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Fractional-order modeling and sliding mode control of energy-saving and emission-reduction dynamic evolution system

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ABSTRACT

This paper proposes the fractional-order modeling for sliding mode control of a complex four-dimensional energy-saving and emission-reduction system (ESERS). In the proposed methodology, the fractional calculus techniques are employed to accurately model the dynamics of the ESERS, and the fractional-order model of the energy-saving and emission-reduction system (FOESERS) is formulated. With the proposed FOESERS, all of the equilibrium points and the corresponding eigenvalues are obtained, and the instability region and the state trajectories of FOESERS are also given. The FOESERS can represent complex dynamic behaviours with chaotic and unstable states on the energy conservation, carbon emissions, economic growth, and renewable energy development, and have a great impact on the formulation of government energy policies. Furthermore, based on the fractional Lyapunov stability and robust control theory, a sliding-mode controller is designed to control the FOESERS with model uncertainties and external disturbances to the equilibrium point in the finite time. Finally, simulation results confirm the effectiveness and robustness of the proposed scheme.

1. Introduction

Energy is important for the global economic development and social progress [1]. Economic growth can promote the structural reformation of energy resource exploitation and utilization, and thus further improvements on energy efficiency and energy intensity are expected [2]. However, the rapid economic growth may lead to an increasing energy demand of fossil fuels, and the excessive use of fossil fuel derivatives will result in greenhouse gas emissions (GHG) and environmental pollution issues, especially in developing countries [3–7]. According to the annual time-series data of energy consumption, Gross Domestic Product (GDP) and renewable energy development during 2006–2016 from China National Statistics Yearbook [8,9], the annual GDP of China increased from 3288.3 billion US dollars in 2006 to 11154.4 billion US dollars in 2016, while the total energy consumption grew from 2447.6 million tons coal equivalent (MTCE) in 2006 to about 4360 MTCE in 2016. Also, the overall installed capacity of renewable energy sources in China accounted for 139.9 GW in 2006 and reached about 600 GW in 2016, while the annual carbon emissions totaled 7.2 billion metric tons in 2006 and reached 10.6 billion metric tons in 2016 [9]. With the surge of fossil fuel prices and increasing environment concerns over the years, great pressure to curb the emissions and energy intensity have forced China to implement various energy-saving and emission-reduction measures in order to establish an energy-efficient and environmentally-friendly society for sustainable development [10,11].

The causal relationship exists among energy consumption, CO_2 emissions, and economic growth. Lots of work has been done to demonstrate the impacts of carbon emissions and economic growth on energy consumption [2,5,6,12–16]. Besides, different mathematical models of energy-saving and emission-reduction system (ESERS) have been developed in [17–20] to simulate the nonlinear coupling dynamics of energy conservation, economic growth, carbon emissions, and renewable energy development in the evolutionary process. The ESERS models can indicate various sophisticated issues, such as energy-saving and emission-reduction, economic growth, carbon emissions, carbon tax, energy intensity, energy efficiency and so on, in a regional energy system [14,20]. By analyzing the reciprocal causation of these factors, the improvements on energy efficiency, energy intensity and

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greenhouse gas emissions can be achieved to promote the energy structure transformation and transition to a low-carbon economy [12,13]. Most notably, Tian LX et al. proposed a three-dimensional model of the ESERS in [17] considering the complicated relationship between energy-saving and emission-reduction, economic growth and carbon emissions. The quantitative coefficients of the proposed ESERS model were identified based on artificial neural networks in [17], and an empirical study with the statistical data from China confirmed the perfect agreement of the model performance with real-world situations. Furthermore, the renewable energy capacity is taken into account to develop a new four-dimensional ESERS model in [18]. The ESERS is a complex oscillatory system and exhibits highly nonlinear characteristics with aperiodic, sudden, or random phenomena. Hence, the stabilization of the ESERS is of a major strategic significance for ensuring economic development, reducing energy security and maintaining environment sustainability, and it is important to develop robust control methodologies for supporting the ESERS with uncertainties and external disturbances.

Because of the high nonlinear complexity of the ESERS, the dynamic behaviours of ESERS have been investigated in [17,18] by the equilibrium points and Lyapunov exponents. Various stability control methods, including linear feedback control [18] and impulsive control [21], have been applied to suppress system chaos for stable equilibrium. The previous modeling and control methods of ESERS in [17–21] are based on the integer-order model. However, the state variables of the ESERS have hereditary properties with long-memory effects, and the evolutionary dynamics of the ESERS are often better described by fractional derivatives due to its global correlation characteristics [22,23]. Thus, the fractional calculus can extend the integer-order calculus models to the non-integer order models [24], and is proven to be a very suitable and flexible tool to characterize the genetic memory properties in various chaotic evolutionary processes [23–28]. So far, many practical nonlinear systems in electrical energy fields [27–34], such as the energy supply-demand system [27], hydro-turbine governing system [29], and wind turbine [31], have been modelled using fractional differential equations. This paper aims to investigate the modeling and control of the fractional-order energy-saving and emission-reduction system (FOESERS) to coordinate the dynamic performance of energy conservation, economic growth, carbon emissions, and renewable energy development.

In this paper, the fractional integrals and derivatives are used to present the complex dynamics of ESERS, and the FOESERS model can be formulated based on fractional order calculus. The fractional differential equations of the ESERS are thoroughly investigated to solve the equilibrium points and their corresponding eigenvalues, and the instability region and the state trajectories of the FOESERS are also given. Numerical simulations on the dynamic behaviours of FOESERS indicate the nonlinear chaotic and unstable phenomena on energy conservation, economic growth, carbon emissions, and renewable energy development. Hence, based on the fractional Lyapunov stability theory and sliding mode control theory, a robust control method is designed to stabilize the FOESERS with model uncertainties and external disturbances to the equilibrium point in a finite time. Comparative results on a practical system with different fractional orders as well as different uncertainty and external disturbances confirm the effectiveness and robustness of the proposed control scheme.

The rest of this paper is organized as follows: The mathematical modeling of a FOESERS with its dynamic behaviours is formulated and investigated in Section 2. In order to enhance the stability of FOESERS, a robust fractional-order finite-time controller based on sliding mode control theory is designed in Section 3. Three illustrative examples are provided in Section 4. Finally, Section 5 concludes this paper.

2. Fractional-order modeling of ESERS

2.1. Integer-order model of ESERS

The dynamic evolution model of ESERS can be formulated as the following mathematical form [18],

$$\begin{cases} \dot{x}_1 = \alpha_1 x_1\left(\frac{x_2}{N}-1\right)-\alpha_2 x_2 + \alpha_3 x_3 \\ \dot{x}_2 = -\beta_1 x_1 + \beta_2 x_2\left(1-\frac{x_2}{K}\right) + \beta_3 x_3\left(1-\frac{x_3}{L}\right)-\delta_4 x_4 \\ \dot{x}_3 = \gamma_1 x_1\left(\frac{x_1}{M}-1\right)-\gamma_2 x_2-\gamma_3 x_3 + \gamma_4 x_4\left(\frac{x_4}{E}-1\right) \\ \dot{x}_4 = \delta_1 x_2 + \delta_2 x_3\left(\frac{x_3}{C}-1\right)-\delta_3 x_4 \end{cases} \tag{1}$$

where x_1 is the variable of energy saving, typically expressed in MTCE; x_2 is a variable of carbon emissions, typically expressed in ton; x_3 is a variable of economic growth GDP, typically expressed in US dollar; x_4 is a variable of renewable energy development in a given period, typically expressed in GW. α_i, β_i, γ_j, δ_j, M, N, C, E are positive constants ($i = 1, 2, 3$, $j = 1, 2, 3, 4$), and the units of M, N, C, E can be converted to tons of standard coal). α_1 is the development factor of x_1; α_2 is the impact factor of x_2 to x_1; α_3 is the impact factor of x_3 to x_1; N is the inflexion (local maximum point) of x_2 to x_1; β_1 is the impact factor of x_1 to x_2; β_2 is the development factor of x_2; β_3 is the impact factor of x_3 to x_2; K is the crest value of x_2 in a given period; L is the crest value of x_3 in a given period; δ_4 is the impact factor of x_4 to x_2; γ_1 is the impact factor of x_1 to x_3; γ_2 is the impact factor of x_2 to x_3; γ_3 is the impact factor to itself; M is the inflexion of x_1 to x_3; γ_4 is the impact factor of x_4 to x_3, and E is the inflexion of x_4 to x_3; δ_1 is the impact factor of x_2 to x_4; δ_2 is the impact factor of x_3 to x_4; C is the inflexion of x_3 to x_4, and δ_3 is the impact factor to itself [18].

Based on the normalization of the ESERS from the statistical data in China [8,9], the impact factors of the system can be obtained by the parameter identification using artificial neural network in [17,18]. Hence, the model parameters are set as follows: $\alpha_1 = 0.09$, $\beta_1 = 0.0412$, $\gamma_1 = 0.035$, $\delta_1 = 0.01$, $\alpha_2 = 0.003$, $\beta_2 = 0.08$, $\gamma_2 = 0.0062$, $\delta_2 = 0.02$, $\alpha_3 = 0.012$, $\beta_3 = 0.8$, $\gamma_3 = 0.08$, $\delta_3 = 0.06$, $\gamma_4 = 0.02$, $\delta_4 = 0.03$, $M = 3.5$, $E = 2$, $C = 2$, $K = 1.6$, $N = 0.9$, $L = 2.8$.

2.2. Fractional-order model of ESERS

In this subsection, the definitions of fractional-order derivatives and the lemmas on fractional order system are provided. Then, following the integer-order model of the ESERS in Eq. (1), the fractional-order model of the ESERS can be formulated based on the fractional-order differential equations.

Definition 1 (*[26]*). The definition of Caputo fractional-order derivative is described by,

$${}_{t_0}^{C}D_t^{q}x(t) = \begin{cases} \frac{1}{\Gamma(n-q)}\int_{t_0}^{t}\frac{x^{n}(\tau)}{(t-\tau)^{q+1-n}}d\tau & n-1 < q < n \\ \frac{d^n x(t)}{dt^n} & q = n \end{cases} \tag{2}$$

where q is the fractional order of the system, and $\Gamma(\cdot)$ which is defined as $\Gamma(\tau) = \int_0^{\infty} t^{\tau-1}e^{-t}dt$ is the gamma function.

Definition 2 (*[24]*). The definition of Riemann-Liouville fractional-order derivative is described by,

$${}_{RL}D_{t0,t}^{q}x(t) = \frac{1}{\Gamma(n-q)}\frac{d^n}{dt^n}\int_{t_0}^{t}(t-\tau)^{n-q-1}x(\tau)d\tau \quad n-1 < q < n \tag{3}$$

Definition 3 (*[24]*). The Laplace transform of the Caputo fractional-order derivative is described by,