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A Behavioural Model for Accurate Investigation of Noisy Lorenz Chaotic Synchronization Systems

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ABSTRACT

This paper presents a behavioral model for noisy Lorenz chaotic synchronization systems. This simple simulation-based model can be used for accurate noise voltage derivation of the chaotic oscillators and the investigation of chaotic synchronization systems. Moreover, the effects of circuitry noise on synchronization of Lorenz systems were analysed by using the proposed model. The performance of the synchronization system was numerically evaluated using ADS and MATLAB-SIMULINK environments. The measurement of Mean Squared Error (MSE) and Error to Noise Ratio (ENR) demonstrates that circuitry noise has a remarkable effect on the performance of chaotic Lorenz synchronization systems. For instance, the results showed that for low Signal to Noise Ratios (SNRs), i.e., $-40\ dB \leq SNR \leq 0dB$, the circuitry noise changed the ENR performance up to 1dB.

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1. INTRODUCTION

Chaotic signals can be generated by electrical circuits and nonlinear deterministic equations. It is shown that chaotic oscillators can be synchronized by linking them together with chaotic signals [1, 2]. Most of the researches on chaotic oscillators and chaotic synchronization systems are using an electrical circuit in a simulated environment [3]. In this paper we suggest a behavioral model for noisy Lorenz chaotic synchronization systems. This model allows us to study the effects of circuitry noise on the changes in the output of a Lorenz chaotic oscillator.

The chaotic waveforms can be used in a wide range of applications. They are major candidates for spread-spectrum schemes due to their wideband characteristics [4]. Moreover, numerous chaos-based modulations have been proposed for digital communications because of their robustness against noise and fading [5]. Many studies have been performed on Low Probability of Interception (LPI) features and secure communication schemes [6]. With these features, low-noise Lorenz chaotic synchronization schemes are promising for new classes of modulators. These signals meet the robustness against noise, convergence, and security requirements of the Ultra Reliable Low Latency Communications (URLLC) [7] and Industrial Internet of Things (IIoT) [8].

In this paper, internal noise is computed by using data sheets, and external noise is modelled as Additive White Gaussian Noise (AWGN) channels. In this study, we assumed that the received signal is corrupted by AWGN channels. In the context of chaotic synchronization, other destructive effects, such as multi-path fading, can be separately considered [9]. Considering AWGN channels has the following advantages:

1) Tractability: A small noise may lead to instability and synchronization error. This assumption makes the problem trackable by avoiding calculation complexity.

2) Necessity: Noise must be considered first, because it exists before any other effects of the communication channel. Other effects, such as fading channels, can be modeled in the next blocks after the noise block.

3) Generality: The performance evaluation of different communication schemes using the AWGN channel remains valid under realistic channel models, e.g., under fading channels.

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1. 1. Related Works Most existing literatures have ignored the influence of circuitry noise. Furthermore, in a few papers, a desired internal noise is simply added to the signals that is not an accurate method. For example, Moskalenko et al. [9] discussed the general effect of noise in master-slave Colpitts oscillators. Their results showed that different values for AWGN channel can be considered and added to the system in order to determine the effects of noise on the system's performance. However, they did not determine the realistic value of noise voltage generated by Colpitts oscillators.

Sangiorgio et al. [10] have extended the analysis from a deterministic to a noisy environment, by considering both observation and structural noise. They have used recurrent neural networks for forecasting complex oscillatory time series on a multi-step horizon. Researchers in the field investigated different machine learning techniques and training approaches on dynamic systems with different degrees of complexity.

Moon et al. [11] investigated on synchronization in a set of high-dimensional generalizations of the Lorenz system obtained from the inclusion of additional Fourier modes. Numerical evidence supports that these systems exhibit self-synchronization. An example application of this phenomenon to image encryption is also provided.

Taheri et al. [12] have proposed a dynamic-free sliding mode control method to synchronize a class of unknown fractional order Laser chaotic systems. The efficacy of the proposed method is demonstrated by applying the method to a chaotic system and its practical applicability is demonstrated by using it to encrypt/decrypt color pictures.

A small noise may be effective on the stability and synchronization time of the chaotic synchronization systems, especially in weakly coupled oscillators [13]. Therefore, neglecting circuitry noise may result in some inaccurate calculations and designs. Behavioural modelling can be used for complexity reduction in circuits by modelling the effects of electrical components at the system level. In this way, electrical components replaced by some simple blocks. Considering noise causes a challenge in behavioural modelling. Order reduction methods are used for linear dynamics and some well-known methods such as sampled data models are presented for nonlinear circuits [14, 15].

1. 2. Innovative Aspects and Outlines Innovative aspects are outlined below:

- In this paper, a simple simulation-based behavioural model is proposed for evaluation of the noisy Lorenz chaotic synchronization systems. This model can be useful for the exact noise voltage calculation of chaos-based circuits and systems. Since the generated noise is obtained from experimental measurements and published datasheets for electrical elements, this method can provide exact values of the noise, without need for physical realization of the chaotic circuits.
- The proposed model enables us to study the effects of circuitry noise on the performance of chaotic synchronization systems. Our results showed that the circuitry noise results in a remarkable error that may be vital in some applications, such as biomedical applications.

The rest of this paper is organized as follows: In section 2, we represented our behavioural model for the noisy Lorenz chaotic synchronisation system. In this section, a brief review on the role of noise in chaotic oscillators is first presented. Then, the circuitry noise measurement process is described. Finally, a filter- based method is described for noise generation in this section. Moreover, the influence of the circuitry noise is theoretically investigated in section 2. In section 3, simulation results are presented. Section 4 deals with concluding remarks.

2. BEVAVIORAL MODEL

The proposed model is shown in Figure 1. This model allows us to study the effects of circuitry noise on the performance of the chaotic synchronization systems. The block diagram of the proposed method contains three main steps.

1) The noise voltage spectrum is calculated using the ADS program. The noise of multipliers is neglected and the noise of other components is modelled by series voltage sources and a parallel current source according to the manufacturer's data-sheet on the online published user-manuals[1].

2) In the second step, the extracted noise voltage values are fed into the output of the oscillators. Thus, based on the obtained spectrum, circuitry noise can be generated using a well-known filter-based method.

3) In the final step, the generated circuitry noise is added to the chaotic synchronization system to evaluate the effect of circuitry noise on the performance of the

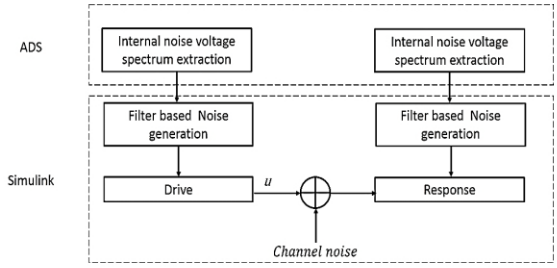

Figure 1. Block diagram of the proposed model

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[1] www.ti.com/product/TL084A/datasheet, www.futurlec.com/Datasheet/Resistor

chaotic synchronization system. MATLAB SIMULINK environment provides a system level simulation for the Lorenz chaotic synchronization system.

In the next section, operation of each block is investigated and a brief review on the noise effects is presented. Finally, the effect of circuitry noise in the Lorenz chaotic synchronization systems is theoretically investigated.

2. 1. The Role of Noise in Conventional and Chaotic Oscillators

In the conventional oscillators, noise can change both the amplitude and phase of a signal generated by an oscillator. The relation between phases is determined. In practical noisy oscillators the output voltage is given by [16]:

$$V_{LO\ output} = A(t)\, f[\omega_c t + \varphi(t)] \qquad (1)$$

In Equation (1), A (t) and φ (t) are the amplitude and phase of the output, respectively. The frequency spectrum of an ideal and a practical oscillator is shown in Figure 2.

Unlike conventional oscillators that the phase rotation is approximately uniform, the phase variations of the chaotic oscillators have a random walk-like behaviour and instantaneous frequency depends on the amplitude. Consider the phase relations in a chaotic generator that called Poincare map [17]:

$$A_{n+1} = T(A_n),\ \frac{d\emptyset}{dt} = \omega(A_n) \equiv \omega_0 + F(A_n) \qquad (2)$$

where A is the amplitude of nth state which is a discrete variable, T is the Poincare map, and ω_0 is the average frequency. The Sum of the average frequency and effective noise $F(A)$ is equal to $\omega(A_n)$. As shown in Equation (2), the phase behavior in chaotic oscillators is similar to the conventional oscillators in the presence of noise. It is shown that the theoretically derivation of $F(A)$ is complex. The above-mentioned characteristic of chaotic signals indicates that simulation-based methods are simpler for measurement of circuitry noise. In this paper, we calculated circuitry noise spectrum for Cumo-Oppenheim circuit using the phase noise analysis tool in an ADS simulation environment.

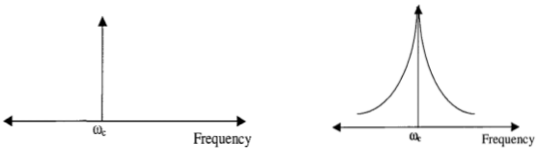
2. 2. Circuit Implimentation and Noise Voltage Spectrum Extraction

This study is based on the circuitry noise of the Lorenz oscillators. We generate a noise for all components from manufacturer's data sheets and import them to ADS environment. Consider the Lorenz oscillator with the following differential function [18]:

$$\dot{u} = \sigma(v - u)$$
$$\dot{v} = ru - v - uw \qquad (3)$$
$$\dot{w} = uv - bw$$

where u, v, w are the generated signals at the transmitter and σ, r, b are the bifurcation parameters. As shown in Figure 3. We used a drive-response structure to obtain a synchronized scheme.

The implementation of oscillator is shown in Figure 4. We used the Cumo-Oppenheim circuit, presented by Cuomo et al. [15]. Drive system sends a signal to the response circuit and both drive and response circuits are similar. We extract noise values of the used components from the published data sheets and input them into the simulated circuit. According to the manufacturer's data, the noise of multipliers is neglected and noise of other components is modelled by a series of voltage source and a parallel current source. The initial conditions are different in the drive and response and the parameters can change using variable resistors. The components are



(a) Ideal oscillator (b) Practical oscillator

Figure 2. Spectrum representation of an oscillator

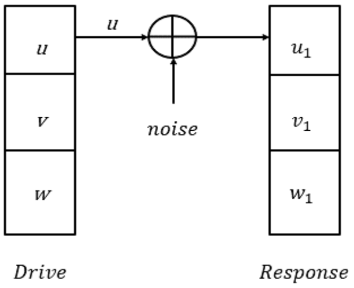


Figure 3. Drive-response synchronization system

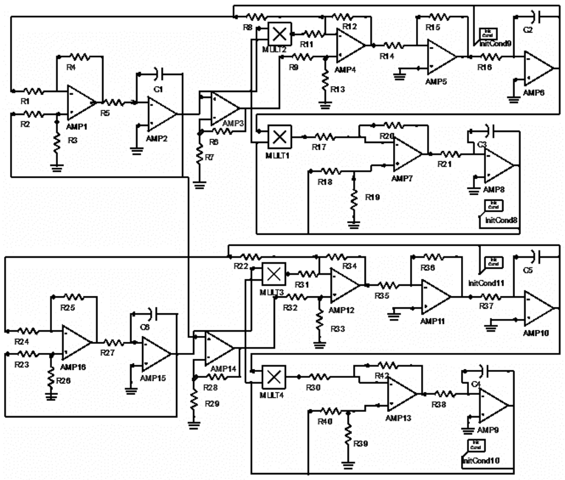


Figure 4. ADS implementation of Lorenz synchronization system

resistors, capacitors, op-amps (LF353) and multipliers (AD632AD).

2. 3. Filter-based Method For Noise Generation in SIMULINK Environment

In this step, the generated noise voltage by ADS tool is input to the chaotic oscillator for completion of the model in MATLAB SIMULINK environment. Thus, we should reconstruct the extracted noise spectrum in MATLAB SIMULINK environment. As mentioned above, the distribution of the noise voltage spectrum of chaotic oscillators is similar to the phase noise behaviour in conventional oscillators. Thus, for system level simulation, we can reconstruct the extracted noise spectrum using a filter-based method, presented by Godbole [19]. Filter-based model contains a white noise generator with power equal to the power of circuitry noise and a digital filter as shown in Figure 5. Finally, we reconstructed the noise can be added to the output of the oscillators in time domain.

The frequency response of the filter for frequency offsets $F(A_n) > 0$ can be calculated as follows:

$$H\big(F(A_n)\big) = 2 \times \sqrt{P(\omega_0 + F(A_n))}, \tag{4}$$

where P shows the power spectral density of the oscillator output. We design a Finite Impulse Response (FIR) filter by using the Filter Design and Analysis Tool (FDATOOL), and then import this filter into the SIMULINK model. Now, a system level analysis of the noisy oscillators can be performed with real circuitry noise values as shown in Figure 1. At the response side, we write the drive signal as follows:

$$\acute{u}(t) = u(t) + z(t). \tag{5}$$

where *z(t)* is total noise. Consider the total noise at the receiver side as the sum of the channel noise and circuitry noise. We assumed that *z(t)* is a zero mean Gaussian random variable with power spectral density σ_z^2. Both the parameters and initial values are assumed to be unknown in response side. We can write:

$$\begin{aligned} u_1(0) &= u(0) + e_u \\ \sigma_1 &= \sigma + \sigma\, e_\sigma \\ v_1(0) &= v(0) + e_v \\ r_1 &= r + r\, e_r \\ w_1(0) &= w(0) + e_w \\ b_1 &= b + b\, e_b \end{aligned} \tag{6}$$

where, $e_u,\ e_v, e_w,\ e_\sigma,\ e_r,\ e_b$ are representation of the added errors to the parameters and initial values. The parameter errors and initial value errors are considered as random numbers distributed uniformly on [0.5, -0.5] and [1, -1], respectively. A similar assumption has been made by Kaddoum and Prunaret [20]. As described by Pecora, et al. [21], Li, et al. [22], Duong et al. [23], Zhou et al. [24], Chernoyarov et al. [25], for using the drive-response synchronization technique we can add a damping term to the response system. The damping term is shown by $\alpha(u' - u_1)$, where α is the strength of coupling.

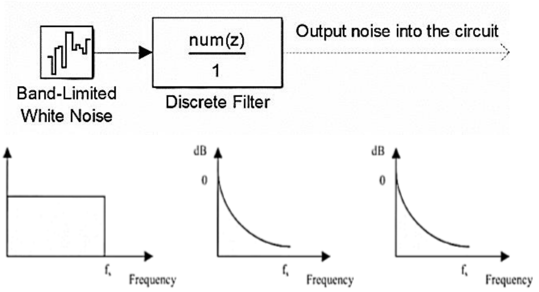


Figure 5. System level simulation of band-limited noise using filter-based method. Lower row shows spectral conditions

$$\begin{cases} \frac{du_1}{dt} = \sigma_1(v_1 - u_1 + \alpha(u' - u_1)) \\ \frac{dv_1}{dt} = -u_1 w_1 + r_1 u_1 - v_1 \\ \frac{dw_1}{dt} = u_1 v_1 - b_1 w_1 \end{cases} \tag{7}$$

A drive-response system can be considered as a communication system. On the receiver side, we have SNR= σ_u^2 / σ_z^2, where σ_u^2 is the power of drive signal at the transmitter side, and the SNR shows the signal to noise ratio. As described by Pecora, et al. [21], we can use mean square error (MSE) of synchronization as a performance metric. If the circuitry noise is modelled as mentioned above, we can write MSE values for different SNRs. Furthermore, the error to noise ratio (ENR) can be employed for synchronization performance evaluation.

$$ENR_{dB} = 10 \log_{10}\left(\frac{MSE}{\sigma_z^2}\right) \tag{8}$$

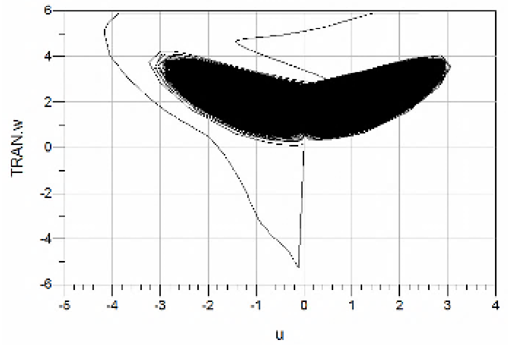
3. SIMULATIONS AND RESULTS

In this section, the simulation results of the proposed model are described.

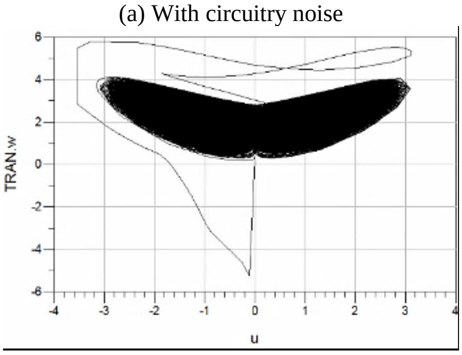
3. 1. The Effects of Circuitry Noise on the Lorenz Oscillator

The noise of components are extracted from manufacturer's data-sheets and are imported to ADS environment. The noise of multipliers is neglected and other components is modelled by a series of voltage source and a parallel current source. We run a simulation of phase noise analysis tool in ADS. The results are shown in Figure 6, with consideration of circuit noise and without it. The bifurcation parameters and initial values of capacitors are equal for the two cases.

The difference between two trajectories indicate that noise changes the attractor. Synchronization occurs after



(a) With circuitry noise



(b) Without circuitry noise

Figure 6. Chaotic attractors projected onto uw-plane

a transient time that depends on the stability of synchronization [10]. In this case, the attractors collide with a chaotic saddle due to applied noise, and this noise create an internal crisis that generates a larger attractor. The key point is that the chaotic saddle contains an unstable steady state of the Lorenz oscillator [22]. In a weak coupling conditions a small noise can be effective on the stability, instability, and synchronization time of the system. In both cases, neglecting circuitry noise may result in some errors in calculations and applications [23].

The ADS program calculates resistors thermal noise plus the noise of other components, then plots the noise voltage spectrum. Figure 7 illustrates the noise spectrum of the output around zero value. Offset frequency is from 1 KHZ to 10 MHZ and the noise voltage is plotted both at the carrier frequency minus the offset frequency and the carrier frequency plus the offset frequency.

3. 2. The Effect of Circuitry Noise on the Synchronization System's Performance

The extracted noise voltage of the oscillator by the phase noise analysis tool of ADS, are used for investigate the circuitry noise effects, as shown in Figure 1. In other words, we have implemented a synchronization system to extract circuitry noise and used it for SIMULINK environment. The FIR filter was designed by MATLAB-FDATOOL and then, it was been imported into the SIMULINK model. It can be assumed that, at the receiver side, the parameters and initial conditions are unknown. This assumption results in that parameter error and initial value error distribute uniformly on [-0.5, 0.5] and [-1, 1], respectively.

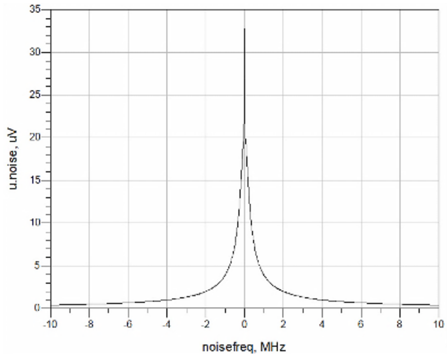
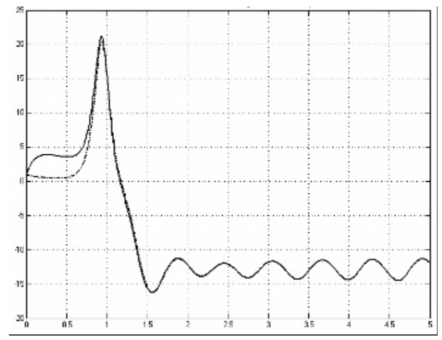
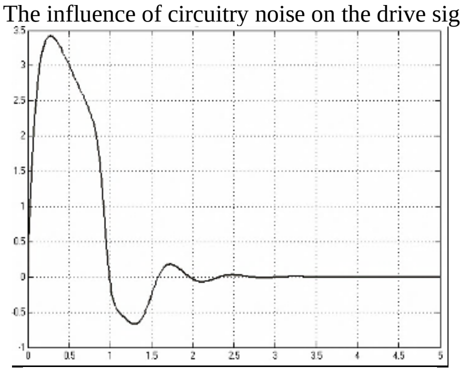


Figure 7. The noise voltage spectrum at the output of Lorenz oscillator

Here, external noise is neglected to deriving the influence of only circuitry noise. Figure 8(a) shows that the circuitry noise changes the receiver output compared to the free-noise case. In Figure 8(b), the error of the drive signal, i.e., the error that comes from neglecting circuitry noise is illustrated. In Figure 9, we can see the effect of circuit noise on u-u$_1$ trajectory plane. The circuitry noise can change the stability of the synchronization subsystems. Furthermore, the circuit noise can change the synchronization time.



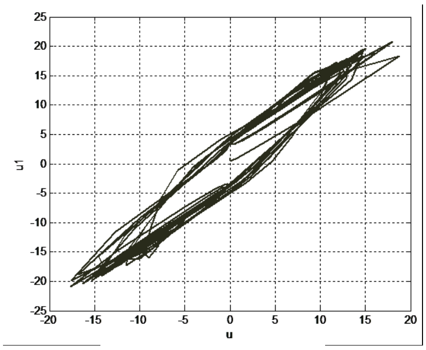
(a) The influence of circuitry noise on the drive signal



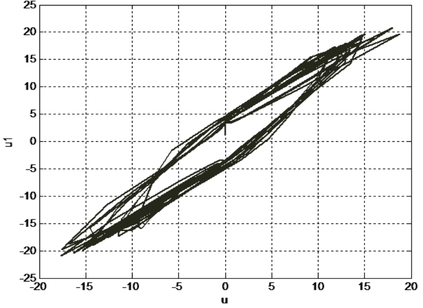
(b) Drive signal error due to circuitry noise

Figure 8. Drive signal at the receiver output

In the previous studies, the artificial noise has been used for simulations of pseudorandom generators [26]. Now, we consider our proposed model to produce practical values for simulation of the circuitry noise. As shown in Figure 10, we measured ENR for different SNRs. The effect of circuitry noise on synchronization error is visible, especially in low SNRs that it may reach to about 1 dB. This may seem a small value, but note that in weak coupling conditions the small noise can change the stability of the subsystems. As shown in Figure 10, in low SNR conditions, for example when the SNR= -40 dB, circuitry noise may be constructive and reduce the synchronization error. As a result, the calculation of MSE and ENR for system shows that with consideration of the behavioural model we can achieve exact accurate results.



(a) With circuitry noise



(b) Without circuitry noise

Figure 9. u-u1 plane of the drive signal at the transmitter

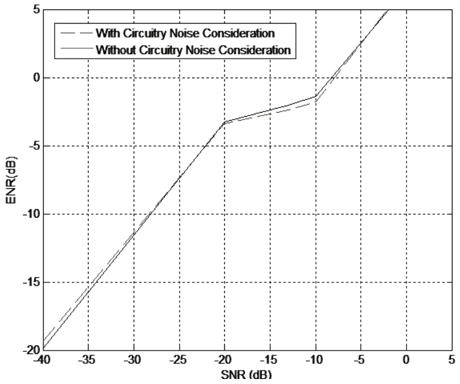


Figure 10. ENR Versus SNR for Lorenz Chaotic synchronization system

5. CONCLUSION

In this paper we present a simple model that evaluates the performance of the chaotic oscillators using a simulation-based method. This method can be used for noise voltage measurements in other chaotic circuits, including higher order differential equations or stimulus-assisted chaotic synchronization systems. Furthermore, the effect of circuitry noise on chaotic synchronization system analyzed using the proposed model. The measurement of the MSE and ENR demonstrates that circuitry noise has a remarkable effect on the performance of chaotic synchronization systems. For example, for Low-SNR conditions, i.e., $-40\,dB \leq SNR \leq 0dB$, the circuitry noise can change the ENR performance up to 1dB. This level of error that incurred by the circuitry noise can have a huge destructive effect in some specific applications, such as rechargeable pace-makers, or may be negligible for other applications, such as communication goals. The results of this paper can be extended to a wide range of applications, from health monitoring, and chaos-based security, to human behaviour analysis and pattern studies in dynamic social networks. Therefore, the capability of the proposed model and the amount of noise effects can be explored for each of the above applications using the proposed method.

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Persian Abstract

چکیده

این مقاله، یک مدل رفتاری برای سیستم‌های سنکرونیزاسیون آشوبی لورنز که به نویز آلوده شده ارائه می‌کند. این مدل ساده مبتنی بر شبیه‌سازی را می‌توان برای استخراج دقیق ولتاژ نویز و بررسی بیشتر سنکرونیزاسیون آشوبی دیگر استفاده کرد. علاوه بر این، اثرات نویز مدار بر سنکرونیزاسیون آشوبی لورنز با استفاده از مدل پیشنهادی تجزیه و تحلیل شده است. عملکرد سیستم سنکرونیزاسیون با استفاده از محیط‌های ADS و MATLAB-SIMULINK بررسی شده است. بررسی معیارهای اندازه‌گیری میانگین مربعات خطا (MSE) و نسبت خطا به نویز (ENR) نشان می‌دهد که نویز مدار تأثیر قابل‌توجهی بر عملکرد سیستم سنکرونیزاسیون آشوبی لورنز دارد. به عنوان مثال، نتایج نشان می دهد که برای نسبت سیگنال به نویز(SNR) پایین، یعنی در بازه صفر تا -٤٠ dB ، نویز مدار می تواند عملکرد ENR را تا ١ dB تغییر دهد.