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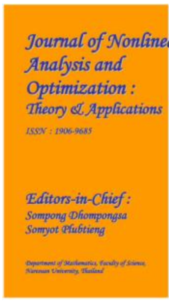

IMPROVED FAULT DETECTION AND LOCATION SCHEME FOR PHOTOVOLTAIC SYSTEM

[1]A Srinivasulu, [2]K Rajkumar, [3]S Rajesh, [4]P Sujjarella

[1234]Assistant Professor, Department of Electrical and Electronics Engineering, Visvesvaraya College of Engineering, Hyderabad.

ABSTRACT

Demand for clean, secure and sustainable energy sources is increasing rapidly day-by-day. Photovoltaic technology is one among them that converts sun's solar energy into electrical energy. But abnormal conditions such as faults, low irradiance etc. lead to the reduction in the available output power from the photovoltaic array. To ensure performance and safety of the PV system, it is necessary to develop techniques that can efficiently localize faults that occur among its components. Among the various faults, this paper presents a fault detection scheme for LL and LG faults in the PV array. Such faults when remain undetected, lower the output of solar system along with damaging the panels and potentially cause fire hazards. The presented fault detection scheme employs Multi-Resolution Signal Decomposition (MSD) technique and two machine learning algorithms namely Fuzzy Logic and K-Nearest Neighbour (KNN) to classify the fault and determine its location. Simulation and experimental results verify the accuracy, reliability and scalability of the presented scheme.

INTRODUCTION

Many physical systems only have the peculiarity of nonnegative states, which are called positive systems, such as absolute temperatures, population levels, height of human body and concentration of a substance in chemical processes [1], [2]. In the past decade, the positive system control has received much attention and many important results have been proposed. On the basis of Gersgorin's theorem, the stabilization methods were proposed for positive linear continuous-time and discrete-time systems in [3]. In [4], a necessary and sufficient linear matrix inequality condition was presented for the stabilization of positive linear systems. A static feedback controller was designed to stabilize the positive linear continuous-time systems in [5]. In [6], the sufficient conditions of asymptotic stability were given for positive Takagi-Sugeno (T-S) fuzzy systems based on multiple Lyapunov functions. The problem of `1-induced controller design was investigated for discrete-time positive systems with the use of linear Lyapunov function in [7]. In [8], the stabilization problem was studied for continuous-time positive systems with interval uncertainties based on a designed `1-induced output-feedback controller. The `1-induced sparse controller was designed for continuoustime positive systems with interval uncertainties in [9]. In [10] and [11], the positive filtering problems were explored for positive continuous-time systems and positive T-S fuzzy systems based on the `1-induced performance. The L∞-gain analysis problem was studied for positive linear systems in [12]–[14]. Furthermore, the stabilization problems of switched positive linear systems were investigated in [15]–[18]. The aforementioned works focus on the investigations of the stabilization problems for positive linear continuous-time systems, discrete-time positive systems, switched positive linear systems and positive T-S fuzzy systems. In addition, many study results have been reported for the control of fractional positive systems (FPS). Over the past decades, the control schemes of integralorder systems have been extensively investigated [19]–[24]. Furthermore, fractional systems have attracted increasing concerns due to many applications of fractional systems in almost all applied sciences such as dynamics of earthquakes, chemical engineering, control of power electronics, signal processing and dynamical processes in self-similar structures [25]–[30]. So far, some important definitions of fractional derivatives have been given, such as Riemann-Liouville (RL) fractional derivative, Caputo definition of fractional derivative and so on [31]. Since fractional calculus naturally has hereditary properties and long memory transients, and is also an extension and promotion of integer-order calculus concept, which can describe positivesystems well [32]. Thus, it is a very active area for the research of positive fractional systems. In particular, stability analysis of fractional systems has attracted more attention [33]–[40]. On the basis of the definitions of fractional derivatives, many significant conclusions have been proposed for FPS [33]. In [34], a new class of continuous-time FPS were introduced and the sufficient conditions were given for the reachability of FPS. The stability and stabilization problems were studied for linear FPS via state feedback method in [35]. In [36], the necessary and sufficient condition was presented for the boundedness of a continuous-time fractional positive system. A minimum energy control problem was investigated for continuous-time FPS with bounded inputs in [37]. In [38], the robust stabilization problem was explored for continuous-time FPS with bounded control. Stabilization problem was studied for continuous-time FPS by using a Lyapunov function in [39]. In [40], a $H\infty$ model reduction problem was studied for FPS. In the literature, the issue of external disturbance has not been considered for FPS. Therefore, the stabilization problem needs to be further investigated for FPS in the present of external disturbances. It is well known that the control performance of plants is characterized by external unknown disturbances. Meanwhile, the issue of FDO based control has not been studied for FPS with external disturbances. In the field of traditional control, it is well-known that the feedforward control provides an effective disturbance compensation method that can achieve prompt disturbance attenuation. However, the disturbance has to be measured by sensors for the implementation of traditional feedforward control. Unfortunately, the disturbances are usually difficult or even impossible to be measured physically by sensors [41]. Since disturbance observers can estimate external disturbances by the known information of the controlled plants and the output of disturbance observers can be used to design the control law [42]. As a result, the disturbance rejection is guaranteed to improve the performance and robustness of the closed-loop system. Therefore, the developing disturbance estimation techniques could alleviate the restriction faced by traditional feedforward control and reject the effect of external disturbances. In past years, the studies of disturbance observers have obtained much attentions. There are many important disturbance observer based control schemes have been presented for integerorder nonlinear systems [43]–[46]. In [47], a nonlinear disturbance observer was developed for robot manipulators. A disturbance observer based control method was proposed for the nonlinear system with disturbance in [48]. In [49], the adaptive fuzzy tracking control scheme was studied based on the disturbance observer for multi-input and multioutput nonlinear systems. An overview of the disturbance observer based control and related methods were reported in [50]. In [51], using a nonlinear disturbance observer, a sliding-mode control method was presented for systems with mismatched uncertainties. The disturbance observer based control schemes were proposed for near-space vehicles (NSV) in [52] and [53]. In [54], a robust adaptive tracking control scheme was proposed for the underwater robot in the presence of parametric uncertainties and unknown external disturbances. The robust attitude control scheme was developed for NSV with time-varying disturbances based on backstepping technique in [55]. According to above discussions, the anti-disturbance ability of control systems can be improved by employing the disturbance observer in the control design for uncertain systems with external disturbances. However, the design methods of FDO has rarely been reported for the control of FPS with unknown disturbances, although a number of studies considered the disturbances in fractional systems [56], [57]. An adaptive sliding mode controller was designed for uncertain fractional chaotic systems with external disturbance in [56]. In [57], an adaptive fractional switching-type control method was explored for the three-dimensional fractional system. However, the uncertainties and disturbances in fractional nonlinear systems were tackled using adaptive estimation methods in [56] and [57]. Therefore, the disturbance observer based control scheme needs to be further investigated for the stabilization of FPS. Motivated by above discussions, the problem of stabilization is investigated for continuous-time fractional systems in the presence of unknown constant disturbances with closedloop positivity based on a FDO. The organization of the paper is as follows. Section 2 details the problem formulation. The FDO is introduced and the stabilization control scheme is presented based on the developed FDO and the state feedback control method in Section 3. Meanwhile, the numerical simulation studies are given to demonstrate the effectiveness of the developed control scheme, followed by some concluding remarks in Section 4. Notation and Definitions: • R n denotes the n-dimensional real space. • N T denotes the transpose of a matrix N. • A matrix N0 ∈ R n×n is called a Metzler matrix if its offdiagonal elements are nonnegative. • A matrix N1 ∈ R n×n can be seen as a nonnegative matrix if all its elements are nonnegative, e.g., N1 ≥ 0. • A vector 8 can be seen as a nonnegative vector if all its elements are nonnegative, e.g., 8 ≥ 0. It is said to be positive if all its components are positive (8 > 0).

LITERATURE SURVEY

L. Farina and S. Rinaldi, Positive Linear Systems: Theory and Applications. New York, NY, USA: Wiley, 2000.

Positive systems are, for instance, networks of reservoirs, industrial processes involving chemical reactors, heat exchangers and distillation columns, storage systems (memories, warehouses,...), hierarchical systems, compartmental systems (frequently used when modeling transport and accumulation phenomena of substances in the human bodies), water and atmospheric pollution models, stochastic models where state variables must be nonnegative since they represent probabilities, and many other models commonly used in economy and sociology. One is tempted to assert that positive systems are the most often encountered systems in almost all areas of science and technology, except electro mechanics, where the variables (voltages, currents, forces, positions, velocities) may assume either positive and negative values. However, the existence of positive systems in an electrical or mechanical context cannot be excluded. Consider, as an example, a simple mechanical system composed of a point mass driven along a straight line by an external force. Position and velocity of the mass cannot become negative provided their initial values are nonnegative and the force is unidirectional: This is a positive system. On the other hand, even the simplest electrical circuit, namely, the R - C circuit, is a positive system since the voltage on the capacitor remains nonnegative if initially such. Positive linear systems, as any other linear system, satisfy the superposition principle and also a peculiar one, that of comparative dynamics. Such a principle can be expressed by saying that "positive perturbations of inputs, states, and parameters cannot produce a decrease of the state and output at any instant of time following the perturbation". This rule can be quite useful whenever one is interested in a qualitative analysis of the influence of some design parameter (or input) on the system. Among a number of properties holding for positive systems, the one concerning a dominant mode undoubtedly stands out. It often allows one to dramatically simplify the stability analysis. This property is expressed through a series of results known as the Frobenius-Perron theorems, holding for matrices with positive entries. But, even more important is the fact that a number of properties rely only on the structure of the system, that is on the structure of existing influences among all the input, state, and output variables. In other words, it often suffices to know "who influences who" in order to give a complete answer to fundamental questions. In fact, if the influence of one variable on another is always positive, the compensation among different paths of influence will not be allowed. Due to this property, the influence graph, which shows the direct influences among the variables, becomes a valuable tool (structural model) of analysis. For this reason, after the definition of positive systems, we will introduce the notion of the influence graph and will systematically highlight which properties rely on the topology of the graph and which on the "level of influence". We will first discuss the classical properties of dynamical systems, that is, stability, reachability, observability, input-output maps, and minimum phase. Obviously, other properties of peculiar interest for positive systems, such as cyclicity, primitivity, excitability, and transparency will also be considered. These properties will enable us to give a better physical interpretation of the various results presented in the book. Following the exposition of the theory, we will consider a number of applications tied to models widely used by researchers and professionals during the last decades. We will discuss, in particular, the Leontief model used by economists for predicting productions and prices; the Leslie model used by demographers to study age-structured populations; the Markov chains; the compartmental models; and the birth and death processes, relevant to the analysis of queueing systems. At the end of this book, we will present a detailed guided bibliography and two appendixes concerning linear algebra and linear systems theory in order to make, if needed, the reader familiar with the mathematics used throughout the book.

T. Kaczorek, Positive 1D and 2D Systems. New York, NY, USA: Springer-Verlag, 2002.

In positive systems inputs, state variables and outputs take only nonnegative values. A variety of models having positive systems behavior can be found in engineering, management science, economics, social sciences, biology and medicine, etc. An overview of the state of the art in positive systems is given in the monographs of Farina and Rinaldi (2000) as well as Kaczorek (2002). Positive continuous-discrete 2D linear systems were introduced by Kaczorek (1998) along with positive hybrid linear systems (Kaczorek, 2007) and positive fractional 2D hybrid systems (Kaczorek, 2008a). Various methods of solvability of 2D hybrid linear systems were discussed by Kaczorek et al. (2008), and the solution to singular 2D hybrids linear systems was derived by Sajewski (2009). The realization problem for positive 2D hybrid systems was addressed by Kaczorek (2008b). Some problems of dynamics and control of 2D hybrid systems were considered by Dymkov et al. (2004) and Gałkowski et al. (2003). The problems of stability and robust stability of 2D continuous-discrete linear systems were investigated by Bistritz (2003), Busłowicz (2010a; 2010b, 2011) and Xiao (2001a; 2001b; 2003). Recently, stability and robust stability of a general model and of a Roesser type model of scalar continuous-discrete linear systems were analyzed by Busłowicz (2010a; 2010b; 2011). In this paper, new necessary and sufficient conditions for asymptotic stability of positive continuous-discrete 2D linear systems will be presented. The following notation will be used: R is the set of real numbers, Z+ stands for the set of nonnegative inte gers, Rn×m denotes the set of n×m real matrices, Rn×m + is the set of n × m matrices with nonnegative entries and Rn + = Rn×1 + , In denotes the n × n identity matrix.

T. Kaczorek, "Stabilization of positive linear systems by state feedback," Pomiary Automatyka Kontrola, vol. 3, pp. 2–5, 1999

This paper is concerned with the stability and stabilization of continuous-time interval systems. For stability analysis and stabilization of positive continuous-time interval systems, new necessary and sufficient conditions are derived. In particular, the proposed conditions can be easily implemented by using linear programming method. It is utilized to stabilize the system being positive and asymptotically stable via dynamic state feedback control. Finally, we provide an example to demonstrate the effectiveness and applicability of the theoretical results. Positive systems mean that the state variables are nonnegative at all times whenever the initial conditions are nonnegative. In the literature [1]-[4], many physical systems and applications are positive in the real world. For example, some applications include population numbers of animals, absolute temperature, chemical reaction, heat exchangers. Since positive systems have numerous applications in various areas, the stability analysis and synthesis problems for positive systems are important and interesting. In the recent years, therefore many results of positive systems have been presented [5]-[19]. Kaczorek [14] use Gersgorin's theorem and quadratic programming to establish a sufficient condition. Recently, some results of state-feedback controller have been obtained by linear matrix inequality (LMI) and linear programming (LP) in [15] and [16], respectively. The necessary and sufficient conditions by using a vertex algorithmic approach are obtained in [17]. Shu [18] fully investigates the observers and dynamic output-feedback controller problems of the positive interval linear systems, with time delay is presented in [19]. In this paper, a necessary and sufficient condition is proposed to solve the positivity and stability problem of interval systems. Combining the proposed condition with linear programming to establish the state-feedback controller, then the closed-loop system is not only asymptotically stable, but also positive.

H. Gao, J. Lam, C. Wang, and S. Xu, "Control for stability and positivity: Equivalent conditions and computation," IEEE Trans. Circuits Syst. II, Exp. Briefs, vol. 52, no. 9, pp. 540–544, Sep. 2005.

This paper investigates the stabilizability of linear systems with closed-loop positivity. A necessary and sufficient condition for the existence of desired state-feedback controllers guaranteeing the resultant closed-loop system to be asymptotically stable and positive is obtained. Both continuous- and discrete-time cases are considered, and all of the conditions are expressed as linear matrix inequalities which can be easily verified by using standard numerical software. Numerical examples are provided to illustrate the proposed conditions. I N MANY practical systems, variables are constrained to be nonnegative. Such constraints abound in physical systems where variables are used to represent levels of heat, population, and storage. For instance, age-structured populations described by certain Leslie models [6], compartmental models used in hydrology and biology applications, can be described by positive systems [13], [18], whose states and outputs are nonnegative whenever the initial condition and input signal are nonnegative. Since positive systems are defined on cones, not on linear spaces, many well-established results of general linear systems cannot be simply applied to positive systems. Therefore, in recent years, many researchers have shown their interests in positive systems and many fundamental results have been reported (see, for instance, [1]–[3], [7], [11], [12], [16], [17], [19], and [20] and the references therein). Among the great number of research results obtained for positive systems, much attention has been devoted to the behavioral analysis of such systems (readers are referred to [8] and [15] for a detailed account of the recent developments in positive systems). Meanwhile, the synthesis problems under the positivity constraint seem to have received relatively less attention. More specifically, the results about how to design controllers to obtain a closed-loop system which is stable and positive are still very limited [10], [21]. That is, given a possibly unstable linear system, does there exist a controller such that the resultant closed-loop system is asymptotically stable and positive? Moreover, if the answer is yes, how can we find one? Recently, Kaczorek [14] investigated the problem mentioned above. Using Gersgorin's theorem, existence conditions for state-feedback controllers were proposed for positive systems. It is worth mentioning that these conditions are only sufficient, and are only suitable for single-input systems. In the present work, we further investigate the stabilization problem for both continuous- and discrete-time multiple-input–multiple-output (MIMO) systems under the condition that the closed-loop system is positive. Instead of using algebraic techniques which have been widely employed for the analysis of positive systems, our development is based on matrix inequalities. Based on the well-established results of Lyapunov stability theory and nonnegative matrix, equivalent conditions in terms of linear matrix inequalities (LMIs) are obtained for the existence of stabilizing state-feedback controllers. A remarkable advantage of these conditions lies in the fact that they are not only necessary and sufficient, but also can be easily verifiable by using some standard numerical software. Moreover, these conditions readily construct a desired controller if it exists. To the authors' knowledge, this work represents the first LMI treatment on control synthesis for guaranteeing asymptotic stability and positivity. The remainder of this paper is organized as follows. Sections II and III present a necessary and sufficient condition for stabilization with positivity constraint, both for continuous- and discrete-time linear systems. Numerical examples are given in Section IV to illustrate the proposed method, and we conclude this paper in Section V. Notations: The notations used throughout the paper are fairly standard. The superscript " " stands for matrix transposition; denotes the -dimensional Euclidean space; is the set of all real matrices of dimension ; is the set of all real matrices with nonnegative entries and ; the notation means that is real symmetric and positive definite; and 0 represent identity matrix and zero matrix, respectively; stands for a block-diagonal matrix. Matrices, if their dimensions are not explicitly stated, are assumed to be compatible for algebraic operations.

C. Wang and T. Huang, "Static output feedback control for positive linear continuous-time systems," Int. J. Robust Nonlinear Control, vol. 23, no. 14, pp. 1537–1544, 2013.

This paper presents anewtechnique todesign static output-feedback controllers for continuous-timepositive uncertain linear systems. The design is performed throughan iterativealgorithmbasedonparameter-dependentlinearmatrixinequalityconditions,solvedby meansofrelaxations,withlocalconvergenceguaranteed.Aqualifiedfeasiblesolutionprovidesa stabilizingoutput-feedbackcontrollerthatalsoassuresthepositivityoftheclosed-loopsystem. Themainadvantageof theproposedmethodologyisthatthecontrolgainishandleddirectly as an optimizationvariable, that is, no change of variables is needed to recover the gain andnoparticular structure (e.g., diagonal) is imposed on theLyapunovor slackvariable matrixtoguaranteeclosed-looppositivity.Thisparticular featurealso facilitates thedesign ofdecentralizedorelement-wiseboundedgains,asillustratedbynumericalexperiments eat advance of the computational processing capac ity have allowed to solve increasingly complex control problems regardingdynamic systems subject to uncer tainties. Inthis scenario, convexoptimizationtechniques basedonsemidefiniteprogrammingstandout, specially those formulated in terms of linearmatrix inequalities (LMIs)[Boydetal.,1994,ElGhaouiandNiculescu,2000]. At the same time, awide range of practical problems is concernedwithsystems thathavenon-negativestates andoutputs,whosevariablesareusuallyassociatedwith physicalparametersthatcanonlyassumepositiveornull values. Inthiscontext, thesocalledpositivesystemscan suitablymodelindustrialprocesseswithchemicalreactors, heatexchangers,water reservoirs,networkflows, storage and communications systems [Berman andPlemmons, 1979,Luenberger,1979,FarinaandRinaldi,2000].Other applicationscanbefoundineconomicsandsociology,with demographic and sociological populationmodels, or in orcellcultures[BermanandPlemmons,1979,Luenberger, 1979,FarinaandRinaldi,2000]. Beyond the practical appealing, anothermotivation to investigate the control of positive systems is that not allmethods employed tohandle linear systems canbe directlyextendedtodealwithpositivesystems [Caccetta andRumchev,2000].Notethattoassurethepositiveness oftheclosed-loopcontinuous-timesystemisequivalentto verifyiftheclosed-loopdynamicmatrixisMetzler(thatis, withnonnegativeoffdiagonalelements).Recently,several approachesemergedinthecontroltheoryliteratureaiming totreat thisproblem[Briat, 2013,Ebiharaetal., 2014, Ait-Rami etal., 2014,ShenandLam, 2015, 2017, 2016, TanakaandLangbort,2011,WangandHuang,2013].One ofthechallengesishowtoextendthemethodsdeveloped forsingle inputsingleoutputsystems,asthosebasedon linear programming [Arneson andLangbort, 2012, Ait Rami, 2011,RoszakandDavison, 2009], tohandle the multi-variablecase.Besidesthat,althoughLMIsynthesis conditions for state-feedbackcontrol of positive systems canbeobtainedas adirect extensionof the techniques presentedinthe literature for traditional linear systems.

A. Benzaouia, A. Hmamed, and A. El Hajjaji, "Stabilization of controlled positive discrete-time T-S fuzzy systems by state feedback control," Int. J. Adapt. Control Signal Process., vol. 24, no. 12, pp. 1091–1106, 2010.

This paper deals with sufficient conditions of asymptotic stability and stabilization for nonlinear discrete-time systems represented by a Takagi–Sugeno-type fuzzy model whose state variables take only nonnegative values at all times *t* for any nonnegative initial state. This class of systems is called positive systems. The conditions of stabilizability are obtained with state feedback control. This work is based on multiple Lyapunov functions. The results are presented in linear matrix inequalities form. A real plant is studied to illustrate this technique This paper proposes a novel Lyapunov stabilization analysis of discrete-time polynomial-fuzzy-model-based (PFMB) control systems with time delay under positivity constraint. The polynomial fuzzy model is constructed to describe the dynamics of a non-linear discrete-time system with time delay. A model-based polynomial fuzzy controller is designed using non-parallel distributed compensation (PDC) technique to stabilize the system while driving the system states to positive using the positivity constraints. The Lyapunov stability and positivity conditions are formulated as sum-of squares (SOS). To relax the conservativeness of the obtained stability results, two main methods are proposed in this paper: 1) the piecewise linear membership functions (PLMFs) is used to introduce the approximate error between piecewise and the original membership functions into the stability analysis, 2) introduce the boundary information of the premise variables into the stability analysis since the premise variables hold rich non-linearity information. A Numerical examples are given to demonstrate the effectiveness of the proposed approach.

X. Chen, J. Lam, P. Li, and Z. Shu, "`1-induced norm and controller synthesis of positive systems," Automatica, vol. 49, no. 5, pp. 1377–1385, 2013.

In this paper, the problem of ℓ1ℓ1-induced controller design for discrete-time positive systems is investigated with the use of linear Lyapunov function. An analytical method to compute the exact value of ℓ1ℓ1-induced norm is first presented. Then, a novel characterization for stability and ℓ1ℓ1-induced performance is proposed. Based on the characterization, a necessary and sufficient condition for the existence of desired controllers is derived, and an iterative convex optimization approach is developed to solve the condition. In addition, the synthesis of the state-feedback controller for single-input multiple-output (SIMO) positive systems is investigated. For this special case, an analytic solution is established to show how the optimal ℓ1ℓ1-induced controller can be designed, and some links to the spectral radius of the closed-loop systems are provided. Finally, the theoretical results are illustrated through a numerical example.

CONCLUSION

In this paper, the FDO-based stabilization control scheme has been studied for continuous-time fractional linear system in the presence of unknown constant disturbances. To improve the ability of disturbance attenuation, a FDO has been employed to approximate the unknown disturbances. By using the developed FDO and the state feedback control method, a stabilization controller has been designed to guarantee the closed-loop system states positive and asymptotically stable. Furthermore, a sufficient condition of stabilization has been given for the case of constrained states offractional systems with constant disturbances. As the same time, two numerical simulations have been shown to illustrate the effectiveness of the developed control scheme.

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