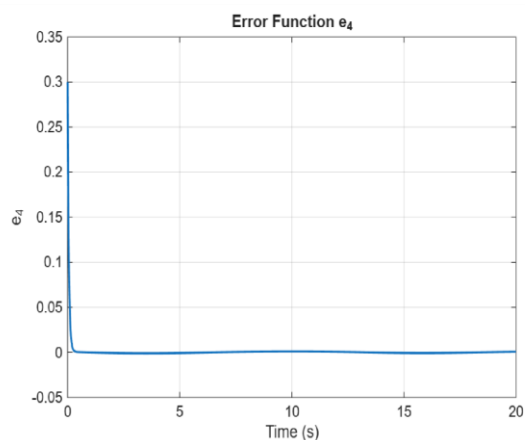


Figure 9: Error function e_4 .

Figures 6–9: present the individual synchronization errors e_1 , e_2 , e_3 , and e_4 , respectively. Each error approaches zero with time, demonstrating convergence of the corresponding multi-switching synchronization channel.

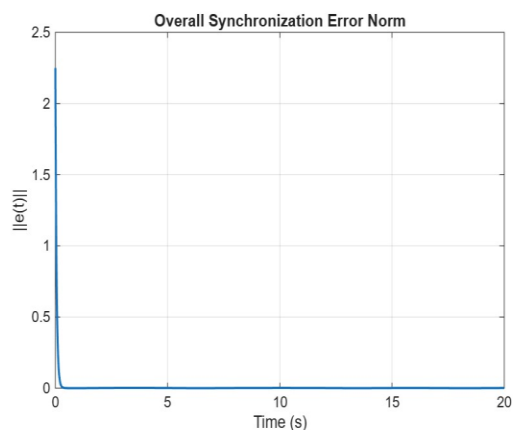


Figure 10: Overall synchronization error norm.

Figure 10 presents the overall synchronization error norm. The reduction of $\|e(t)\|$ towards zero demonstrates the collective convergence of the synchronization errors and confirms that the aggregate multi-switching synchronization error is effectively suppressed.

4.4 Lyapunov Stability and Lyapunov Exponent Analysis

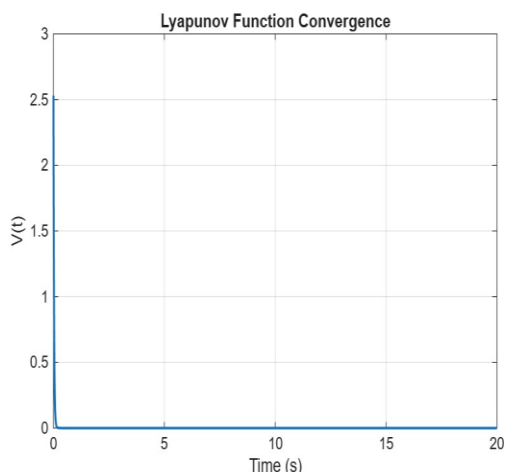


Figure 11: Lyapunov function convergence. Figure 11 shows that the Lyapunov function decreases towards zero as the synchronization errors converge. This numerical behaviour is consistent with the fractional-order Lyapunov stability analysis presented in Section 3.7 and supports the asymptotic convergence of the synchronization error system.

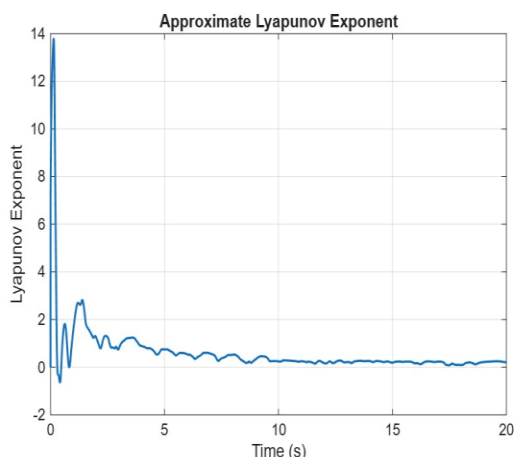


Figure 12: Approximate Lyapunov exponent. Figure 12 presents the approximate Lyapunov exponent obtained from the simulated trajectory. Positive values indicate sensitivity to initial conditions and provide evidence of chaotic divergence. However, rigorous verification of hyperchaotic behaviour requires evaluating the full Lyapunov spectrum and confirming at least two positive Lyapunov exponents.
Phase Portrait and Hyperchaotic Attractor Analysis

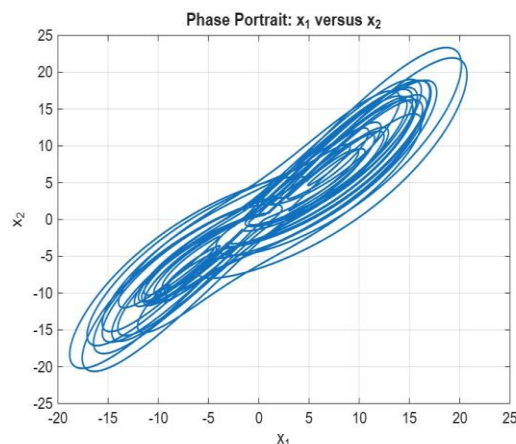


Figure 13: Phase portrait of x_1 versus x_2 .

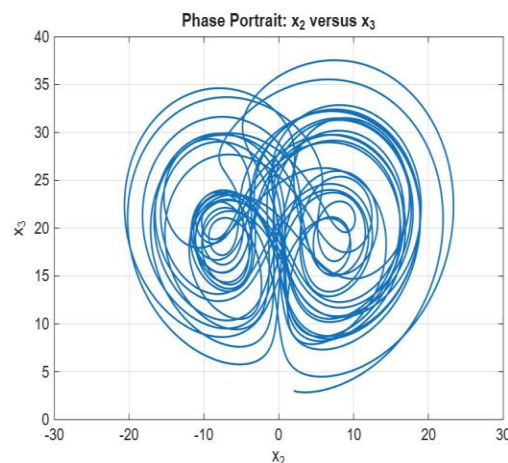


Figure 14: Phase portrait of x_2 versus x_3 .

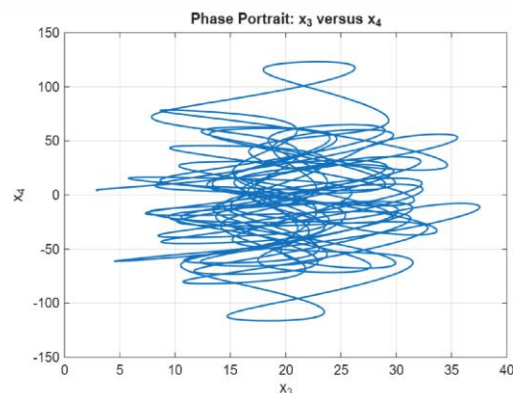


Figure 15: Phase portrait of x_3 versus x_4 . Figures 13–15 present the two-dimensional phase portraits of the selected state variables. The bounded, irregular, and complex attractor patterns illustrate the nonlinear dynamical behaviour of the drive system and demonstrate the complexity of its state-space trajectories.

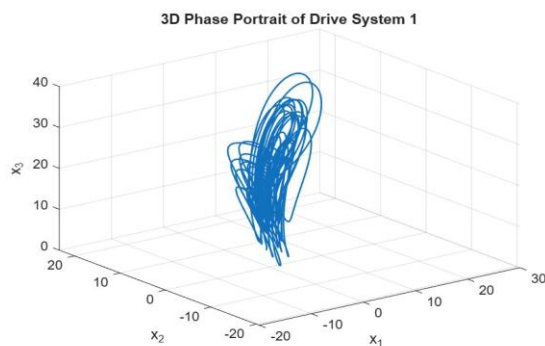


Figure 16: Three-dimensional phase portrait of Drive System 1.

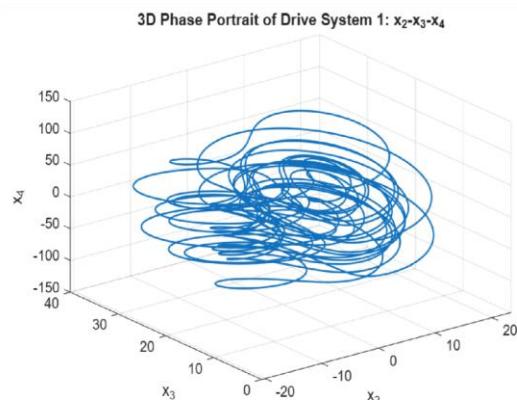


Figure 17: Three-dimensional phase portrait of Drive System 1 in the $x_2 - x_3 - x_4$ space.

Figures 16 and 17 reveal complex bounded attractor structures in the selected state spaces, illustrating the nonlinear dynamical behaviour of the drive system. These phase-space characteristics support the system's suitability for generating complex signal carriers.

Drive-Response Synchronization Comparisons

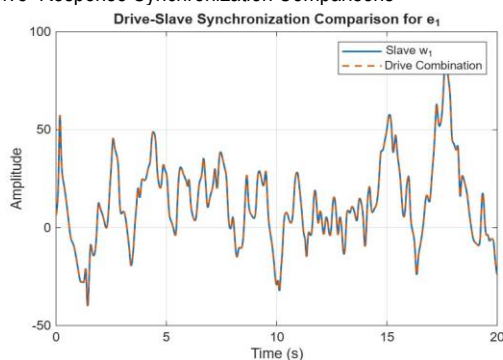


Figure 18: Drive-response synchronization comparison for e_1 .

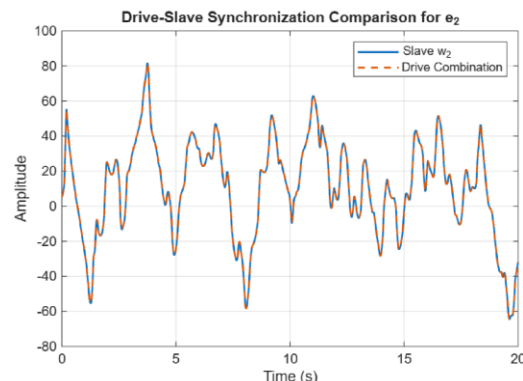


Figure 19: Drive-response synchronization comparison for e_2 .

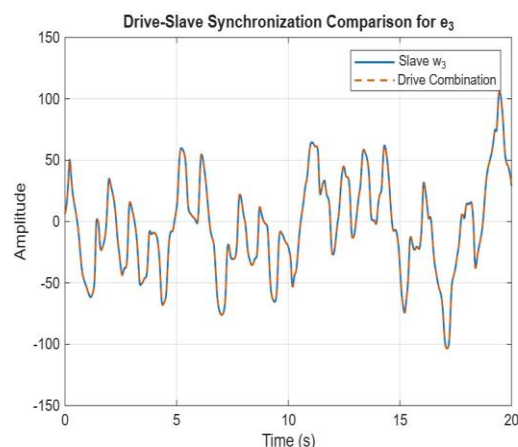


Figure 20: Drive-response synchronization comparison for e_3 .

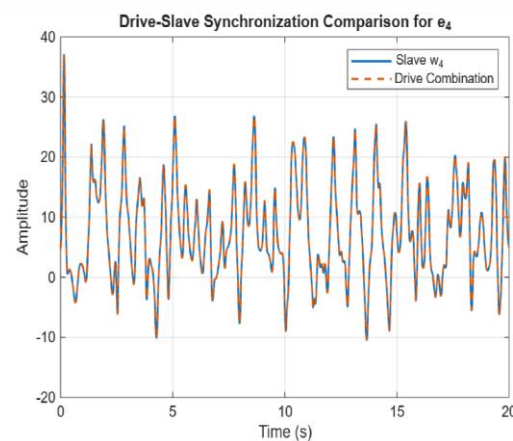


Figure 21: Drive-response synchronization comparison for e_4 .

Figures 18–21 present drive-response synchronization comparisons for the four multi-switching error channels. The close agreement between the response states and their prescribed combinations of the drive-system states demonstrates the effectiveness of the proposed multi-switching synchronization scheme. This behaviour is consistent with the convergence of the synchronization errors towards zero observed in Figures 5–10.

Renewable Energy Microgrid Fluctuation Analysis

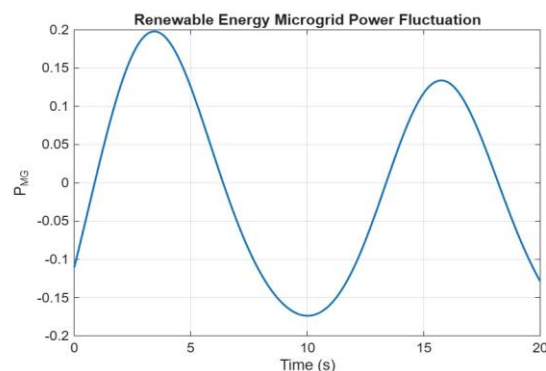


Figure 22: Renewable energy microgrid power fluctuation. Figure 22 presents renewable energy microgrid power fluctuations associated with time-varying contributions from renewable energy sources and microgrid operating conditions. The variation illustrates the intermittent and dynamic nature of renewable power generation considered in the proposed framework. This provides the renewable-energy context within which the synchronization-based secure signal transmission scheme is investigated. Secure Signal Transmission Performance

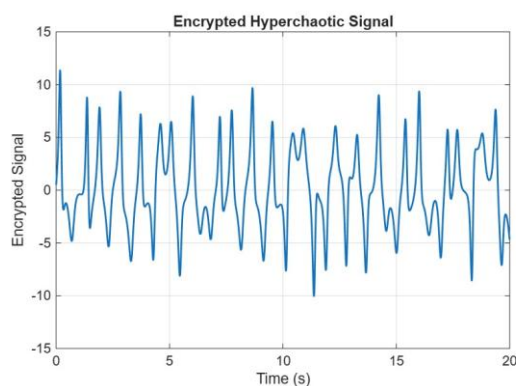


Figure 23: Encrypted hyperchaotic signal. Figure 23 presents the encrypted signal generated by combining the information signal with the multi-switching carrier. The resulting irregular waveform illustrates how the information signal is masked within the complex carrier dynamics, obscuring the original message during transmission.

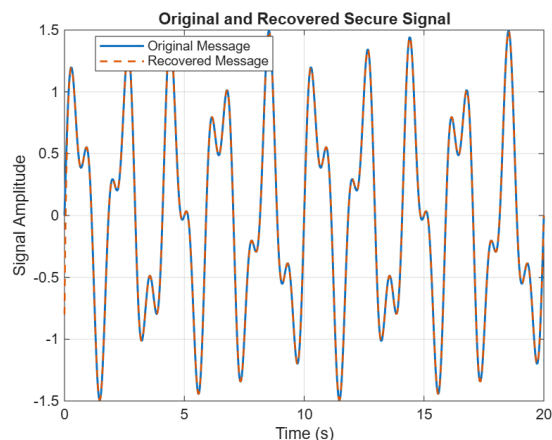


Figure 24: Original and recovered secure signal.

Figure 24 compares the original information signal with the recovered signal obtained using the synchronized response state. Following the initial synchronization transient, the recovered signal closely tracks the original message, as demonstrated by the near-complete overlap of the two waveforms. This confirms that synchronization of the response state with the prescribed multi-switching carrier enables effective reconstruction of the transmitted information signal.

Conclusion

This study developed a fractional-order hyperchaotic multi-switching synchronization framework for secure signal transmission in renewable energy microgrids. The framework integrates fractional-order modelling, complex nonlinear dynamics, nonlinear controller design, multi-switching synchronization, Lyapunov stability analysis, renewable microgrid disturbance modelling, and synchronization-based signal masking.

The mathematical derivation showed that the proposed nonlinear controllers cancel the corresponding nonlinear terms in the synchronization error dynamics and reduce the closed-loop error system to a stable negative-feedback structure. The fractional-order Lyapunov stability analysis established asymptotic convergence of the synchronization errors. The numerical results demonstrated bounded complex drive-system behaviour, convergence of the four synchronization errors, decreasing Lyapunov-function behaviour, sensitivity to initial conditions indicated by the approximate Lyapunov-exponent analysis, complex phase-space trajectories, and close agreement between the response states and their prescribed multi-switching drive combinations.

The renewable energy microgrid simulation further illustrated the time-varying power conditions considered in the framework. For secure communication, the information signal was masked using the multi-switching carrier and reconstructed using the synchronized response state. The close overlap between the original and recovered signals after the initial synchronization transient demonstrated effective signal recovery. Overall, the proposed framework provides a useful synchronization-based approach for secure signal transmission in renewable energy microgrid communication networks.

Recommendations

Future research should extend the proposed framework to real-time renewable energy microgrid testbeds, hardware-in-the-loop simulation, FPGA implementation, and embedded controller design. Further work should also consider stochastic renewable profiles, false data injection attacks, communication delays, blockchain-enabled secure coordination, and **machine-learning-based adaptive parameter tuning**.

REFERENCES

- Ackermann, T. (Ed.). (2012). *Wind power in power systems* (2nd ed.). Wiley.
- Aghmadi, A., Hussein, H., Polara, K. H., & Mohammed, O. A. (2023). A comprehensive review of architecture, communication, and cybersecurity in networked microgrid systems. *Inventions*, 8(4), 84. <https://doi.org/10.3390/inventions8040084>
- Ayele, E. D., Hossain, M. J., & Pota, H. R. (2024). Enhancing cybersecurity in distributed microgrids: Communication requirements, vulnerabilities, and

- protection strategies. *Energies*, 17(3), 705. <https://doi.org/10.3390/en17030705>
- Guerrero, J. M., Vásquez, J. C., Matas, J., de Vicuña, L. G., & Castilla, M. (2011). Hierarchical control of droop-controlled AC and DC microgrids: A general approach toward standardization. *IEEE Transactions on Industrial Electronics*, 58(1), 158–172. <https://doi.org/10.1109/TIE.2010.2066534>
- Kundur, P. (1994). *Power system stability and control*. McGraw-Hill.
- Li, R., Wang, H., & Huang, D. (2025). Finite-time modified function projective synchronization between different fractional-order chaotic systems based on RBF neural network and its application to image encryption. *Fractal and Fractional*, 9(10), 659. <https://doi.org/10.3390/fractalfract9100659>
- Lin, L., Zhuang, Y., Xu, Z., Yang, D., & Wu, D. (2023). Encryption algorithm based on fractional-order chaotic system combined with nonlinear predefined time synchronization. *Frontiers in Physics*, 11, 1202871. <https://doi.org/10.3389/fphy.2023.1202871>
- Nail, B., Ladaci, S., & Bensafia, Y. (2024). Real-time synchronisation of multiple fractional-order chaotic systems: An application study in secure communication. *Fractal and Fractional*, 8(2), 104. <https://doi.org/10.3390/fractalfract8020104>
- Ojo, K. E., Ogunjuyigbe, A. S. O., & Ayodele, T. R. (2025). Review of advances in renewable energy-based microgrid systems: Control strategies, emerging trends, and future possibilities. *Energies*, 18(14), 3704. <https://doi.org/10.3390/en18143704>
- Pecora, L. M., & Carroll, T. L. (1990). Synchronization in chaotic systems. *Physical Review Letters*, 64(8), 821–824. <https://doi.org/10.1103/PhysRevLett.64.821>
- Podlubny, I. (1999). *Fractional differential equations*. Academic Press.