Frequency Stabilization Design for Interconnected Microgrid based on T-S Fuzzy Model with Multiple Time Delays

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Abstract—**In an interconnected microgrid, the problems about the time delays and the lack of uniform control model cannot be ignored. To solve such problems for better stabilization, this paper establishes a T-S fuzzy model with multiple time delays. In addition, a parallel distributed compensation control is designed and the stability of the proposed closed-loop system has been proved. Then, the state feedback stabilization design is proposed, which can obtain fast frequency recovery and eligible stabilization effect. Simulation results which are carried out in a typical interconnected microgrid, have verified the effectiveness of the proposed method.**

Keywords—T-S fuzzy model, microgrid, stabilization design, multiple time delays.

I. INTRODUCTION

Small autonomous grids have existed for many decades in remote communities where the interconnection with the main power grid is not feasible due to technical and/or economical reasons[1][2]. As a result, the time delays cannot be ignored in most power grids. On the other hand, with the increasing concerns related to conventional energy cost[3], microgrid is proposed to enable the wide spread utilization of renewable energy[4], such as wind and solar generation connected to the main grid. Actually, it is difficult to build an accurate mathematical model of the control system[5],[6], because of the various devices, various nonlinearity, uncertainties, time delays and stochastic disturbance of objects or process. Due to the lack of uniform model required by traditional control, interconnected microgrid is faced with some critical bottlenecks and technological drawbacks: bi-directional power flow and frequency rise caused by inverters, power supply intermittent brought by renewable resources, and more disturbance or oscillation caused by mismatching between load and generation controls. In addition, the operation schemes for frequency, such as IEEE 1547 standard, have to cut off all renewable generations faced with frequency drop. That is, a significant weakness of existing power supply.

To solve the problems about lack of precise or uniform control models, the fuzzy control, proposed by Professor Zadeh in 1965[7], presents an excellent advantage. After decades of research, the fuzzy control has developed into three types of fuzzy model: the Mamdani model, the Takagi-Sugeno (T-S) model and the fuzzy model based on the fuzzy state function. It has been proved that T-S fuzzy systems are universal approximators. Based on this model, we can use the analysis and control method in the tradition linear theory to analyze and control fuzzy systems. Takagi and Sugeno used fuzzy implications to represent local linear input/output relations of nonlinear systems. The T-S fuzzy system has emerged as one of the most active and fruitful areas of the fuzzy control. Using a T-S fuzzy model, a complex dynamic model can be composed of a set of local linear subsystems via fuzzy inference, which inspires researchers to use T-S fuzzy model to solve problems in industrial areas, such as interconnected microgrid.

This paper first establishes a uncertain T-S fuzzy model with multiple time delays in Section 2. Subsequently, in Section 3, a parallel distributed compensation control is designed. In Section 4, the paper provides the stability of the closed-loop system. Then, the state feedback stabilization design is presented in Section 5. In Section 6, simulation results are carried out in a typical interconnected microgrid. Analysis and results have been verified the effectiveness of the proposed method. Finally, the conclusion is obtained in Section 7.

II. UNCERTAIN T-S FUZZY MODEL WITH MULTIPLE TIME DELAYS

In an typical interconnected microgrid, as shown in Fig.1, different types of generations, such as generators and inverters, are involved. For traditional generators, the mathematical model represents as $2H\dot{\omega} = P_0 - P_e - D\omega$; for inverters brought by distributed generations (DGs), the control model is designed as $\omega = \omega_0 - m(P - P_0)$; while, for more devices in microgrid, they lack precise or uniform control model, such as some battery.

On the other hand, in practical systems, time delays cannot be ignored, due to existing communication technologies and devices. As a result, in this section, a new kind of T-S model is established. In the model there exist uncertainties and multiple time delays. Here, we assume uncertainties and time delays both are in the state of the dynamic part. We get the ith rule of the T-S fuzzy model which is described as follows:

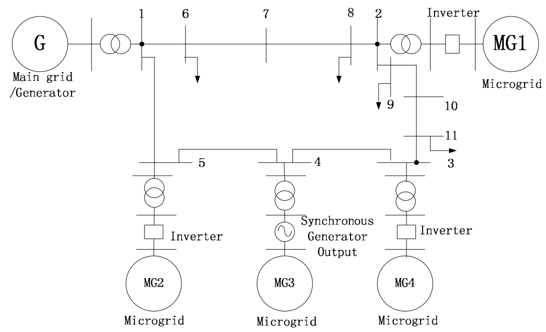

Fig.1 Structure of interconnected microgrid

Dynamic Part:

R^i : IF $z_1(t)$ *is* N_{i1} , …, and $z_l(t)$ *is* N_{il}

THEN

$$\begin{aligned} \dot{f}(t) &= [A_{i0} + \Delta A_{i0}(t)]f(t) \\ &+ \sum_{k=1}^{N}[A_{ik} + \Delta A_{ik}(t)]f(t-\tau_k) + B_i u(t) \\ i &= 1,2,\cdots,n; j = 1,2,\cdots,l \end{aligned} \tag{1}$$

Output Part:

R^i : IF $z_1(t)$ *is* N_{i1} , …, and $z_l(t)$ *is* N_{il} ,

THEN

$$y(t) = C_i f(t), i = 1,2,\cdots,n \tag{2}$$

where

R^i denotes the ith fuzzy inference rule;

l and n denote the number of the promise variable and the fuzzy inference rule;

$\tau_k > 0$ represents delay times;

k is the number of time delays y(t) and z(t) respectively denote the output and parameter vectors;

N_{ij} denotes the fuzzy value associated with the ith rule and jth parameter component;

$f(t) \in R^n$ denotes the frequency of the generation or load;

$u(t) \in R^m$ denotes the input of the device;

y(t) and z(t) respectively denote the output and parameter of generations or loads;

$z_j(t)$ denotes the jth component of $z(t)$. Each $z_j(t)$ is a measurable time-varying quantity. In general, these parameters may be functions of the state variables, external disturbances, and/or time.

A_{i0} , A_{ik} , B_i and C_i represent the ith local model parameters of the fuzzy system

ΔA_{i0} , ΔA_{ik} are uncertain real constant matrices. They reflect the uncertainty of time-varying parameters in the each model of fuzzy subsystems.

Assume the uncertainty in this section has norm bound and structure as follows:

$$\begin{aligned} &[\Delta A_{i0}(t) \quad \Delta A_{i1}(t) \quad \cdots \quad \Delta A_{iN}(t)] = \\ &D_i F_i(t)[E_{i0} \quad E_{i1} \quad \cdots \quad E_{iN}] \end{aligned} \tag{3}$$

where E_{i0} , $E_{i1}, \cdots, E_{iN}$ and D_i are constant matrices which have proper dimension reflect structure of the uncertainty system. $F_i(t)$ is a unknown matrix with the Lebesgue measurability. It satisfies the equation:

$$F_i(t)^T F_i(t) \le I \tag{4}$$

where I is an identity matrix which has proper dimension.

By using a singleton fuzzifier, product inference and a center-average defuzzifier[8], the dynamic global model of the above fuzzy control system can be described as follows:

$$\begin{aligned} \dot{f}(t) &= \sum_{i=1}^{n} h_i(z(t))\{[A_{i0} + \Delta A_{i0}(t)]f(t) \\ &+ \sum_{k=1}^{N}[A_{ik} + \Delta A_{ik}(t)]f(t-\tau_k) + B_i u(t)\} \end{aligned} \tag{5}$$

where

$z(t) = [z_1(t), z_2(t), \cdots z_l(t)]$,

$f_i(z(t)) = \prod_{j=1}^{l} N_{ij}(z_j(t))$

$h_i(z(t)) = \omega_i(z(t)) \Big/ \sum_{i=1}^{r} f_i(z(t))$ is firing probability, and $\sum_{i=1}^{n} h_i(z(t)) = 1$, $N_{ij}(z_j(t))$ denotes the grade of membership which variable $z_j(t)$ correspond with fuzzy value N_{ij} .

Equation (5) is the global system on the basis of the fuzzy model (1). Although, the consequence part of every fuzzy rule is linear, the global system is nonlinear in general. It is because that the membership function is nonlinear and the system has been dealt with a singleton fuzzifier, product inference and a center-average defuzzifier.

It has been proved that T-S model can approximate to a practicality plant in any accurateness with the increasing of fuzzy rules. In the bound of allow errors, Equation (5) can describe characters for complex plants. From the above equation, we can find that although the global system is nonlinear, every linear fuzzy subsystem provide the conveniences to analyze the complex system.

III. PARALLEL DISTRIBUTED COMPENSATION CONTROL

Use the concept of PDC to design fuzzy controllers to stabilize the T-S fuzzy system. The idea is to design a compensator for each rule of the fuzzy model. The resulting overall fuzzy controller, which is nonlinear in general, is a fuzzy blending of each individual linear controller. The controller is composed of a group of IF~THEN rules. Each rule is a local state feedback controller. Through the group of each rule, we can get the global fuzzy controller[10]. In this section, T-S fuzzy controller is designed as follows:

R^i : IF $z_1(t)$ *is* M_{i1} , …, and $z_l(t)$ *is* M_{il}

THEN

$$u(t) = K_i f(t), \qquad i = 1, 2, \cdots, n \tag{6}$$

where K_i denotes state feedback gains of the ith local model. The fuzzy controller shares the same fuzzy set with the fuzzy system (1).

By using the same singleton fuzzifier, product inference and center-average defuzzifier, the following dynamic global controller can be obtained:

$$\begin{aligned} u(t) &= \sum_{i=1}^{n} \omega_i(z(t)) K_i f(t) \Big/ \sum_{i=1}^{n} \omega_i(z(t)) \\ &= \sum_{i=1}^{n} h_i(z(t)) K_i f(t) \end{aligned} \tag{7}$$

Substituting (7) into (5), and noting $\sum_{i=1}^{n} h_i(z(t)) = 1$, we obtain the corresponding closed-loop system

$$\begin{aligned} \dot{f}(t) = \sum_{i=1}^{n}\sum_{j=1}^{n} h_i(z(t)) h_j(z(t)) \{ [A_{i0} + \Delta A_{i0}(t)] f(t) \\ + \sum_{k=1}^{N} [A_{ik} + \Delta A_{ik}(t)] f(t-\tau_k) + B_i K_j f(t) \} \end{aligned} \tag{8}$$

IV. STABILITY OF THE CLOSED-LOOP SYSTEM

On the basis of the (8), we will use the Lyapunov stability theory to get stability condition of the system at first. Then the design method of fuzzy controllers will be given later.

Theorem 4.1 If there exist symmetric matrices $P > 0, R > 0$ and K_i to any allowed uncertainty such that the following matrix inequalities are satisfied, the closed-loop system (4-8) is quadratically stable.

(a) For every $1 \le i \le n$, the following equation is satisfied.

$$\begin{aligned} & P W_{ii} + W_{ii}^T P + \sum_{k=1}^{N} R_k + \\ & \sum_{k=1}^{N} [P(A_{ik} + \Delta A_{ik}) R_k^{-1} (A_{ik} + \Delta A_{ik})^T P] < 0 \end{aligned} \tag{9}$$

(b) For every pair of indices satisfying $1 \le i < j \le n$ the equation

$$\begin{aligned} & P\left(\frac{W_{ij} + W_{ji}}{2}\right) + \left(\frac{W_{ij} + W_{ji}}{2}\right)^T P + \sum_{k=1}^{N} R_k \\ & + \sum_{k=1}^{N} P M_{ijk} R_k^{-1} M_{ijk}^T P < 0 \end{aligned} \tag{10}$$

holds, where

$W_{ij} = A_{i0} + \Delta A_{i0} + B_i K_j$,

$M_{ijk} = \dfrac{1}{2}((A_{ik} + \Delta A_{ik}) + (A_{jk} + \Delta A_{jk}))$.

Proof: For stability analysis we use the Lyapunov direct method[9].

V. STATE FEEDBACK STABILIZATION DESIGN

Given a plant described by a T-S model with time delays, find a PDC control that quadratically stabilizes the closed-loop system. The design variables in this problem are gain matrices K_i $(1 \le i \le n)$. Taken together, these conditions form an LMI feasibility problem. If this problem is analyzed numerically and a feasible solution is found, then a set of stabilizing gain matrices can be computed directly from the solution data.

Theorem 4.2 Matrix inequalities (9) (10) come into existence, if and only if there exist real number $\varepsilon > 0$, symmetric positive define matrices $X > 0, W_k > 0$ and M_i to any fuzzy subsystem R^i ($1 \le i \le n$) the following two LMI conditions hold:

(a) For every $1 \le i \le n$, the following equation is satisfied.

$$\begin{bmatrix} \tilde{\Phi}_i & A_{i1}W_1 & \cdots & A_{i1}W_N & XE_{i0}^T & X \\ W_1 A_{i1}^T & -W_1 & \cdots & 0 & W_1 E_{i1}^T & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ W_N A_{i1}^T & 0 & \cdots & -W_N & W_N E_{i1}^T & 0 \\ E_{i0} X & E_{i1} W_1 & \cdots & E_{i1} W_N & -\varepsilon I & 0 \\ X & 0 & \cdots & 0 & 0 & -\sum_{k=1}^{N} W_k \end{bmatrix} < 0 \tag{11}$$

(b) For every pair of indices satisfying $1 \le i < j \le n$ the equation

$$\begin{bmatrix} \tilde{\Phi}_{ij} & (A_{i1} + A_{j1})W_1 & \cdots & (A_{i1} + A_{j1})W_N & XE_{ij0}^T & X \\ W_1 (A_{i1} + A_{j1})^T & -2W_1 & \cdots & 0 & W_1 E_{ij1}^T & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ W_N (A_{i1} + A_{j1})^T & 0 & \cdots & -2W_{\mathrm{N}} & W_N E_{ij1}^T & 0 \\ E_{ij0} X & E_{ij1} X & \cdots & E_{ijN} X & -\varepsilon I & 0 \\ X & 0 & \cdots & 0 & 0 & -\frac{1}{2}\sum_{k=1}^{N} W_k \end{bmatrix} < 0 \tag{12}$$

holds, where

$\tilde{\Phi}_i = A_{i0} X + X A_{i0}^T + B_i M_i + M_i^T B_i^T + \varepsilon D_i D_i^T$,

$$\tilde{\Phi}_{ij} = A_{i0}X + XA_{i0}^T + B_iM_j + M_j^TB_i^T + \varepsilon D_iD_i^T$$
$$+A_{j0}X + XA_{j0}^T + B_jM_i + M_i^TB_j^T + \varepsilon D_jD_j^T ,$$
$$+A_{j0}X + XA_{j0}^T + B_jM_i + M_i^TB_j^T + \varepsilon D_jD_j^T$$

$$E_{ijo} = \begin{bmatrix} E_{i0} \\ E_{j0} \end{bmatrix}, E_{ij1} = \begin{bmatrix} E_{i1} \\ E_{j1} \end{bmatrix}, ..., E_{ijN} = \begin{bmatrix} E_{iN} \\ E_{jN} \end{bmatrix}$$

Furthermore, if these matrices exist which satisfies these inequalities, then the feedback gains $K_i = M_iX^{-1}, 1 \le i \le n$, will provide a quadratically stabilizing PDC controller to the uncertain T-S model with multiple time-delay.

VI. SIMULATION

To verify the effect of proposed control method, a simulation, that simulates five-node interconnected microgrid, is presented as Fig.2. The simulation system contains main grid, photovoltaic, wind turbines, and local loads. The detailed parameters of the simulation system are summarized in Table 1.

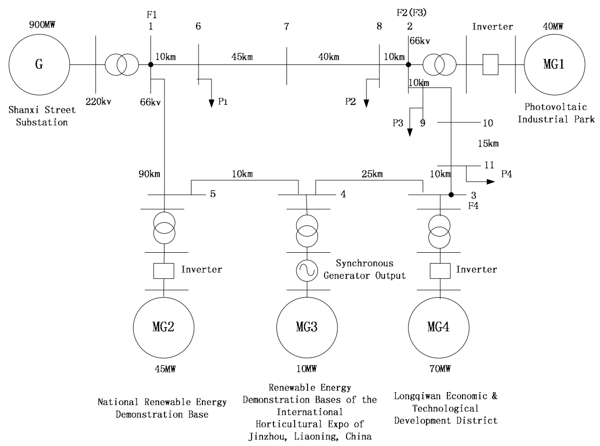

Fig.2 Structure of Jinzhou grid of Liaoning province.

TABLE I. LINE PARAMETERS

line	R(Ω)	X(Ω)
1-6	0.72	0.085
7-8	1	0.119
1-5	1.7	0.39
2-8, 4-5	0.576	0.17
3-4	0.85	0.1
6-7	1.61	0.32

In the simulation which is used for testing the effect of proposed method, load change and renewable fluctuation are considered. To design frequency stabilization, the proposed uncertain T-S fuzzy model with multiple time delays for the simulation system is developed. Besides, the fuzzy rules are given by

Rule 1: IF $f_2(t)$ is N_1 (e.g. Small)

THEN

$$\dot{f}(t) = [A_{10} + \Delta A_{10}(t)]f(t) + [A_{11} + \Delta A_{11}(t)]f(t-\tau_1)$$
$$+[A_{12} + \Delta A_{12}(t)]f(t-\tau_2) + B_1u(t)$$

Rule 2: IF $f_2(t)$ is N_2 (e.g. Big)

THEN

$$\dot{f}(t) = [A_{20} + \Delta A_{20}(t)]f(t) + [A_{21} + \Delta A_{21}(t)]f(t-\tau_1)$$
$$+[A_{22} + \Delta A_{22}(t)]f(t-\tau_2) + B_2u(t)$$

According to the system parameters listed in Table 1, the parameters of the fuzzy rules can be obtained as follows,

$$A_{10} = \begin{bmatrix} 1.0010 & -0.4993 \\ 1 & 0 \end{bmatrix}, A_{20} = \begin{bmatrix} -1.003 & -0.5 \\ 0.9897 & 0 \end{bmatrix},$$

$$A_{11} = \begin{bmatrix} 0 & -0.1997 \\ 0.2001 & 0 \end{bmatrix}, A_{21} = \begin{bmatrix} 0 & -0.1997 \\ 0.2001 & 0 \end{bmatrix},$$

$$A_{12} = \begin{bmatrix} 0 & 0.2 \\ -0.2 & 0 \end{bmatrix}, A_{22} = \begin{bmatrix} 0 & 0.2 \\ -0.2 & 0 \end{bmatrix},$$

$$\Delta A_{10} = \begin{bmatrix} r_1(t) & r_1(t) \\ 0 & 0 \end{bmatrix}, \Delta A_{20} = \begin{bmatrix} r_4(t) & r_4(t) \\ 0 & 0 \end{bmatrix},$$

$$\Delta A_{11} = \begin{bmatrix} r_2(t) & r_2(t) \\ 0 & 0 \end{bmatrix}, \Delta A_{21} = \begin{bmatrix} r_5(t) & r_5(t) \\ 0 & 0 \end{bmatrix},$$

$$\Delta A_{12} = \begin{bmatrix} r_3(t) & r_3(t) \\ 0 & 0 \end{bmatrix}, \Delta A_{22} = \begin{bmatrix} r_6(t) & r_6(t) \\ 0 & 0 \end{bmatrix},$$

$$B_1 = B_2 = \begin{bmatrix} 1 \\ 0 \end{bmatrix}.$$

Uncertain parameters satisfied: $|r_1(t)|, |r_2(t)|, |r_3(t)|, |r_4(t)|, |r_5(t)|, |r_6(t)| < 0.1$.

Let $F_i = 10 \times r_i(t), i = 1,2,3,4,5,6$,

Membership functions[10] in this example are as follows:

$N_1 = 1 - 0.1 \times f_2$, $\quad N_2 = 0.1 \times f_2$.

To design a PDC controller to stabilize this system, Theorem 2 is used to obtain the feedback gains of the PDC controller

$K_1 = [-4.6935 \quad -3.4745]$,

$K_2 = [-2.6935 \quad -3.4745]$.

A. *Case 1 Load change at t=2s*

In the system shown as Fig.2, a total 60kw load, containing nodes 1, 3, and 4, is connected and shedding and at the time of 2s. The subsequent results to this change are shown in Fig.3-5, where the blue lines represent changes without proposed stabilization control and red dotted lines represent changes with stabilization control.

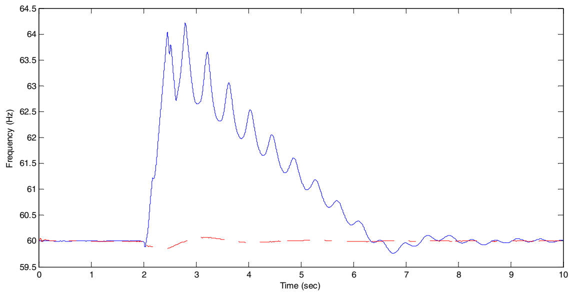

Fig.3 Frequency change of the system.

In Fig.3, at t=2s, load shedding leads to frequency rise immediately. Subsequently, load rejoining leads to frequency fall down. The alternative fluctuation caused by consumers' real-time demand change, brings oscillation to the system frequency. After adjustment of inverters and generators, it takes nearly 6s to recover. However, the recovered frequency is still in fluctuation, at an amplitude of 0.1Hz.

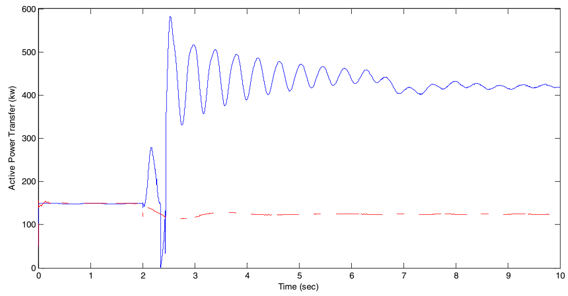

Fig.4 Active power change between node 4 and 10.

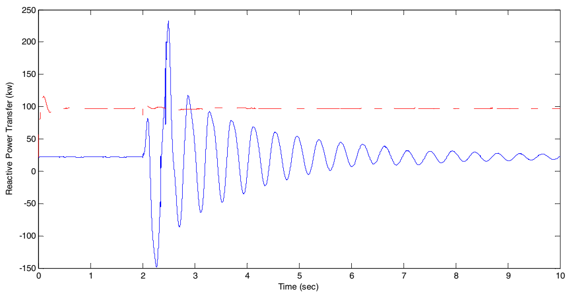

Fig.5 Reactive power change between node 4 and 10.

Similarly, the active and reactive power changes are shown in Fig.4 and Fig.5, respectively. From the comparison in Fig.3-5, we can find that the recovery time is significantly shorter than original system without proposed control. On the other hand, the proposed frequency stabilization control reallocates power flow among the system. As a result, the recovery condition becomes more stable and steady. In other words, the proposed stabilization which contributes to stabilization of interconnected microgrid, is important to the industrial consumers which need high-quality electricity.

B. *Case 2 Fluctuation happens to wind speed*

In this case study, another case which is common in the interconnected microgrid is studied.

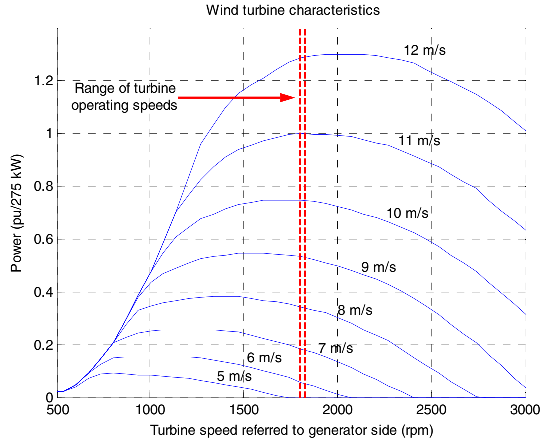

Fig.6 The regulation characteristics of wind turbines.

Due to the intermittent of renewable energy, such as sheltering in photovoltaic and fluctuation in wind generation, another common case is the oscillation caused by intermittent of renewable energy.

In this simulation, a fluctuation of wind speed is simulated. At the time of 2s, a fluctuation happens at MD4-a 70kw wind turbine. With the wind turbines' own regulation, such as the regulation shown is Fig.6, the generation can be regulated according to the wind speed ranges. However, if the wind is in a fluctuation, the regulation will result in a repeated change, such as the angular frequency and frequency fluctuation shown in Fig.7-8.

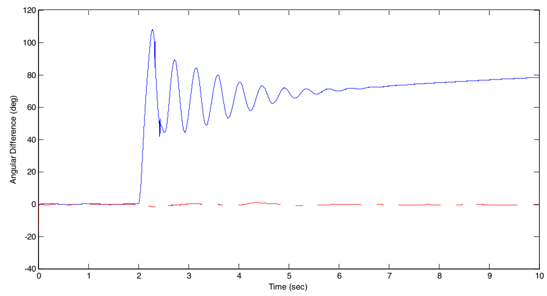

Fig.7 Angular frequency change of the system.

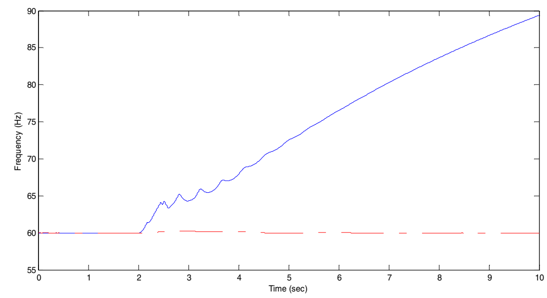

Fig.8 Active power change between node 4 and 10.

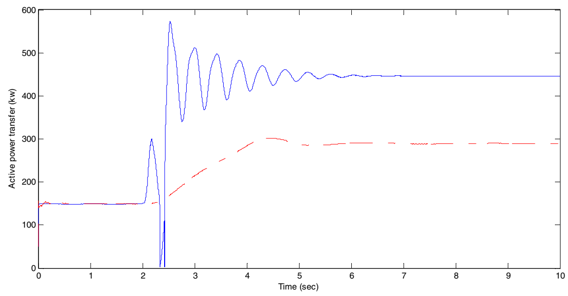

Fig.9 Active power change between node 4 and 10.

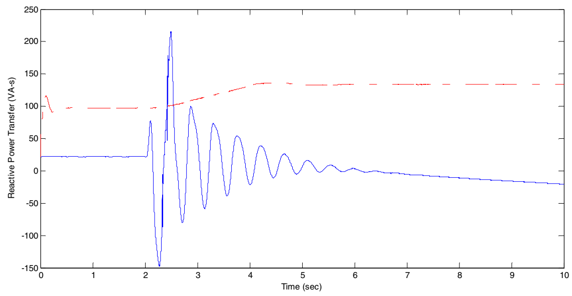

Fig.10 Reactive power change between node 4 and 10.

With respect to the active and reactive power adjustment by the wind turbines, the powers are regulated following the change of wind speed, as shown in Fig.9-10.

From the comparison between the output without control and the output with stabilization design, it is clear that the proposed frequency stabilization design improves the frequency and transfer power of the system. There are less fluctuation in the output of generation, smaller amplitude of fluctuation, and shorter time to recovery. Especially when the system comes to instability, the proposed stabilization still maintains the system stable.

VII. CONCLUSION

In this paper, an uncertain T-S fuzzy model for interconnected microgrid with multiple time delays is introduced. Time delays and uncertainties all exist in state. A design methodology for stabilization this kind of nonlinear time delay system based on Lyapunov approach is presented. The design procedure is conceptually simple and natural. Moreover, the control design problems can be solved very efficiently in practice. The simulation example shows the effectiveness of the presented method.

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