2024 Tenth Indian Control Conference (ICC)
9 - 11 December, 2024
IISER Bhopal, India

T-S fuzzy-based Load Frequency Control Design for Nonlinear Power Systems Under Stochastic Actuator Failures

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***Abstract*— This paper investigates the switched load frequency control techniques for nonlinear power systems together with energy storage system (ESS) subject to actuator faults. In this regard, the faults of actuator are assumed to occur randomly and the fault rates are characterized by stochastic variables that satisfy certain probability conditions. Next, a Takagi-Sugeno fuzzy model is employed to describe the nonlinear characteristics in turbine and governor dynamics of power systems with ESS. The reliable proportional-integral (PI)-type load frequency control is proposed by utilizing the switching approach and Lyapunov-Krasovskii functional with the membership function information, which ensures the asymptotic stability of power system with ESS in the mean-square sense via H_∞ performance index. At last, the numerical examples are presented to illustrate the superiority of the proposed method.**

I. INTRODUCTION

The stability of frequency is a critical measure of power system performance. Sudden changes in load can cause deviations in tie-line power exchanges and lead to frequency fluctuations. To handle this situation, load frequency control (LFC) has been utilized in power systems for many years due to its exceptional capability to maintain the frequency and regulate power exchanges with neighboring areas at predetermined levels [1]–[4]. For example, H_∞-based LFC scheme has been developed in [4] for a hybrid power systems with renewable energy sources (RES). Also, a distributed LFC framework has been addressed for multi-area power interconnection systems in [2]. Moreover, the authors in [3] have designed the proportional integral (PI) derivative-based LFC scheme for power system, which efficaciously preserved the frequency response at a stable state.

Besides, due to the reduction of fossil fuel reserve and its impact on the environment, some RES have been extensively utilized and developed [5]. However, the intermittent and unpredictable nature of these resources presents the remarkable challenges to the stability and frequency control of power systems. As a result, more operating reserves will be needed to address the imbalance between generation and load. Further, energy storage systems (ESS) has been focused more on power system operation planning over the past few decades [6]–[8]. In addition, the authors in [9] addressed that ESS offers potential advantages in managing uncertainties associated with RES by facilitating charging or discharging to address frequency deviations as they arise. Therefore, this study focuses on the LFC design of power systems with ESS (PSWESS).

On the other hand, the occurrence of non-linearity by valve position limits poses the additional difficulties for power system stability and LFC scheme design. In this regard, the Takagi-Sugeno (T-S) fuzzy systems approach mathematically represent the nonlinear systems as a weighted sum of linear system with membership functions. By the T-S fuzzy model, the research results of various nonlinear systems have been extensively employed, see [10]–[12]. To mention a few, the T-S fuzzy model has been utilized in [13] to investigate the stability of nonlinear large-scale interconnected power systems instead of linearizing the nonlinear model at a certain operating point. In [14], a delayed T-S fuzzy model has been established for the LFC design of three-area power system under event-triggered scheme. In addition, the nonlinearity in valve position limit on the governor has been handled for uncertain power systems based on the T-S fuzzy approach [15]. Recently, the T-S fuzzy approach has been applied to the PSWESS by examining the nonlinearities in turbine and governor dynamics [16].

Meanwhile, actuator plays a crucial role in control systems if it undergoes failures which can disrupt the normal operation or even cause power systems to cease functioning, resulting in varying degrees of economic losses [17], [18]. Therefore, the power system requires a reliable control strategy to ensure and maintain desirable performance even in the presence of faulty actuators. To ease this situation, the authors in [19]–[21] addressed the actuator failures in power systems via fault tolerant control technique and enhances the system performance. In practical point of view, the actuator fault happens not only deterministic but also in a stochastic manner due to the random nature of fault patterns [22], [23]. Thus, the previously discussed cases may not fully capture the diversity of actuator faults. It is more appropriate and meaningful to consider fault factors that follow probabilistic distributions within specific intervals. However, to the best of authors knowledge, there has been no reported work on LFC design of T-S fuzzy-based PSWESS subject to the stochastic actuator faults under the switching technique.

Motivated by the above, the present study investigates the stability and stabilization of PSWESS. The main contributions of the study are summarized as follows.

- By considering the non-linearity of valve position limits, the T-S fuzzy-based PSWESS is formulated under stochastic actuator fault.

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- A T-S fuzzy membership function-based Lyapunov-Krasovskii functional (LKF) is developed. By using the LKF and property of membership function, a novel switching-based PI-type H_∞ LFC scheme is devised for the stabilization of T-S fuzzy-based PSWESS.
- In a numerical example, the advantages of proposed method is demonstrated via comparative analysis with existing results.

II. PROBLEM DESCRIPTION

This section presents the state space model for nonlinear PSWESS via T-S fuzzy approach.

A. Mathematical Model of PSWESS

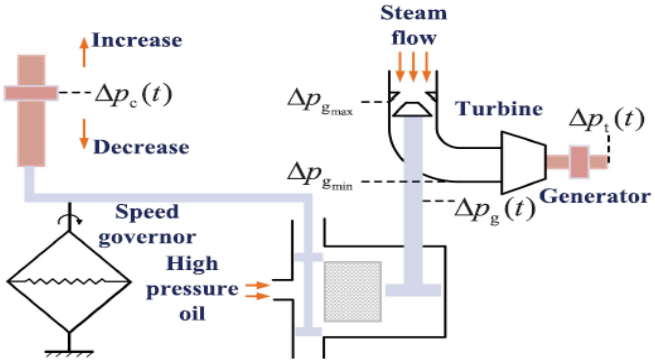


Fig. 1: Typical structure of turbine.

Consider the schematic diagram of mechanical structure of turbine as in Fig. 1. From Fig.1, the inflow of steam is regulated by the mechanical limits of the valve position, which causes the nonlinearities in turbine and governor dynamics. In addition, a nonlinear function of $\Delta p_g(t)$ is represented by $\zeta(\Delta p_g(t))$ with the upper and lower bounds $\zeta_{\max}$ and $\zeta_{\min}$. Hence, the non-linearity of valve position limits are considered in this study and state-space model for nonlinear PSWESS is described as

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu^f(t-\delta(t)) + F_i w(t) \\ y(t) = Cx(t) \\ x(t) = \psi(t),\ t \in [-\delta_2, 0] \end{cases}, \quad (1)$$

here, the state vector $x^T(t) = [\Delta f(t) \quad \Delta p_t(t) \quad \Delta p_g(t) \quad \Delta p_e(t) \quad \int ACE(t)]$, $y^T(t) = [ACE(t) \quad \int ACE(t)]$ is the output vector, in which $ACE(t)$ is defined by $ACE(t) = \beta\Delta f(t)$. $w(t) = \Delta p_d(t)$ is the external disturbance which satisfies $\|\Delta p_d(t)\| \le \bar{p}_d$, and $\psi(t)$ represents the initial condition. The system matrices are given as

$$A = \begin{bmatrix} -\frac{\mathcal{D}}{\mathcal{M}} & \frac{1}{\mathcal{M}} & 0 & \frac{1}{\mathcal{M}} & 0 \\ 0 & -\frac{1}{\mathcal{T}_t} & \frac{\zeta(\Delta p_g(t))}{\mathcal{T}_t \Delta p_g(t)} & 0 & 0 \\ -\frac{1}{\mathcal{T}_g \mathcal{R}} & 0 & \frac{\zeta(\Delta p_g(t))}{\mathcal{T}_g \Delta p_g(t)} & 0 & 0 \\ \frac{\rho_e k_e}{\mathcal{T}_e} & 0 & 0 & -\frac{1}{\mathcal{T}_e} & 0 \\ \beta & 0 & 0 & 0 & 0 \end{bmatrix}, B = \begin{bmatrix} 0 \\ 0 \\ \frac{\alpha_1}{\mathcal{T}_g} \\ \frac{\alpha_2 k_e}{\mathcal{T}_e} \\ 0 \end{bmatrix},$$

$$F = \begin{bmatrix} -\frac{1}{\mathcal{M}} & 0 & 0 & 0 & 0 \end{bmatrix}^T,$$

$$C = \begin{bmatrix} \beta & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}^T.$$

Also, $\delta(t)$ is the time-varying signal transmission delay, satisfying $0 \le \delta(t) \le \delta_2$ and $\dot{\delta}(t) \le \sigma < 1$. The parameter descriptions are given in Table I. Here, α_1 and α_2 denote the participation ratios of governor and ESS with $\alpha_1 + \alpha_2 = 1$.

Furthermore, the stochastic actuator fault is described as

$$u^f(t) = \Xi u(t)$$

where $u(t) = \Delta p_c(t)$ is the control input, Ξ is a random variable which takes the values in the interval $[0, 1]$. The mean and variance of Ξ is denoted as $\bar{\Xi}$ and $\hat{\Xi}^2$, respectively. Hence, one can obtain $\mathbb{E}\{\Xi - \bar{\Xi}\} = 0$.

TABLE I: Parameter descriptions of nonlinear PSWESS

Parameter	Description
$\Delta f(t)$	Frequency deviation
$\Delta p_t(t)$	Generator mechanical power deviation
$\Delta p_g(t)$	Turbine value position deviation
$\mathcal{T}_t$	Time constant of turbine
$\Delta p_d(t)$	Load deviation
$\Delta p_c(t)$	Load reference set-point deviation
$\mathcal{M}$	Equivalent inertia constant
$\mathcal{D}$	Damping coefficient
$\mathcal{R}$	Governor droop coefficient
β	Frequency bias factor
$\mathcal{T}_g$	Time constant of governor
$\Delta p_{g_{\max}}$	Open limits of turbine value position
$\Delta p_{g_{\min}}$	Close limits of turbine value position
$\Delta p_e(t)$,	Power output deviation of ESS
$\mathcal{T}_e$	Time constant of ESS
k_e	Unit adjustment factor of ESS

B. T-S Fuzzy Representation

In this section, the analytic T-S fuzzy system can be formulated for the nonlinear PSWESS (1) by representing the nonlinear term $\zeta(\Delta p_g(t))$ as a convex combinations of suitable vertices. Here, $\Delta p_g(t)$ is a premise variable and assume that $\Delta p_g(t) \in [\Lambda_L, \Lambda_U]$. Then, we consider that

$$\begin{cases} \zeta(\Delta p_g(t)) = \Gamma_1(\Delta p_g(t))\Delta p_g(t) + \eta\Gamma_2(\Delta p_g(t))\Delta p_g(t) \\ \Gamma_1(\Delta p_g(t)) + \Gamma_2(\Delta p_g(t)) = 1 \end{cases}, \quad (2)$$

where $\eta = \min\left(|\frac{\zeta_{\min}}{\Lambda_L}|, |\frac{\zeta_{\max}}{\Lambda_U}|\right)$. From (2), we obtain

$$\begin{cases} \Gamma_1(\Delta p_g(t)) = \frac{\zeta(\Delta p_g(t)) - \eta\Delta p_g(t)}{(1-\eta)\Delta p_g(t)} \\ \Gamma_2(\Delta p_g(t)) = 1 - \Gamma_1(\Delta p_g(t)) \end{cases}, \quad (3)$$

Hence, the T-S fuzzy model for the nonlinear PSWESS (1) is expressed by the following if-then rules

Plant Rule i: If $\Delta p_g(t)$ is $\Gamma_i(\Delta p_g(t))$, then

$$\begin{cases} \dot{x}(t) = A_i x(t) + B_i u^f(t-\delta(t)) + F_i w(t) \\ y(t) = C_i x(t)\ i = 1, 2 \end{cases}, \quad (4)$$

where $B_1 = B_2 = B$, $C_1 = C_2 = C$, $F_1 = F_2 = F$, and

$$A_1 = \begin{bmatrix} -\frac{D}{M} & \frac{1}{M} & 0 & \frac{1}{M} & 0 \\ 0 & -\frac{1}{T_t} & \frac{1}{T_t} & 0 & 0 \\ -\frac{1}{T_g R} & 0 & -\frac{1}{T_g} & 0 & 0 \\ \frac{\rho_e k_e}{T_e} & 0 & 0 & -\frac{1}{T_e} & 0 \\ \beta & 0 & 0 & 0 & 0 \end{bmatrix},$$

$$A_2 = \begin{bmatrix} -\frac{D}{M} & \frac{1}{M} & 0 & \frac{1}{M} & 0 \\ 0 & -\frac{1}{T_t} & \frac{\eta}{T_t} & 0 & 0 \\ -\frac{1}{T_g R} & 0 & -\frac{1}{T_g} & 0 & 0 \\ \frac{\rho_e k_e}{T_e} & 0 & 0 & -\frac{\eta}{T_e} & 0 \\ \beta & 0 & 0 & 0 & 0 \end{bmatrix}.$$

The overall dynamics of T-S fuzzy system are established as

$$\begin{cases} \dot{x}(t) = \sum_{i=1}^{2} \mu_i(\Delta p_g(t))\big(A_i x(t) + B_i u^f(t-\delta(t)) \\ \qquad +F_i w(t)\big) \\ y(t) = \sum_{i=1}^{2} \mu_i(\Delta p_g(t)) C_i x(t) \end{cases} \tag{5}$$

where the membership functions are defined by $\mu_i(\Delta p_g(t)) = \Gamma_i(\Delta p_g(t))/\sum_{i=1}^{2}\Gamma_i(\Delta p_g(t))$ and $\sum_{i=1}^{2}\mu_i(\Delta p_g(t)) = 1$.

C. Reliable LFC Design

In the following, we develop the reliable LFC scheme for PSWESS.

Control Rule j: If $\Delta p_g(t)$ is $\Gamma_j(\Delta p_g(t))$, then

$$u(t) = -K_{Pj} ACE(t) - K_{Ij}\int ACE(t)dt,\ j = 1, 2, \tag{6}$$

here, K_{Pj} and K_{Ij} represent the PI control gains. Hence, the overall T-S fuzzy control scheme is expressed as

$$u(t) = -\sum_{j=1}^{2}\mu_j(\Delta p_g(t)) K_j C x(t), \tag{7}$$

where $C = C_1 = C_2$, and $K_j = [K_{Pj}\ K_{Ij}]$. Substitute (7) into (5), which gives

$$\begin{cases} \dot{x}(t) = \sum_{i=1}^{2}\sum_{j=1}^{2}\mu_i(\Delta p_g(t))\mu_j(\Delta p_g(t-\delta(t)))\big(A_i \\ \qquad \times x(t) - B_i \Xi K_j C x(t-\delta(t)) + F_i w(t)\big) \\ y(t) = \sum_{i=1}^{2}\mu_i(\Delta p_g(t)) C_i x(t). \end{cases} \tag{8}$$

III. Main Results

In this section, we establish the stability and stabilization conditions for the T-S fuzzy-based PSWESS (8).

Theorem 1: Given $\delta_2 > 0$, $\gamma > 0$, $\sigma < 1$, and gain matrix $K_{\lambda,j}$, if there exist matrices $P_i = \begin{bmatrix} P_{11i} & P_{12i} \\ * & P_{22i} \end{bmatrix} > 0$, $Q_i > 0$, $R_i > 0$, $Z_i > 0$, M_1, and M_2, satisfying the following conditions for $i, j, \lambda = 1, 2$:

$$\dot{P}_\mu \le 0, \dot{Q}_\mu \le 0, \dot{R}_\mu \le 0, \dot{Z}_\mu \le 0, \tag{9}$$

$$\Omega_{ij} < 0, \tag{10}$$

where

$$\Omega_{ij} = \begin{bmatrix} \Omega_{11ij} & \Omega_{12ij} & \Omega_{13ij} & \Omega_{14ij} & \Omega_{15ij} & M_1 F_i \\ * & \Omega_{22ij} & 0 & 0 & \Omega_{25ij} & 0 \\ * & * & \Omega_{33ij} & \Omega_{34ij} & 0 & 0 \\ * & * & * & \frac{-12}{\delta_2^2} Z_i & P_{12i}^T & 0 \\ * & * & * & * & \Omega_{55ij} & M_2 F_i \\ * & * & * & * & * & -\gamma^2 I \end{bmatrix},$$

with

$$\begin{aligned} \Omega_{11ij} =& P_{12i} + P_{12i}^T + Q_i - 4Z_i + R_i + C^T C + 2M_1^T A_i, \\ \Omega_{12ij} =& -M_1^T B_i \bar{\Xi} K_{\lambda,j} C,\ \Omega_{13ij} = -P_{12i} - 2Z_i, \\ \Omega_{14ij} =& P_{22i} + 6\delta_2^{-1} Z_i,\ \Omega_{15ij} = P_{11i} + A_i^T M_2 - M_1, \\ \Omega_{22ij} =& -(1-\sigma) R_i,\ \Omega_{25ij} = -(B_i \bar{\Xi} K_{\lambda,j} C)^T M_2 \\ \Omega_{33ij} =& -Q_i - 4Z_i,\ \Omega_{34ij} = -P_{22i} + 6\delta_2^{-1} Z_i, \\ \Omega_{55ij} =& \delta_2^2 Z_i - M_2 - M_2^T, \end{aligned}$$

then, the system (8) is asymptotically stable in the mean-square sense with H_∞ performance index.

Proof: Consider the following LKF:

$$V(x(t)) = V_1(x(t)) + V_2(x(t)) + V_3(x(t)) + V_4(x(t)), \tag{11}$$

where

$$\begin{aligned} V_1(x(t)) =& \sum_{i=1}^{2}\mu_i(\Delta P_g(t))\varrho^T(t) P_i \varrho(t), \\ V_2(x(t)) =& \int_{t-\delta_2}^{t}\sum_{i=1}^{2}\mu_i(\Delta P_g(t)) x^T(s) Q_i x(s) ds, \\ V_3(x(t)) =& \delta_2 \int_{-\delta_2}^{0}\int_{t+\rho}^{t}\sum_{i=1}^{2}\mu_i(\Delta P_g(t))\dot{x}^T(s) Z_i \dot{x}(s) ds d\rho, \\ V_4(x(t)) =& \int_{t-\delta(t)}^{t}\sum_{i=1}^{2}\mu_i(\Delta P_g(t)) x^T(s) R_i x(s) ds, \end{aligned}$$

where $\varrho^T(t) = [x^T(t)\ \int_{t-\delta_2}^{t} x^T(s)ds]$. Define the infinitesimal operator $\mathcal{L}$ of $V(x(t))$ as follows:

$$\mathcal{L}V(x(t)) = \lim_{\Delta\to 0}\frac{1}{\Delta}\{\mathbb{E}\{V(x(t+\Delta))|x(t)\} - V(x(t))\}.$$

By taking the infinitesimal operator $\mathcal{L}$ of LKF (11) along the system (8) and applying the mathematical expectation on both sides, we get

$$\mathbb{E}\{\mathcal{L}V_1(x(t))\} = \mathbb{E}\{2\varrho^T(t) P_\mu \dot{\varrho}(t) + \varrho^T(t)\dot{P}_\mu \varrho(t)\}, \tag{12}$$

$$\begin{aligned} \mathbb{E}\{\mathcal{L}V_2(x(t))\} =& \mathbb{E}\{x^T(t) Q_\mu x(t) + \int_{t-\delta_2}^{t} x^T(s)\dot{Q}_\mu x(s) ds \\ & - x^T(t-\delta_2) Q_\mu x(t-\delta_2)\}, \end{aligned} \tag{13}$$

$$\mathbb{E}\{\mathcal{L}V_3(x(t))\} = \mathbb{E}\{\delta_2^2 \dot{x}^T(t) Z_\mu \dot{x}(t) - \delta_2 \int_{t-\delta_2}^{t}\dot{x}^T(s) Z_\mu \dot{x}(s) ds$$

$$+\delta_2\int_{-\delta_2}^{0}\int_{t+\rho}^{t}\dot{x}^T(s)\dot{Z}_\mu\dot{x}(s)dsd\rho\}, \quad (14)$$

$$\mathbb{E}\{\mathcal{L}V_4(x(t))\} =\mathbb{E}\{x^T(t)R_\mu x(t)+\int_{t-\delta(t)}^{t}x^T(s)\dot{R}_\mu x(s)ds - (1-\sigma)x^T(t-\delta(t))R_\mu x(t-\delta(t))\}. \quad (15)$$

Applying the lemma as in [25] to the inequality of $\mathbb{E}\{\mathcal{L}V_3(x(t))\}$, we have

$$-\delta_2\int_{t-\delta_2}^{t}\dot{x}^T(s)\mathbb{Z}_i\dot{x}(s)ds \le -[x(t)-x(t-\delta_2)]^T Z_i \times [x(t)-x(t-\delta_2)] - 3\left[x(t)+x(t-\delta_2)-\frac{2}{\delta_2}\int_{t-\delta_2}^{t}x(s)ds\right]^T \times Z_i\left[x(t)+x(t-\delta_2)-\frac{2}{\delta_2}\int_{t-\delta_2}^{t}x(s)ds\right]. \quad (16)$$

Now, we examine that $\dot{P}_\mu \le 0$, $\dot{Q}_\mu \le 0$, $\dot{R}_\mu \le 0$, and $\dot{Z}_\mu \le 0$. By applying the property of membership functions, we have $\sum_{i=1}^{2}\dot{\mu}_i(\Delta P_g(t)) = 0$, Hence, we obtain

$$\begin{cases} \dot{P}_\mu = \sum_{i=1}^{2}\dot{\mu}_i(\theta(\Delta P_g(t)))P_i = \dot{\mu}_1(\Delta P_g(t))(P_1-P_2) \\ \dot{Q}_\mu = \sum_{i=1}^{2}\dot{\mu}_i(\Delta P_g(t))Q_i = \dot{\mu}_1(\Delta P_g(t))(Q_1-Q_2) \\ \dot{R}_\mu = \sum_{i=1}^{2}\dot{\mu}_i(\Delta P_g(t))R_i = \dot{\mu}_1(\Delta P_g(t))(R_1-R_2) \\ \dot{Z}_\mu = \sum_{i=1}^{2}\dot{\mu}_i(\Delta P_g(t))Z_i = \dot{\mu}_1(\Delta P_g(t))(Z_1-Z_2). \end{cases}$$

Then, the switching technique can be utilized to ensure $\dot{P}_\mu \le 0$, $\dot{Q}_\mu \le 0$, $\dot{R}_\mu \le 0$, and $\dot{Z}_\mu \le 0$ as follows:

$$\text{If } \dot{\mu}_1(\Delta P_g(t)) < 0, \text{ then } P_1-P_2>0,\ Q_1-Q_2>0, \quad R_1-R_2>0,\ Z_1-Z_2>0, \quad (17)$$

$$\text{If } \dot{\mu}_1(\Delta P_g(t)) \ge 0, \text{ then } P_1-P_2\le 0,\ Q_1-Q_2\le 0, \quad R_1-R_2\le 0,\ Z_1-Z_2\le 0. \quad (18)$$

Hence, we have two possible cases. Let $\lambda \in \{1,2\}$ and

$$\mathcal{A}_\lambda = \{\lambda:\ \text{The possible permutations of } \dot{\mu}_1(\Delta P_g(t))\}$$
$$\mathcal{B}_\lambda = \{\lambda:\ \text{The possible constraints of } P_i,\ Q_i,\ R_i,\ Z_i\}.$$

Then, from (17) and (18), we have

$$\text{If } \mathcal{A}_\lambda, \text{ then } \mathcal{B}_\lambda. \quad (19)$$

By using the switching technique in (19), the fuzzy controller can be designed for different $\mathcal{A}_\lambda$, and $\mathcal{B}_\lambda$ as follows:

$$u_\lambda(t) = K_{\lambda,\mu}y(t-\delta(t))$$

where $K_{\lambda,\mu} = \sum_{j=1}^{r}\mu_j(\Delta P_g(t))K_{\lambda,j}$. Thus, the final switched T-S fuzzy-based LFC scheme (7) becomes,

$$u(t) = \begin{cases} u_1(t) = K_{1,\mu}y(t-\delta(t)) \\ u_2(t) = K_{2,\mu}y(t-\delta(t)). \end{cases} \quad (20)$$

Noting that for any matrices M_1 and M_2, we get (21) based on (8):

$$2\sum_{i=1}^{2}\sum_{j=1}^{2}\mu_i(\Delta P_g(t))\mu_j(\Delta P_g(t-\delta(t)))\Big[\Big(x^T(t)M_1^T + \dot{x}^T(t)M_2^T\Big)\Big(-\dot{x}(t)+A_ix(t)-B_i\Xi K_jCx(t-\delta(t)) + F_iw(t)\Big)\Big] = 0. \quad (21)$$

Considering the H_∞ performance and accumulating (12)-(21), it follows that

$$\mathbb{E}\{\mathcal{L}V(x(t))\} + y^T(t)y(t) - \gamma^2 w^T(t)w(t) \le \sum_{i=1}^{2}\mu_i(\Delta P_g(t))\mu_j(\Delta P_g(t-\delta(t)))\Upsilon^T(t)\Omega_{ij}\Upsilon(t), \quad (22)$$

where $\Upsilon^T(t) = [x^T(t)\ \ x^T(t-\delta(t))\ \ x^T(t-\delta_2)\ \ \int_{t-\delta_2}^{t}x^T(s)ds\ \ \dot{x}^T(t)\ \ w^T(t)]$. From (9) and (22), one can obtain $\mathbb{E}\{\mathcal{L}V(x(t))\} \le \mathbb{E}\{-y^T(t)y(t)+\gamma^2w^T(t)w(t)\}$. Then, by applying the same procedure in [23], we get $\mathbb{E}\{\|y(t)\|_2\} \le \gamma\mathbb{E}\{\|w(t)\|_2\}$. Hence, the asymptotically stability of system (8) is verified in the mean-square sense with the H_∞ performance. ■

In the following, we aim to determine the unknown control gain matrices of the T-S fuzzy-based LFC scheme for PSWESS based on Theorem 1.

Theorem 2: Given $\delta_2 > 0$, $\gamma > 0$, $\sigma < 1$ and $\epsilon \to 0$, if there exist matrices $\hat{P}_i = \begin{bmatrix} \hat{P}_{11i} & \hat{P}_{12i} \\ * & \hat{P}_{22i} \end{bmatrix} > 0$, $\hat{Q}_i > 0$, $\hat{R}_i > 0$, $\hat{Z}_i > 0$, $M > 0$, any matrix $X_{\lambda,j}$, and full rank invertible matrix G, satisfying the following inequalities for $i,j,\lambda = 1,2$:

$$\dot{P}_\mu \le 0, \dot{Q}_\mu \le 0, \dot{R}_\mu \le 0, \dot{Z}_\mu \le 0, \quad (23)$$

$$\begin{bmatrix} -\epsilon I & (GC-CM)^T \\ (GC-CM) & -I \end{bmatrix} < 0, \quad (24)$$

$$\hat{\Omega}_{ij} < 0, \quad (25)$$

where $\hat{\Omega}_{ij} =$

$$\begin{bmatrix} \hat{\Omega}_{11ij} & \hat{\Omega}_{12ij} & \hat{\Omega}_{13ij} & \hat{\Omega}_{14ij} & \hat{\Omega}_{15ij} & F_i & M^TC^T \\ * & \hat{\Omega}_{22ij} & 0 & 0 & \hat{\Omega}_{25ij} & 0 & 0 \\ * & * & \hat{\Omega}_{33ij} & \hat{\Omega}_{34ij} & 0 & 0 & 0 \\ * & * & * & \frac{-12}{\delta_2^2}\hat{Z}_i & \hat{P}_{12i}^T & 0 & 0 \\ * & * & * & * & \hat{\Omega}_{55ij} & \alpha F_i & 0 \\ * & * & * & * & * & -\gamma^2 I & 0 \\ * & * & * & * & * & * & -I \end{bmatrix}$$

with

$$\begin{aligned}
\hat{\Omega}_{11ij} =& \hat{P}_{12i} + \hat{P}_{12i}^T + \hat{Q}_i - 4\hat{Z}_i + \hat{R}_i + 2A_iM, \\
\Omega_{12ij} =& -B_i\bar{\Xi}X_{\lambda,j}C,\ \Omega_{13ij} = -\hat{P}_{12i} - 2\hat{Z}_i, \\
\Omega_{14ij} =& \hat{P}_{22i} + 6\delta_2^{-1}\hat{Z}_i,\ \Omega_{15ij} = \hat{P}_{11i} + \alpha M^T A_i^T - M^T, \\
\Omega_{22ij} =& -(1-\sigma)\hat{R}_i,\ \Omega_{25ij} = -(B_i\bar{\Xi}X_{\lambda,j}C)^T \\
\Omega_{33ij} =& -\hat{Q}_i - 4\hat{Z}_i,\ \Omega_{34ij} = -\hat{P}_{22i} + 6\delta_2^{-1}\hat{Z}_i, \\
\Omega_{55ij} =& \tau_2^2\hat{Z}_i - \alpha M - \alpha M^T,
\end{aligned}$$

then, the system (8) is globally asymptotically stable in the mean-square sense with H_∞ performance index. Moreover, the control gain matrices are calculated by $K_{\lambda,j} = X_{\lambda,j}G^{-1}$.

Proof: Define $M_1 = M^{-1}$ and $M_2 = \alpha M^{-1}$, where α is a parameter to be tuned, and let $\hat{P}_{11i} = M^T P_{11i} M$, $\hat{P}_{12i} = M^T P_{12i} M$, $\hat{P}_{22i} = M^T P_{22i} M$, $\hat{Q}_i = M^T Q_i M$, $\hat{R}_i = M^T R_i M$, $\hat{Z}_i = M^T Z_i M$. Also, the system matrix C is not invertible. Hence, by letting $X_{\lambda,j}C = K_{\lambda,j}CM$, $GC = CM$, and $K_{\lambda,j} = X_{\lambda,j}G^{-1}$, the nonlinear terms in (10) are regenerated by W-problem as in [24]. Then, the inequalities in (9) is pre-and post multiplied by M^T and its transpose, which yields (23). (10) is pre-and post multiplied by $diag\{M^T, M^T, M^T, M^T, M^T, I\}$ and its transpose, then based on the Schur complement, we obtain (25). Moreover, we can express the inequality (24) for any positive scalar ϵ and by applying the Schur complement in $(GC - CM)^T(GC - CM) = 0$, with $M > 0$ and G is a full rank inveritible matrix. ■

IV. NUMERICAL EXAMPLE

In this section, the stabilization criteria for T-S fuzzy-based PSWESS will be examined to demonstrate the superiority of the proposed design method and less conservatism than existing results.

A. Reliable H_∞ LFC Scheme Under Actuator Faults

Consider the T-S fuzzy systems (8) with stochastic actuator fault. According to [16], the PSWESS parameters are chosen as $\mathcal{M} = 10$, $\mathcal{T}_t = 0.3$, $\mathcal{T}_g = 0.1$, $\mathcal{R} = 0.05$, $\beta = 21$, $\mathcal{T}_e = 0.1$, $k_e = 1$, $\alpha_1 = \alpha_2 = 0.5$, and $\rho_e = 1/\mathcal{R}$. The remaining parameters are chosen as $\alpha = 0.1$, $\eta = 0.5$. Further, the stochastic variable Ξ is assumed to obey Gaussian distribution with mean 0.2 and variance 0.5. By utilizing the values specified above, the stabilization conditions in (23)-(25) are solved under the constraint $\mathcal{B}_1 : \{\hat{P}_1 > \hat{P}_2,\ \hat{Q}_1 > \hat{Q}_2,\ \hat{Z}_1 > \hat{Z}_2,\ \hat{R}_1 > \hat{R}_2\}$, and obtained the maximum upper bound of $\delta(t)$ is $\delta_2 = 2.163$. For $\mathcal{A}_1 : \{\mu_1(\Delta P_g(t)) < 0\}$, the corresponding PI-based LFC gains are determined as follows.

$$\begin{aligned}
K_{1,1} &= \left[\ K_{P1,1},\ K_{I1,1}\ \right] = \left[\ 1.6580,\ 2.0807\ \right], \\
K_{1,2} &= \left[\ K_{P1,2},\ K_{I1,2}\ \right] = \left[\ 1.6580,\ 2.0807\ \right].
\end{aligned}$$

Simultaneously, by taking the same values, the inequalities in Theorem 2 are solved for the constraint $\mathcal{B}_2 : \{\hat{P}_1 \leq \hat{P}_2,\ \hat{Q}_1 \leq \hat{Q}_2,\ \hat{Z}_1 \leq \hat{Z}_2,\ \hat{R}_1 \leq \hat{R}_2\}$, and obtained the maximum upper bound of time-varying delay $\delta_2 = 2.051$.

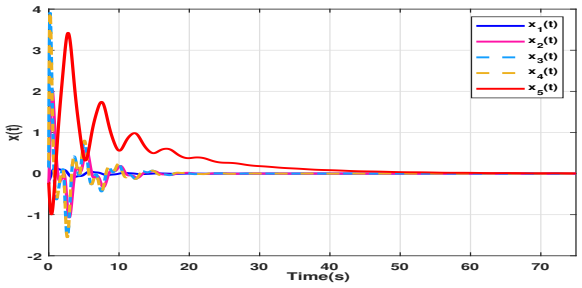


Fig. 2: State trajectories of power system with ESS (8).

For $\mathcal{A}_2 : \{\mu_1(\Delta P_g(t)) \geq 0\}$, the corresponding PI-based LFC gains are determined as follows.

$$\begin{aligned}
K_{2,1} &= \left[\ K_{P2,1},\ K_{I2,1}\ \right] = \left[\ 1.6577,\ 2.0730\ \right], \\
K_{2,2} &= \left[\ K_{P2,2},\ K_{I2,2}\ \right] = \left[\ 1.6566,\ 2.0751\ \right].
\end{aligned}$$

Hence, the final maximum upper bound of time-varying delay is $\delta_2 = 2.051$. For a simulation purpose, the time varying delay is taken as $\delta(t) = 0.05\sin(t) + 2.001$ with $\delta_2 = 2.051$ and $\sigma = 0.05$. The load disturbances are considered as $w(t) = 0.002\sin(t)$. Furthermore, the state trajectories of T-S fuzzy-based PSWESS are displayed in Fig. 2 based on the aforementioned control gains. From Fig. 2, we can confirm that the PSWESS subject to stochastic actuator fault is asymptotically stable under the designed PI-based LFC scheme, which verifies the efficiency of the proposed method.

B. Calculate the Maximum Upper Bounds

Based on the system matrices in Subsection IV-A, we consider that the PSWESS has no stochastic actuator fault (i.e. $\Xi = 1$). In order to show the superiority of proposed method,

TABLE II: Calculating maximum upper bound values of $\delta(t)$ with various control gains $[K_{Pj},\ K_{Ij}]$.

Methods / $[K_{Pj},\ K_{Ij}]$	$[0.1,\ 0.05]$	$[0.1,\ 0.1]$	$[0.1,\ 0.15]$
Corollary 1 in [16]	9.239	11.636	10.482
Theorem 2 in [16]	9.330	11.723	10.563
Theorem 1 in this paper	9.513	12.001	10.568

the obtained stability criteria in Theorem 1 are solved for different PI-based LFC gains and determined the allowable maximum upper bound of time varying delay $\delta(t)$ which are listed in Table II. From Table II, we confirm that the proposed method leads to a largest upper bounds of $\delta(t)$ compared to the prior method in [16]. For simulation purpose, we select the time-varying delay as $\delta(t) = 0.8\sin(t) + 0.8$ which satisfy $\delta_2 = 1.6$ and $\sigma = 0.8$. Also, the load disturbance is chosen as $w(t) = 0.04sin(t)$. Then, the stabilization criteria in Theorem 2 are solved with $\bar{\Xi} = 1$ and the constraint $\mathcal{B}_1 : \{\hat{P}_1 > \hat{P}_2,\ \hat{Q}_1 > \hat{Q}_2,\ \hat{Z}_1 > \hat{Z}_2,\ \hat{R}_1 > \hat{R}_2,\}$. Then, the obtained PI-based LFC gain matrices are

$$\begin{aligned}
K_{1,1} &= \left[\ K_{P1,1},\ K_{I1,1}\ \right] = \left[\ 0.3320,\ 0.4183\ \right], \\
K_{1,2} &= \left[\ K_{P1,2},\ K_{I1,2}\ \right] = \left[\ 0.3320,\ 0.4183\ \right].
\end{aligned}$$

Simultaneously, the inequalities in Theorem 2 are solved

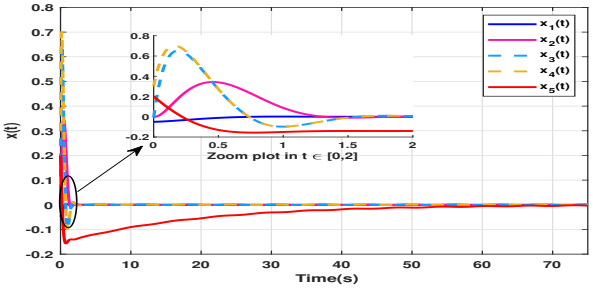


Fig. 3: State trajectories of system (8) without stochastic actuator fault.

for the constraint $\mathcal{B}_2 : \{\hat{P}_1 \leq \hat{P}_2,\ \hat{Q}_1 \leq \hat{Q}_2,\ \hat{Z}_1 \leq \hat{Z}_2,\ \hat{R}_1 \leq \hat{R}_2\}$, and obtained the corresponding PI-based LFC gain matrices as follows.

$$K_{2,1} = \left[\ K_{P2,1},\ K_{I2,1}\ \right] = \left[\ 0.0095,\ 0.2000\ \right],$$
$$K_{2,2} = \left[\ K_{P2,2},\ K_{I2,2}\ \right] = \left[\ 0.0095,\ 0.2000\ \right].$$

Based on the above, the state trajectories of T-S fuzzy-based PSWESS (8) without stochastic actuator fault is given in Fig. 3. From the above, the stability of considered T-S fuzzy-based PSWESS (8) without stochastic actuator fault can be ensured under the designed control scheme.

V. CONCLUSIONS

In this paper, the reliable H_∞ LFC has been designed for nonlinear PSWESS which has stochastic actuator fault and external load disturbances. To do this, the occurrence of non-linearity in turbine and governor dynamics is handled by T-S fuzzy systems. By constructing the fuzzy membership function-dependent LKF and using the switching approach, corresponding stability and stabilization criteria have been established in terms of linear matrix inequality under the designed control scheme. Finally, the comparative example has been given to show the efficiency and superiority of proposed method.

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