

Finite-frequency control and energy optimization of nonlinear wind turbines using T–S fuzzy models

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Abstract: - This paper proposes an integrated fuzzy control and energy management strategy for nonlinear wind energy systems by combining the generalized Kalman–Yakubovich–Popov (gKYP) lemma with Takagi–Sugeno (T–S) fuzzy modeling. The nonlinear dynamics of the wind turbine are represented by a T–S fuzzy model, which enables the design of a finite-frequency Linear Matrix Inequality (LMI)-based controller. An observer-based structure incorporating a fuzzy Sliding Mode Observer (SMO) is developed to estimate unmeasured states and improve robustness against disturbances and modeling uncertainties. The control law is designed according to a Parallel Distributed Compensation (PDC) structure, while finite-frequency analysis is employed to enhance stability and disturbance attenuation over specified frequency ranges. In addition, a Stateflow-based energy management strategy is developed to regulate power flow, supply the load, and protect the battery by maintaining its state of charge within predefined limits. Simulation results demonstrate the effectiveness of the proposed approach in maintaining stable generator operation, improving disturbance rejection, and ensuring efficient power management under varying operating conditions.

Key-Words: - Energy conversion system; Energy management system; Takagi–Sugeno fuzzy model; Sliding Mode Observer; Finite-frequency control; Generalized Kalman–Yakubovich–Popov lemma; Linear Matrix Inequality; Observer-based control; Wind turbine.

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1 Introduction

The integration of wind energy systems into modern power grids has been significantly impacted by the growing global need for sustainable and renewable energy sources. Due to its abundance and low environmental impact, wind energy is seen as one of the most promising renewable resources. However, the stability, efficiency, and dependability of wind power systems are affected by nonlinear dynamics, wind speed variability, and extreme disturbances, [1], [2].

Various control strategies have been proposed in the literature to overcome these challenges. The Takagi–Sugeno (T–S) fuzzy modeling framework has gained recognition for its ability to approximate complex nonlinear systems using a set of linear submodels, [3]. This representation makes it possible to apply advanced control techniques based on Linear Matrix Inequalities (LMIs), which are widely used in robust control design to ensure system stability under parameter uncertainties and external disturbances, [4], [5].

In recent years, the generalized Kalman–Yakubovich–Popov (gKYP) lemma has been

developed as a powerful tool for finite-frequency analysis and control design, [6]. This approach is especially appropriate for wind energy systems, since specific frequency bands are primarily affected by disturbances and uncertainties. Control performance can be enhanced by incorporating the gKYP lemma into LMI-based synthesis while retaining strong stability over a defined frequency range, [7]. Moreover, accurate state estimation is a fundamental requirement for implementing observer-based control structures. The robustness of Sliding Mode Observers (SMOs) in estimating unmeasured states under modeling uncertainties and measurement noise is well-known, [8], [9]. Combining fuzzy observers with SMO techniques improves estimation precision and robustness, which is essential for real-time control of wind energy systems.

The nonlinear dynamics of the wind turbine system are represented by the T–S fuzzy model. Due to the effects of aerodynamics and fluctuating wind speeds, wind turbines display considerable nonlinear behavior. The T–S fuzzy approach simplifies the design of the control law by allowing the nonlinear system to be expressed as a weighted combination of

local linear models. Furthermore, this framework ensures the stability and robustness of the closed-loop system while enabling the use of LMIs for systematic control synthesis.

In hybrid renewable systems, efficient energy management techniques are just as important as robust control. These strategies guarantee effective power flow, battery safety, and load control. The flexible implementation of logical and rule-based control mechanisms for energy storage and dispatch is made possible by the use of Stateflow modeling tools, [10], [11]. In order to prevent overcharging and deep discharging and to guarantee system reliability in the face of varying wind conditions, this integration is crucial.

This research proposes a new fuzzy robust control and energy management approach for wind energy systems. The method integrates gKYP-based finite-frequency LMI control and observer design with T–S fuzzy modeling, [12], [13]. To precisely estimate system states in the presence of uncertainties, a reliable fuzzy-SMO observer structure is developed. Lyapunov-based analysis is used to verify the control architecture, which employs a Parallel Distributed Compensation (PDC) framework. Additionally, a Stateflow-based complete energy management scheme is implemented to maximize energy dispatch and guarantee safe battery and load operation. Simulation experiments support the proposed approach and show how it can improve performance, enhance robustness, and optimize wind power utilization.

Modeling Using the T–S Fuzzy Approach

By fusing fuzzy logic with linear system theory, the Takagi–Sugeno (T–S) fuzzy model provides an efficient framework for describing nonlinear systems. By approximating the behavior of nonlinear systems using a collection of linear submodels, each of which is activated under particular operating conditions, it streamlines the analysis and control design of nonlinear systems. Fuzzy If-Then rules, in which the consequent sections describe linear state-space equations and the premise variables specify the working regions, are used to connect these submodels. Depending on the degree of membership of the current state in each fuzzy region, a weighted average of these local models is then used to determine the global system response. This framework makes it easier to construct reliable and effective controllers while also simplifying the modeling of nonlinear systems. The T–S fuzzy model serves as the foundation for system representation

and is formulated as follows, [3]:

$$\begin{cases} \dot{\mathbf{x}}(t) = \sum_{i=1}^r \tilde{\lambda}_i(z(t)) [A_i \mathbf{x}(t) + B_i u(t) + B_{2i} \delta(t)] \\ \mathbf{y}(t) = \sum_{i=1}^r \tilde{\lambda}_i(z(t)) [C_i \mathbf{x}(t)] \end{cases} \quad (1)$$

2 Implementation of an Observer-Based Controller

Designing a control strategy for a wind turbine system within a finite frequency domain is the goal of this work, [14]. The control law is created using the traditional Parallel Distributed Compensation (PDC) paradigm to overcome this difficulty. Each fuzzy rule of the Takagi–Sugeno model is associated with a local linear controller inside this structure to create a fuzzy controller. In order to ensure a smooth and efficient control response under various operating conditions, the local controllers are subsequently blended in accordance with the membership degrees to obtain the overall control input.

$$u(t) = -\sum_{j=1}^r \tilde{\lambda}_j(z(t)) k_j \hat{\mathbf{x}}(t) \quad (2)$$

Where k_j are the gain matrices with the appropriate dimension $j = 1, 2, \dots, r$

In this case, an observer-based method is utilized to estimate the unknown components of the wind energy system in order to lessen the consequences of disturbances brought on by variations in wind speed. The following T–S observer is suggested to obtain precise state estimates for the nonlinear system described by the Takagi–Sugeno (T–S) model, [15]:

$$\begin{cases} \dot{\hat{\mathbf{x}}}(t) = \sum_{i=1}^r \sum_{j=1}^r \tilde{\lambda}_i(z(t)) h_j(z(t)) [A_i \hat{\mathbf{x}}(t) + B_i u(t) + L_i (y(t) - \hat{y}(t))] \\ \hat{y}(t) = \sum_{i=1}^r \tilde{\lambda}_i(z(t)) [C_i \hat{\mathbf{x}}(t)] \end{cases} \quad (3)$$

Where $L_j (j=1, \dots, r)$ the observers are gains to be determined and $\hat{\mathbf{x}}(t)$ is the state estimation.

Let us consider the estimation error:

$$\begin{aligned} \dot{\mathbf{e}}_x(t) &= \dot{\mathbf{x}}(t) - \dot{\hat{\mathbf{x}}}(t) \\ \dot{\tilde{\mathbf{x}}}(t) &= \sum_{i=1}^r \sum_{j=1}^r \tilde{\lambda}_i(z(t)) \tilde{\lambda}_j(z(t)) [\bar{A} \tilde{\mathbf{x}}(t) + \bar{B} \delta(t)] \\ (1 \leq i < j \leq r) \end{aligned} \quad (4)$$

$$\begin{aligned} \tilde{\mathbf{x}}(t) &= \begin{bmatrix} \mathbf{x}(t) \\ \mathbf{e}(t) \end{bmatrix}, \quad \tilde{\mathbf{x}}(t) = \begin{bmatrix} \mathbf{x}(t) \\ \mathbf{e}(t) \end{bmatrix}, \\ \text{Where} \quad \bar{A} &= \begin{bmatrix} A_i - B_i k_j & B_i k_j \\ 0 & A_i - L_j C_i \end{bmatrix}, \quad \bar{B} = \begin{bmatrix} B_{2i} \\ B_{2i} \end{bmatrix} \end{aligned} \quad (5)$$

3 Finite Frequency Domain Stability of the Observer-Based Control System

The goal is to design a Takagi–Sugeno (T–S) fuzzy model controller that leverages finite frequency domain techniques, an observer-based approach, and the generalized Kalman–Yakubovich–Popov (gKYP) lemma. This controller aims to stabilize the augmented system while meeting desired performance criteria. The finite frequency control problem is thus formulated as designing a controller that satisfies the following two conditions, [16]:

Closed-loop system (4) is asymptotically stable

The following finite frequency index holds:

$$\int_{\omega_1 \leq \omega \leq \omega_2} \chi(\omega)^T \chi(\omega) d\omega \leq \gamma^2 \int_{\omega_1 \leq \omega \leq \omega_2} w(\omega)^T w(\omega) d\omega \quad (6)$$

Where $\omega \in [\omega_1, \omega_2]$, ω_1, ω_2 represent the upper and lower bounds of the concerned frequency, $\gamma > 0$ is a prescribed scalar.

The interval frequency given by:

$$\begin{cases} \omega \in \mathbb{R}, & |\omega| \leq \omega_1, & \omega_1 \geq 0 & \text{(LF)} \\ \omega \in \mathbb{R}, & \omega_1 \leq \omega \leq \omega_2, & 0 \leq \omega_1 \leq \omega_2 & \text{(MF)} \\ \omega \in \mathbb{R}, & |\omega| \geq \omega_h, & \omega_h \geq 0, & \text{(HF)} \end{cases} \quad (7)$$

In order to properly analyze and develop the control system, the frequency spectrum is separated into three distinct ranges in this work: low-frequency (LF), middle-frequency (MF), and high-frequency (HF) bands. Targeted controller design and performance evaluation within these domains are made possible by the fact that each frequency range records distinct dynamic behaviors and disturbance characteristics of the system.

Several basic lemmas are presented to facilitate the theoretical development and stability analysis of the suggested controller. These lemmas offer the required mathematical tools and inequalities, such as those pertaining to Lyapunov stability theory and the generalized Kalman–Yakubovich–Popov (gKYP) lemma, which will be crucial in demonstrating the primary findings and guaranteeing thorough validation of the control method.

Lemma 1 (Generalized KYP Lemma, [16]) A key finding in control theory is the generalized Kalman–Yakubovich–Popov (gKYP) lemma, which connects linear matrix inequalities (LMIs) and frequency-domain inequalities (FDIs). Examine the linear system that (3) defines. The gKYP lemma gives necessary and sufficient conditions represented as LMIs that correspond to specific frequency-domain inequalities over given frequency ranges for a given scalar parameter γ .

Consider the linear system $(\bar{A}, \bar{B}, C)$, Let $\gamma > 0$ be a given scalar.

Given a symmetric matrix, the following statements are equivalent.

There exist symmetric matrices

$P = P^T, Q = Q^T \succ 0$ such that:

$$\begin{bmatrix} \bar{A} & \bar{B} \\ I & 0 \end{bmatrix}^T \Xi \begin{bmatrix} \bar{A} & \bar{B} \\ I & 0 \end{bmatrix} + \begin{bmatrix} I & 0 \\ 0 & -\gamma^2 I \end{bmatrix} \prec 0 \quad (8)$$

Low-frequency range $|\omega| \leq \omega_1$

$$\Xi = \begin{bmatrix} -Q & P \\ P & \omega_1^2 Q \end{bmatrix} \quad (9)$$

Middle-frequency range $\omega_1 \leq \omega \leq \omega_2$

$$\omega_c = \frac{\omega_1 + \omega_2}{2}$$

$$\Xi = \begin{bmatrix} -Q & P + j\omega_c Q \\ P - j\omega_c Q & -\omega_1 \omega_2 Q \end{bmatrix} \quad (10)$$

High-frequency range $|\omega| \geq \omega_h$

$$\Xi = \begin{bmatrix} Q & P \\ P & -\omega_h^2 Q \end{bmatrix} \quad (11)$$

Lemma 2. (Projection Lemma). Given a symmetric matrix $\Omega \in \mathbb{R}^{m \times m}$ and two matrices Γ, Π of column dimension m , there exists a matrix F such that the following LMI holds:

$$\Omega + \Gamma F \Pi + \Pi^T F^T \Gamma^T < 0 \quad (12)$$

If and only if the following projection inequalities with respect to F are satisfied

$$\Gamma^\perp \Omega \Gamma^{\perp T} < 0 \quad (13)$$

$$\Pi^\perp \Omega \Pi^{\perp T} < 0 \quad (14)$$

Using Lemmas 1 and 2, this problem can be formulated in terms of convex optimization, which can guarantee the asymptotic stability and the FF performance of the whole system (6) as shown in the next theorem.

Theorem 1. For $\gamma > 0$ system (6) is asymptotically stable if there exist hermitian matrices

$$\tilde{P} = \begin{bmatrix} \tilde{P}_1 & \tilde{P}_2 \\ * & \tilde{P}_3 \end{bmatrix}, \quad \tilde{Q} = \begin{bmatrix} \tilde{Q}_1 & \tilde{Q}_2 \\ * & \tilde{Q}_3 \end{bmatrix} \succ 0 \quad (15)$$

$$\tilde{Y} = \begin{bmatrix} \tilde{Y}_1 & \tilde{Y}_2 \\ * & \tilde{Y}_3 \end{bmatrix} \succ 0 \quad (16)$$

a symmetric matrix

$$F = \begin{bmatrix} F_1 & F_1 \\ F_1 & F_1 \end{bmatrix} \quad (17)$$

such that the following LMIs conditions hold in (17) for any $1 \leq i < j \leq r$:

$$\begin{cases} \Phi \prec 0 \\ \Psi \prec 0 \end{cases} \quad (17)$$

Where

$$\Phi = \begin{bmatrix} -\bar{F}_1^T - \bar{F}_1 & -\bar{F}_1^T - \bar{F}_1 & \Phi_{13} & \Phi_{14} \\ * & -\bar{F}_1^T - \bar{F}_1 & \Phi_{23} & \Phi_{24} \\ * & * & \Phi_{33} & \Phi_{34} \\ * & * & * & \Phi_{44} \end{bmatrix} \prec 0 \quad (18)$$

$$\Psi = \begin{bmatrix} \Psi_{11} & \Psi_{12} & \Psi_{13} & \Psi_{14} & \bar{F}_1 B_{2i} \\ * & \Psi_{22} & \Psi_{23} & \Psi_{24} & \bar{F}_1 B_{2i} \\ * & * & \Psi_{33} & \Psi_{34} & 0 \\ * & * & * & \Psi_{44} & 0 \\ * & * & * & * & -\gamma^2 I \end{bmatrix} \prec 0 \quad (19)$$

We have:

$$\begin{aligned} \Phi_{13} &= \tilde{Y}_1 + A_i \bar{F}_1^T - B_i X_j - \bar{F}_1 \\ \Phi_{14} &= \tilde{Y}_2 + B_i X_j + A_i \bar{F}_1^T - C_i Z_j - \bar{F}_1 \\ \Phi_{23} &= \tilde{Y}_2 + A_i \bar{F}_1^T - B_i X_j - \bar{F}_1 \\ \Phi_{24} &= \tilde{Y}_3 + B_i X_j + A_i \bar{F}_1^T - C_i Z_j - \bar{F}_1 \\ \Phi_{33} &= A_i \bar{F}_1^T - B_i X_j + \bar{F}_1 A_i^T - X_j^T B_i^T \\ \Phi_{34} &= B_i X_j + X_j^T B_i^T + A_i^T \bar{F}_1^T + \bar{F}_1 A_i - C_i Z_j - Z_j^T C_i^T \\ \Phi_{44} &= B_i X_j + X_j^T B_i^T + A_i^T \bar{F}_1^T + \bar{F}_1 A_i - C_i Z_j - Z_j^T C_i^T \end{aligned} \quad (20)$$

The expressions of Ψ given as follows:

Low-frequency (LF) domain $|\omega| \leq \omega_1$

$$\begin{aligned} \Psi_{11} &= -\tilde{Q}_1 - \bar{F}_1^T - \bar{F}_1 \\ \Psi_{12} &= -\tilde{Q}_2 - \bar{F}_1^T - \bar{F}_1 \\ \Psi_{13} &= \tilde{P}_1 + A_i \bar{F}_1^T - B_i X_j - \bar{F}_1 \\ \Psi_{14} &= \tilde{P}_2 + A_i \bar{F}_1^T - C_i Z_j - \bar{F}_1 + B_i X_j \\ \Psi_{22} &= -\tilde{Q}_3 - \bar{F}_1^T - \bar{F}_1 \\ \Psi_{23} &= \tilde{P}_2 + A_i \bar{F}_1^T - B_i X_j - \bar{F}_1 \\ \Psi_{24} &= \tilde{P}_3 + A_i \bar{F}_1^T - C_i Z_j - \bar{F}_1 + B_i X_j \\ \Psi_{33} &= \omega_1^2 Q_1 + A_i \bar{F}_1^T - B_i X_j + \bar{F}_1 A_i^T - X_j^T B_i^T \\ \Psi_{34} &= \omega_1^2 \tilde{Q}_2 + B_i X_j + A_i \bar{F}_1^T - C_i Z_j + X_j^T B_i^T + \bar{F}_1 A_i^T - Z_j^T C_i^T \\ \Psi_{44} &= \omega_1^2 \tilde{Q}_3 + B_i X_j + A_i \bar{F}_1^T - C_i Z_j + X_j^T B_i^T + \bar{F}_1 A_i^T - Z_j^T C_i^T \end{aligned} \quad (21)$$

Middle-frequency (MF) domain $\omega_1 \leq \omega \leq \omega_2$

$$\begin{aligned} \Psi_{11} &= -\tilde{Q}_1 - \bar{F}_1^T - \bar{F}_1 \\ \Psi_{12} &= -\tilde{Q}_2 - \bar{F}_1^T - \bar{F}_1 \\ \Psi_{13} &= \tilde{P}_1 + j\omega_c Q_1 + A_i \bar{F}_1^T - B_i X_j - \bar{F}_1 \\ \Psi_{14} &= \tilde{P}_2 + j\omega_c Q_2 + A_i \bar{F}_1^T - C_i Z_j - \bar{F}_1 + B_i X_j \\ \Psi_{22} &= -\tilde{Q}_3 - \bar{F}_1^T - \bar{F}_1 \\ \Psi_{23} &= \tilde{P}_2 + j\omega_c Q_2 + A_i \bar{F}_1^T - B_i X_j - \bar{F}_1 \\ \Psi_{24} &= \tilde{P}_3 + j\omega_c Q_3 + A_i \bar{F}_1^T - C_i Z_j - \bar{F}_1 + B_i X_j \\ \Psi_{33} &= -\omega_1 \omega_2 \tilde{Q}_1 + A_i \bar{F}_1^T - B_i X_j + \bar{F}_1 A_i^T - X_j^T B_i^T \\ \Psi_{34} &= -\omega_1 \omega_2 \tilde{Q}_2 + B_i X_j + A_i \bar{F}_1^T - C_i Z_j + X_j^T B_i^T + \bar{F}_1 A_i^T - Z_j^T C_i^T \\ \Psi_{44} &= -\omega_1 \omega_2 \tilde{Q}_3 + B_i X_j + A_i \bar{F}_1^T - C_i Z_j + X_j^T B_i^T + \bar{F}_1 A_i^T - Z_j^T C_i^T \end{aligned} \quad (22)$$

High-frequency (HF) domain $|\omega| \geq \omega_\square$

$$\begin{aligned} \Psi_{11} &= -\tilde{Q}_1 - \bar{F}_1^T - \bar{F}_1 \\ \Psi_{12} &= -\tilde{Q}_2 - \bar{F}_1^T - \bar{F}_1 \\ \Psi_{13} &= \tilde{P}_1 + A_i \bar{F}_1^T - B_i X_j - \bar{F}_1 \\ \Psi_{14} &= \tilde{P}_2 + A_i \bar{F}_1^T - C_i Z_j - \bar{F}_1 + B_i X_j \\ \Psi_{22} &= -\tilde{Q}_3 - \bar{F}_1^T - \bar{F}_1 \\ \Psi_{23} &= \tilde{P}_2 + A_i \bar{F}_1^T - B_i X_j - \bar{F}_1 \\ \Psi_{24} &= \tilde{P}_3 + A_i \bar{F}_1^T - C_i Z_j - \bar{F}_1 + B_i X_j \\ \Psi_{33} &= -\omega_h^2 Q_1 + A_i \bar{F}_1^T - B_i X_j + \bar{F}_1 A_i^T - X_j^T B_i^T \\ \Psi_{34} &= -\omega_h^2 \tilde{Q}_2 + B_i X_j + A_i \bar{F}_1^T - C_i Z_j + X_j^T B_i^T + \bar{F}_1 A_i^T - Z_j^T C_i^T \\ \Psi_{44} &= -\omega_h^2 \tilde{Q}_3 + B_i X_j + A_i \bar{F}_1^T - C_i Z_j + X_j^T B_i^T + \bar{F}_1 A_i^T - Z_j^T C_i^T \end{aligned} \quad (23)$$

Proof: First, we consider the middle-frequency case. Using Lemma 1, equation (6) can be rewritten as:

$$\begin{bmatrix} \bar{A} & \bar{B} \end{bmatrix}^T \begin{bmatrix} -Q & P + j\omega_c Q & 0 \\ P - j\omega_c Q & -\omega_1 \omega_2 Q & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \bar{A} & \bar{B} \\ I & 0 \\ 0 & I \end{bmatrix} + \begin{bmatrix} \bar{A} & \bar{B} \end{bmatrix}^T \begin{bmatrix} 0 & 0 & 0 \\ 0 & I & 0 \\ 0 & 0 & -\gamma^2 I \end{bmatrix} \begin{bmatrix} \bar{A} & \bar{B} \\ I & 0 \\ 0 & I \end{bmatrix} \prec 0 \quad (24)$$

$$\begin{bmatrix} \bar{A} & \bar{B} \end{bmatrix}^T \begin{bmatrix} -Q & P + j\omega_c Q & 0 \\ P - j\omega_c Q & -\omega_1 \omega_2 Q & 0 \\ 0 & 0 & -\gamma^2 I \end{bmatrix} \begin{bmatrix} \bar{A} & \bar{B} \\ I & 0 \\ 0 & I \end{bmatrix} \prec 0 \quad (25)$$

The projection lemma 2 is applied, and we obtain the inequality

$$\Phi + \Gamma F \Pi + \Pi^T F \Gamma^T < 0 \quad (26)$$

Where

$$\Gamma = \begin{bmatrix} I \\ I \\ 0 \end{bmatrix} \quad \Pi = \begin{bmatrix} -I & \bar{A} & \bar{B} \end{bmatrix}$$

$$\Phi = \begin{bmatrix} -Q & P + j\omega_c Q & 0 \\ P - j\omega_c Q & -\omega_1 \omega_2 Q & 0 \\ 0 & 0 & -\gamma^2 I \end{bmatrix} \quad (27)$$

$$\begin{bmatrix} -Q & P + j\omega_c Q & 0 \\ P - j\omega_c Q & -\omega_1 \omega_2 Q & 0 \\ 0 & 0 & -\gamma^2 I \end{bmatrix} + \begin{bmatrix} I \\ 0 \end{bmatrix} F \begin{bmatrix} -I & \bar{A} & \bar{B} \end{bmatrix} + \begin{bmatrix} -I & \bar{A} & \bar{B} \end{bmatrix}^T F^T \begin{bmatrix} I \\ 0 \end{bmatrix} < 0 \quad (28)$$

after calculating, we get :

$$\begin{bmatrix} -Q - F - F^T & P + j\omega_c Q + F A_i - F B_i k_j - F^T & F B_{2i} \\ * & -\omega_1 \omega_2 Q + F A_i - F B_i k_j + A_i^T F^T - k_j^T B_i^T F^T & F B_{2i} \\ * & * & -\gamma^2 I \end{bmatrix} < 0 \quad (29)$$

To solve the nonlinear problem, we perform a congruence transformation by multiplying both sides of the equation by the full rank matrix $\text{diag}\{F^{-1} \ F^{-1} \ I\}$ and its transpose from the right and the left, we get:

$$\begin{bmatrix} -\tilde{Q} - \tilde{F}^T - \tilde{F} & \tilde{P} + j\omega_c \tilde{Q} + A_i \tilde{F}^T - B_i X_j - \tilde{F} & B_{2i} \tilde{F}^T \\ * & -\omega_1 \omega_2 \tilde{Q} + A_i \tilde{F}^T - B_i X_j + \tilde{F} A_i^T - X_j^T B_i^T & B_{2i} \tilde{F}^T \\ * & * & -\gamma^2 I \end{bmatrix} < 0 \quad (30)$$

Consider a candidate of the Lyapunov function

$$\bar{A}^T P + P \bar{A} < 0 \quad (31)$$

Which is given in the form

$$\begin{bmatrix} \bar{A} \\ I \end{bmatrix}^T \begin{bmatrix} 0 & P \\ P & 0 \end{bmatrix} \begin{bmatrix} \bar{A} \\ I \end{bmatrix} < 0 \quad (32)$$

by Lemma 2, the equations are equivalent to

$$\begin{bmatrix} 0 & P \\ P & 0 \end{bmatrix} + \begin{bmatrix} F \\ F \end{bmatrix} \begin{bmatrix} -I & \bar{A} \end{bmatrix} + \begin{bmatrix} -I & \bar{A} \end{bmatrix}^T \begin{bmatrix} F \\ F \end{bmatrix} < 0 \quad (33)$$

Where $\bar{A} = A_i - B_i k_j$ $\bar{B} = B_{2i}$

In order to stabilize the closed-loop system, the projection Lemma is applied. After some easy manipulations, we get Theorem 1.

4 Illustrative example Wind system

A wind turbine mechanically connected to an electrical generator via a drive train makes up the Wind Energy Conversion System (WECS) in this study, [13]. The turbine's inherent rotational speed is frequently insufficient to provide optimal energy output due to wind speed variations brought on by shifting climatic conditions. A mechanical speed multiplier, represented as a gain factor GGG, is added between the turbine and the generator to get around this restriction. By bringing the generator closer to its ideal rotational speed, this gadget improves overall

efficiency. Additionally, as shown in Figure 1 (Appendix), a specific control method is used to keep the turbine operating at the Maximum Power Point (MPP).

The simulation is performed with MATLAB by using the Toolbox LMI. The resolution of LMIs given in (17) provides the following gains. Feedback and observer gain matrices obtained by the following values:

$$k_1 = \begin{bmatrix} 0.0007 & -0.0003 & 0.1156 & -0.0022 \\ -181.4361 & 19.5755 & 0.2852 & -2.4789 \end{bmatrix}$$

$$k_2 = \begin{bmatrix} 0.0007 & -0.0004 & 0.1314 & -0.0043 \\ -181.6694 & 19.6006 & 0.3340 & -2.4821 \end{bmatrix}$$

$$k_3 = \begin{bmatrix} 0.0007 & -0.0002 & 0.1161 & 0.0006 \\ -181.3347 & 19.5646 & 0.2856 & -2.4776 \end{bmatrix}$$

$$k_3 = \begin{bmatrix} 0.0007 & -0.0003 & 0.1159 & -0.0026 \\ -181.2910 & 19.5599 & 0.2543 & -2.4769 \end{bmatrix}$$

$$L_1 = \begin{bmatrix} 0.0052 \\ 0.0001 \\ -0.2067 \\ -0.0806 \end{bmatrix}, \quad L_2 = \begin{bmatrix} -0.0004 \\ 0.0000 \\ -0.2209 \\ -0.0620 \end{bmatrix}$$

$$L_3 = \begin{bmatrix} 0.00514 \\ 0.0001 \\ -0.2087 \\ -0.07020 \end{bmatrix}, \quad L_4 = \begin{bmatrix} 0.0055 \\ 0.0001 \\ -0.2044 \\ -0.0896 \end{bmatrix}$$

and $\gamma = 0.110$

When the results of this work are compared to those of, [19], it becomes clear that the suggested method performs well and minimizes changes in the generator's speed and control forces.

The time response of the generator speed with PDC command and a finite frequency Takagi Sugeno fuzzy with observer-based controller as shown in Figure 2 (Appendix), We can see that the system performs well under the suggested condition using a finite frequency technique, and the suggested method makes the system more stable.

If $\text{SOC} < 20\%$ and $\text{wind} \geq \text{load}$, wind supplies load + recharges battery.

If $\text{SOC} < 20\%$ and $\text{wind} < \text{load}$, both load and battery are supplied by a diesel generator.

The energy management system we put in place with the State flow tool is described by the algorithm as shown in Figure 3 (Appendix). This system is built to manage a variety of potential operational situations. In order to protect the battery from excessive discharge and overcharging, the wind energy management technique proposed here efficiently controls both the wind power input and energy storage, [14], [17]. The control logic relies on three key input parameters:

Pwind: Available wind power

Load: Power demand from the load

SOC (State of Charge): Battery charge level, where the SOC is limited between a minimum of 20% (to prevent deep discharge) and a maximum of 80% (to prevent overcharging), [18]

Five different operational circumstances are taken into account by the system:

Cases:

If SOC is within limits and $\text{wind} \geq \text{load}$, wind power supplies the load + charges the battery.

If SOC within limits but $\text{wind} < \text{load}$, battery supplements the power.

If $\text{SOC} \geq 80\%$, wind is diverted to auxiliary battery.

The EMA, the energy management algorithm optimizes energy production while maintaining stability. Using the T–S model, control actions for pitch and torque are computed to maximize energy capture within frequency-stability limits.

While preserving system stability, the Energy Management Algorithm (EMA) maximizes energy production. It computes control actions for the pitch and generator torque using the T-S fuzzy model and real-time measurements. The technique, which maximizes energy capture while maintaining stability margins, is computationally efficient and concentrates on finite-frequency management.

Several recent studies have investigated robust fuzzy control techniques, [18], [19].

5 Conclusion

This study proposes an integrated fuzzy resilient control and energy management approach for wind energy systems by combining the advantages of Takagi–Sugeno (T–S) fuzzy modelling, and the extended Kalman–Yakubovich–Popov (gKYP) lemma. By linearizing the nonlinear dynamics of wind turbines and employing LMI-based optimization in the finite frequency domain, the proposed controller ensures both robust performance and asymptotic stability. Using a fuzzy sliding mode observer enhances the system's ability to estimate and correct for uncertainties and external disruptions. A Stateflow-based energy management algorithm also effectively controls power flow, safeguards battery health, and adjusts to shifting operating conditions. It is verified that the strategy can optimize wind power use, improve system resilience, and guarantee stable and reliable operation.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this work, the author(s) utilized artificial intelligence (AI) technologies solely for the purpose of linguistic refinement and grammatical correction. Following the application of these tools, the author(s) comprehensively reviewed, verified, and edited the resulting text. The author(s) maintain full accountability and responsibility for the accuracy, integrity, and final content of the publication.

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The author contributed to the conception, design, implementation, and validation of the proposed approach, and approved the final version of the manuscript.

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Conflict of Interest

The author declares that there is no.

Data Availability (optional)

The data used in this study are available from the author upon reasonable request.

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APPENDIX

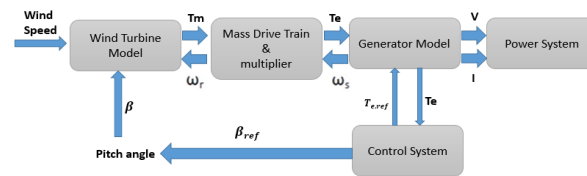


Fig. 1: Control strategy of wind energy conversion system, [14]

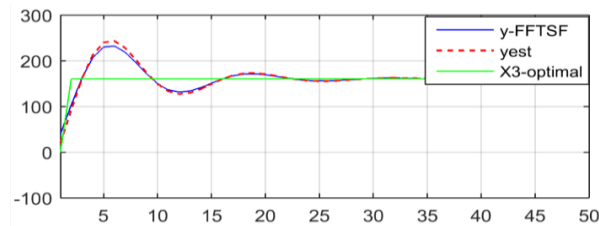


Fig. 2: Generator rotated speed (rd/s) with FFTSF controller based on observers, [14]

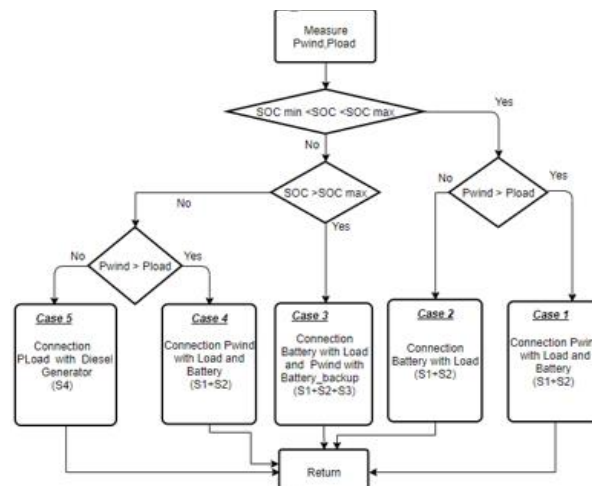


Fig. 3: Management energy algorithm of the wind system, [14]