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Uniform stable observer for the disturbance estimation in two renewable energy systems

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A B S T R A C T

In this study, an observer for the states and disturbance estimation in two renewable energy systems is introduced. The restrictions of the gains in the proposed observer are found to guarantee its stability and the convergence of its error; furthermore, these results are utilized to obtain a good estimation. The introduced technique is applied for the states and disturbance estimation in a wind turbine and an electric vehicle. The wind turbine has a rotatory tower to catch the incoming air to be transformed in electricity and the electric vehicle has generators connected with its wheels to catch the vehicle movement to be transformed in electricity.

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1. Introduction

The disturbances are undesired signals presented as inputs of a system which affect the outputs. This problem has been studied in many systems. Estimation of a disturbance in the system output is required since they can affect the sensors, actuators, plants, or controls, causing accidents or unnecessary costs. Thus, an observer to estimate the systems disturbance is an important and current issue, in the theory and applications.

There is some research about the disturbance rejection control. In [1], an active disturbance rejection methodology applied to a large class of uncertain flat systems is mentioned. A problem on bounded functional state estimation for time-delay systems with unknown bounded disturbances is studied in [2,14]. In [3,5], the geometric control for the disturbance rejection is mentioned. The methodology of active disturbance rejection control and its theoretical analysis are reviewed in [7]. In [10], the structure at infinity of infinite-dimensional linear time invariant systems with input and output spaces is discussed. In [11], local controllers are designed such that the system achieves the output synchronization with a desired disturbance attenuation performance. Control of a platoon of vehicles is designed in [12] when some suffer from disturbances. The structure at infinity method of [15,16] is employed for the disturbance rejection in linear systems. In [22], the disturbance estimations are considered into a virtual control law in each step to compensate the mismatched disturbances. The geometric approach is highly explained in [23]. In [24], the author review the status of geometric state space theory as developed for application of linear systems. A novel solution for electro-hydraulic variable valve timing system based on the concept of active disturbance rejection control is proposed in [25]. In [26], the authors study a singular perturbation margin and a generalized gain margin for linear time-invariant systems from the view of perturbations. The problem of composite hierarchical anti-disturbance control is addressed in [27]. In [28], the problems of the composite disturbance-observer-based output feedback control and passive control for Markovian jump systems with multiple disturbances are considered. A novel modification of active disturbance rejection control is proposed in [29] so that good disturbance rejection is achieved. Active disturbance rejection control has been designed in [30] for plants with delay. In [31], the problem of aperiodic-disturbance estimation and rejection in a modified repetitive-control system is analyzed.

From the aforementioned research, in [1,7,14,22,25,27–31], the authors have used observers for the disturbance estimation; thus, it should be interesting to analyze the stability and convergence of this observer for the estimation of the states and disturbance.

In this research, an alternative observer for the states and disturbance estimation in disturbed systems is studied. The contribution is to present some methods to find the gains of the

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proposed observer to guarantee its stability and the convergence of its error with the final objective of obtaining a good estimation. The introduced technique is applied for the states and disturbance estimation in a wind turbine and in an electric vehicle. The wind turbine has a rotatory tower and the electric vehicle has generators connected with the wheels, the first is for attracting the incoming air to be become in electricity and the other for attracting the vehicle movement to be become in electricity.

The rest of the paper is organized as follows. Section 2 shows the observer and its stability analysis for the systems without a disturbance. Section 3 presents the observer, its stability, convergence analysis, and disturbance estimation for the systems with a disturbance. Sections 4 and 5 employ the introduced strategy to estimate the states and disturbance in a wind turbine and an electric vehicle, respectively. Section 6 presents the conclusion and future research.

2. Observer for the systems without a disturbance

Consider the following not disturbed system (A, B, C, D):

$$\dot{x} = Ax + Bu$$
$$y = Cx + Du \tag{1}$$

where $t \geq 0$, $x \in \Re^n$ is the state, $u \in \Re^m$ is the control input, $y \in \Re^p$ is the output. $A \in \Re^{n\times n}$, $B \in \Re^{n\times m}$, $C \in \Re^{p\times n}$, and $D \in \Re^{p\times m}$ are matrices representing the maps $\mathbf{A}: \Re^n \to \Re^n$, $\mathbf{B}: \Re^m \to \Re^n$, $\mathbf{C}: \Re^n \to \Re^p$, and $\mathbf{D}: \Re^m \to \Re^p$, respectively.

2.1. Observer design

A device, or even a program that estimates the state variables of a system is called observer. If the observer estimates all the n state variables, it is called full-order observer.

The mathematical model of the observer, this is, the dynamics of the estimated state, is

$$\dot{\hat{x}} = A\hat{x} + Bu + L(\tilde{y})$$
$$\hat{y} = C\hat{x} + Du \tag{2}$$

where $\hat{x}$ denotes the estimated state vector, $\hat{y}$ is the estimated output and the term L is a map denoted as $L: \Re^p \to \Re^n$, whose matrix representation is called output-injection matrix. $\tilde{y} = y - \hat{y}$ is the output error.

The observer error is the difference between the real state and the state estimated by the observer, it is $\tilde{x} = x - \hat{x}$.

2.2. Stability analysis of the observer

In this section, the error of the observer applied to the not disturbed system is guaranteed to be exponentially stable based on the solution of the Lyapunov method.

From (1), and (2), the following equality is obtained:

$$\tilde{y} = C\tilde{x} \tag{3}$$

From (1) and (2), and the observer error equation can be formed as follows:

$$\dot{\tilde{x}} = A\tilde{x} - L\tilde{y} = [A - LC]\tilde{x} = A_0\tilde{x} \tag{4}$$

where $A_0 = A - LC$.

The following theorem shows the stability of the observer.

Theorem 1. *The error of the observer (14) and (15) used to estimate the parameters x of the system (1) is exponentially stable; thus, the observer error* $\tilde{x}$ *satisfies*

$$\|\tilde{x}\|^2 \leq \gamma e^{-\beta t}\|\tilde{x}_0\|^2 \tag{5}$$

where $\tilde{x}_0$ *is the initial condition of* $\tilde{x}$, $\gamma = \frac{\lambda_{\max}(P)}{\lambda_{\min}(P)}$, $\beta = \lambda_{\min}(QP^{-1})$, $\|\cdot\|$ *is the Euclidean norm in* $\Re^n$, $P \in \Re^{n\times n}$ *and* $Q \in \Re^{n\times n}$ *are positive matrices which satisfy the following equation*:

$$A_0^T P + PA_0 = -Q \tag{6}$$

where A_0 *is given in (4).*

Proof. Consider the following candidate Lyapunov function:

$$V = \tilde{x}^T P\tilde{x} \tag{7}$$

The derivation along the solution of (7) is

$$\dot{V} = \dot{\tilde{x}}^T P\tilde{x} + \tilde{x}^T P\dot{\tilde{x}}$$
$$\dot{V} = \tilde{x}^T\left(A_0^T P + PA_0\right)\tilde{x} \tag{8}$$

Considering $\tilde{y} = C\tilde{x}$ of (3) and $A_0^T P + PA_0 = -Q$ of (6) in (8), it gives

$$\dot{V} = -\tilde{x}^T Q\tilde{x} \tag{9}$$

(9) can be written as follows:

$$\dot{V} \leq -\beta V \tag{10}$$

where $\beta = \lambda_{\min}(QP^{-1})$. From (10), it is known that the error of the observer applied to the systems is exponentially stable. Using (10), its solution is obtained as follows:

$$e^{\beta t}\dot{V} \leq -e^{\beta t}\beta V$$
$$e^{\beta t}\dot{V} + e^{\beta t}\beta V \leq 0$$
$$\frac{d}{dt}\left(e^{\beta t}V\right) \leq 0$$
$$\int_0^t \frac{d}{d\tau}\left(e^{\beta\tau}V\right)\, d\tau \leq 0$$
$$e^{\beta\tau}V\Big|_0^t \leq 0$$
$$e^{\beta t}V - V_0 \leq 0$$
$$e^{\beta t}V \leq V_0$$
$$V \leq e^{-\beta t}V_0 \tag{11}$$

where V_0 is the initial condition of V. Using the definition of (7) in the last equation of (11) gives

$$\lambda_{\min}(P)\|\tilde{x}\|^2 \leq \tilde{x}^T P\tilde{x} = V$$
$$\leq e^{-\beta t}V_0 = e^{-\beta t}\tilde{x}_0^T P\tilde{x}_0 \leq \lambda_{\max}(P)e^{-\beta t}\|\tilde{x}_0\|^2$$
$$\Longrightarrow \|\tilde{x}\|^2 \leq \frac{\lambda_{\max}(P)}{\lambda_{\min}(P)}e^{-\beta t}\|\tilde{x}_0\|^2 \tag{12}$$

where $\tilde{x}_0$ is the initial condition of $\tilde{x}$. By using $\gamma = \frac{\lambda_{\max}(P)}{\lambda_{\min}(P)}$ of (5), Eq. (5) is established.□

The following section shows the observer for the systems with a disturbance.

3. Observer for the systems with a disturbance

Consider the following disturbed system (A, B, C, D, E):

$$\dot{x} = Ax + Bu + Ed$$
$$y = Cx + Du \tag{13}$$

where $t \geq 0$, $x \in \Re^n$ is the state, $u \in \Re^m$ is the control input, $y \in \Re^p$ is the output, $d \in \Re^m$ is the disturbance. $A \in \Re^{n\times n}$, $B \in \Re^{n\times m}$, $C \in \Re^{p\times n}$, $D \in \Re^{p\times m}$, and $E \in \Re^{n\times m}$ are matrices representing the maps $\mathbf{A}: \Re^n \to \Re^n$, $\mathbf{B}: \Re^m \to \Re^n$, $\mathbf{C}: \Re^n \to \Re^p$, $\mathbf{D}: \Re^m \to \Re^p$, and $\mathbf{E}: \Re^m \to \Re^n$, respectively.

3.1. Observer design

In this section, an observer will be designed based on the assumption that the input u and output y are known, but the disturbance d is unknown. Let $\hat{x} \in \Re^n$ be the estimation of the

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