Power Quality Control of Hybrid Wind Power Generation System Using Fuzzy-Robust Controller

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Abstract. This paper proposes a modeling and controller design approach for a wind-diesel hybrid generation system that includes a wind-turbine and dump load. The proposed control scheme is based on the Takagi-Sugeno (TS) fuzzy model and the sliding mode nonlinear control. The TS fuzzy model expresses the local dynamics of a nonlinear system through sub-systems partitioned by linguistic rules. Thus, the TS fuzzy model provides a mechanism to take an advantage of the advances in modern control theory in designing a nonlinear controller. In the simulation study, the proposed controller is compared with a proportional-integral (PI) controller. Simulation results show that the proposed controller is more effective against disturbances caused by wind speed and load variation than the PI controller, and thus it contributes to a better quality wind-hybrid power generation system.

1 Introduction

The drawback of wind power generation is its dependence on nature — power output varies widely due to changes in wind speed, which are difficult to model and predict. Excessive fluctuation of power output negatively influences the quality of electricity, particularly frequency and voltage, in small-scale system such as in islands and in remote areas [1,2]. A hybrid system is generally composed of a wind-turbine coupled with an induction generator, an energy storage system, a dump load, and a backup diesel engine-driven synchronous generator for operation when wind power is insufficient. There can be several possible modes of operation [2-4].

This paper considers a mode where both the wind turbine-induction generator unit and the dump load operate in parallel. In this mode, wind-generated power is sufficient to supply loads and the diesel engine is disconnected from the synchronous generator. The synchronous generator acts as a synchronous condenser, to generate or absorb the reactive power that contributes to its terminal voltage in stabilizing the system. The dump load is applied to the frequency control by absorbing the excess active power in the network. Since no dynamic model of a wind-dump load system

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has been reported, this paper develops a novel nonlinear dynamic model of a wind-dump load system.

The nonlinear model is reduced for the purpose of designing the controller. With a reduced-order model, the proposed controller is designed based on the sliding mode control and the TS fuzzy model [5]. The TS fuzzy model provides a simple and straightforward way to decompose the task of modeling and controller design into a group of local tasks, which tend to be easier to handle and, in the end, the TS fuzzy model also provides the mechanism to blend these local tasks together to deliver the overall model and control design. Therefore, by employing the TS fuzzy model, we devise a control methodology to take advantage of the advances of modern control.

2 System Model

A wind-dump load hybrid system consists of a wind turbine, an induction generator (IG), a diesel engine (DE), a synchronous generator (SG), a dump load, and a load. The DE is disconnected from the SG by an electromagnetic clutch. A three-phase dump load is used with each phase consisting of seven transistor-controlled resistor banks [6]. Fig. 1 shows the structure of a wind-dump load system: e_{fd} is the excitation field voltage, f is the frequency, V_b is the bus voltage, C_a is the capacitor bank, P_{dump} is the required dump load power, and r_{dump} is the dump load resistance.

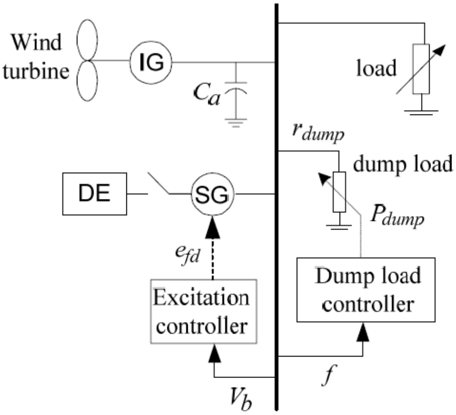

Fig. 1. The overall control structure of a wind-dump load system

3 Fuzzy-Robust Controller Design

The proposed controller is deigned based on the state feedback approach. In practical systems, it is difficult or impossible to measure all states as required. Therefore, special considerations are needed when a controller is designed, based on state feedback.

In this paper, two considerations are made for a controller design: first, a reduced-order nonlinear model is derived to describe the nonlinear system with only target states, which are easily measurable. Second, an extended state-space model is presented to overcome a non-zero final state problem because the state feedback approach is usually based on the zero final states. For a non-zero final state, an output feedback and a state observer approach are normally used [7]. The design procedure presented in this paper, however, is simpler than the output feedback and state observer approaches.

Fig. 2 depicts the input and output relationship of the wind-dump load system from the control point of view. The control inputs are the excitation field voltage (u_1) of the SG and the dump load resistance (u_2). The measurements are the voltage amplitude (y_1) and the frequency (y_2) of the AC bus. The wind speed (v_1) and load (v_2) are considered to be disturbances. The wind turbine generator and the dump load run in parallel, serving the load. From the control point of view, this is a coupled 2×2 multi-input-multi-output nonlinear system, since every input controls more than one output and every output is controlled by more than one input.

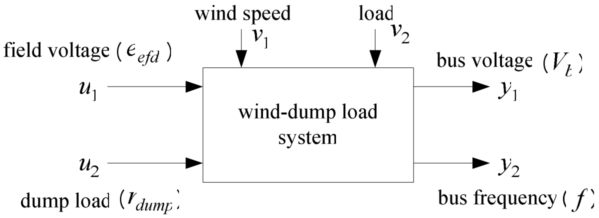

Fig. 2. The wind-dump load control system

3.1 Generator and Dump Load Model

The models of the generators are based on the standard Park's transformation [8] that transforms all stator variables to a rotor reference frame described by a direct and quadratic (*d*-*q*) axis.

Fig. 3 is the three-phase dump load, where each phase consists of 7 transistor-controlled resistor banks with binary resistor sizing in order to minimize quantum effects and provide more-or-less linear resolution.

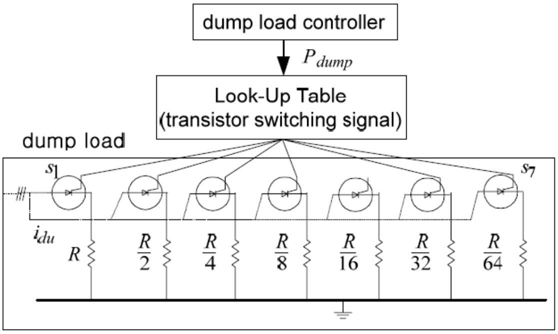

Fig. 3. The structure of the dump load with binary resistor sizing

Fig. 4 shows how the transistors are switched to meet the required power. For example, based on the rated AC line voltage of 230V and per-phase resistance of R (=120Ω), if the required dump load power from the dump load controller is 880W, step-2 is identified, and only switch S2 is turned ON.

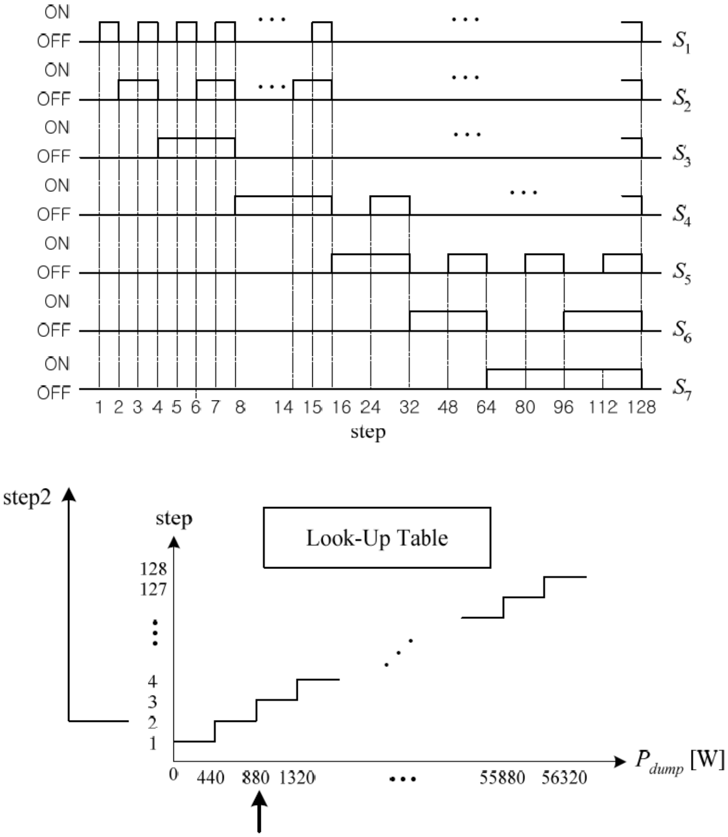

Fig. 4. Transistor switching signal

3.2 Reduced-Order Model

The nonlinear mathematical model of the wind-dump load system [6] is reduced to the following second-order model, to be used for a controller design:

$$\dot{\omega}_s = \frac{1}{J_s}\left(-D_s\omega_s - T_s\right),\ \dot{\psi}_f = \frac{1}{\tau'_{do}}\left(-\psi_f + L_{md}i_{sd}\right) + e_{fd} \tag{1}$$

The reduced-order model (1) can be slightly modified to present dump load effect in the system by noting that the air gap torque of the synchronous generator T_s can be represented as

$$T_s = P/\omega_s = \left(P_{dump} + P_{load} - P_{ind}\right)/\omega_s \tag{2}$$

where P_{dump}, P_s, and P_{ind} are the power of dump load, the synchronous generator, and the induction generator, respectively, and ω_s is the angular speed, which is proportional to frequency f. Applying (2) into (1), the reduced-order model becomes

$$\dot{\omega}_s = \frac{1}{J_s}\left(-D_s\omega_s + \frac{P_{ind} - P_{load}}{\omega_s} - \frac{1}{\omega_s}P_{dump}\right), \quad \dot{\psi}_f = \frac{1}{\tau_{do}^{'}}\left(-\psi_f + L_{md}i_{sd}\right) + e_{fd} \tag{3}$$

In (3), flux linkage ψ_f can be modified in terms of the bus voltage and the frequency. This is because, in local operating point, the following assumption can be made such that the rate of change of voltage is a linear combination of the rate of change of rotor flux and angular speed of the SG:

$$\dot{V}_b = \eta_1\dot{\psi}_f + \eta_2\dot{\omega}_s \tag{4}$$

where $\eta_1 = \partial V_b / \partial \psi_f$ and $\eta_2 = \partial V_b / \partial \omega_s$. Here, η_1 and η_2 are approximated as 1 [p.u.]. Therefore, from (3) and (4) the final reduced-order model is derived as

$$\dot{x}(t) = Ax(t) + Bu(t), \; y(t) = Cx(t) \tag{5}$$

where $x(t) = \begin{bmatrix} V_b & \omega_s \end{bmatrix}^T$, $u(t) = \begin{bmatrix} e_{fd} & P_{dump} \end{bmatrix}^T$, and

$$A = \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} -\dfrac{L_f}{T_{do}^{'}L_{md}\omega_s} & \dfrac{L_f}{T_{do}^{'}\omega_s L_{md}}\left(L_d i_{sd} - \dfrac{r_a i_{sq}}{\omega_s}\right) \\ \dfrac{P_{ind} - P_{load}}{J_s V_b \omega_s} & -\dfrac{D_s}{J_s} \end{bmatrix}, \quad B = \begin{bmatrix} 1 & -\dfrac{1}{J_s\omega_s} \\ 0 & -\dfrac{1}{J_s\omega_s} \end{bmatrix}, \quad C = \mathbf{I}_2.$$

Note that the model (5) is in the linear form for fixed system matrices A, B and C. However, matrices A and B are not fixed, but changes as functions of state variables, thus making the model nonlinear. Therefore, even though the reduced-order model is used to design a controller, the TS fuzzy-model based controller can be designed taking into account model imperfections and uncertainties. The proposed controller is designed in the following sub-sections.

3.3 Fuzzy-Robust Controller

The main feature of the Takagi-Sugeno fuzzy model expresses the local dynamics of a nonlinear system through linear sub-systems partitioned by linguistic rules. Therefore, by employing the TS fuzzy model, modern linear control theory can be utilized in devising a control methodology for the nonlinear system. In this paper, three linear sub-systems are considered as the state-space model:

$$\dot{x}(t) = A_i x(t) + B_i u(t), \quad y(t) = C_i x(t), \quad i = 1,2,3 \tag{6}$$

where $A_i \in \Re^{n \times n}$, $B_i \in \Re^{n \times m}$, and $C_i \in \Re^{p \times n}$. Here, n, m, and p are the number of states, inputs, and outputs, respectively. It can be seen from the reduced model (5) that n=m=p=2. The sub-systems are obtained by partitioning the state-space into overlapping ranges of low, medium, and high states. For each sub-space, different model

(i=1, 2, 3) is applied. The degree of membership function for each state-space is depicted in Fig. 5. Here, *LP*(i=1), *BP*(i=2), and *HP*(i=3) stand for possible low, most possible, and possible high membership functions, respectively. Even if the subsystems are linear model, the composite system represents the nonlinear system.

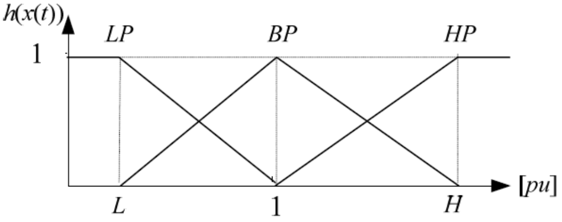

Fig. 5. The membership function for states

When the three controllers are obtained for each sub-system, each control input is weighted by its own membership function shown in Fig. 5. The fuzzy-robust controller output is obtained by deffuzification as

$$u_{FR}(t) = \left(\sum_{i=1}^{3} h_i(x(t)) u_i(t) \right) \Bigg/ \left(\sum_{i=1}^{3} h_i(x(t)) \right) \tag{7}$$

where $u_{FR}(t)$ is the fuzzy-robust controller output, $u_i(t)$ is the controller output for each linear sub-system, and $h_i(x(t))$ is the membership value of each linear system.

3.4 Sliding Mode Controller

The final states may not be zero but constants, such as in the system under study. Therefore, the modified state vector with the additional state $x_r(t) \in \Re^p$ [7] is obtained as follows:

$$\tilde{x}(t) = \begin{bmatrix} x_r(t) & x(t) \end{bmatrix}^T \tag{8}$$

where $x_r(t) = \int \big(r(t) - y(t) \big) dt$ and $r(t) = ref = 1$, and $\tilde{x}(t) \in \Re^{p+n}$ is the augmented state and the associated augmented system is represented as

$$\dot{\tilde{x}}(t) = \tilde{A}\tilde{x}(t) + \tilde{B}u(t) \tag{9}$$

where $\tilde{A} \in \Re^{(p+n)\times(p+n)}$, $\tilde{B} \in \Re^{(p+n)\times m}$ and with matrix A, B, and C of i^{th} subsystem

$$\tilde{A} = \begin{bmatrix} 0 & -C \\ 0 & A \end{bmatrix}, \quad \tilde{B} = \begin{bmatrix} 0 \\ B \end{bmatrix} \tag{10}$$

The proposed controller can then be designed with (9). The motivation to utilize the sliding mode control design is to enable robust control design utilizing multiple linear systems [9]. The controller for each linear sub-system (9) can be obtained as

$$u(t) = -(S\tilde{B})^{-1}(S\tilde{A} - \xi S)\tilde{x}(t) \tag{11}$$

where S is the hyperplane system matrix and where $\xi \in \Re^{m\times m}$ is a stable design matrix. The overall proposed control scheme is given in Fig. 6. Here, $u_F(t)$ is the final control input in the form

$$u_F(t) = r(t) + u_{FR}(t) \tag{12}$$

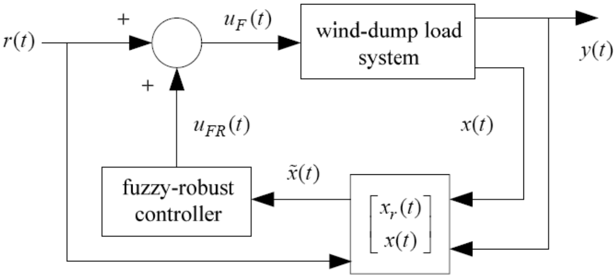

Fig. 6. The overall wind-dump load control scheme

4 Evaluation by Simulation

4.1 System Parameters

The system under study consists of a fixed wind turbine, an induction generator (IG) rated at 55kW, a 50kW turbocharged diesel engine (DE) driving a 55kVA brushless synchronous generator (SG). Nominal system frequency is 50Hz, and the rated line AC voltage is 230V [6]. The dump load consists of seven transistor-controlled resistor banks, rated at 55kW. Load is rated at 40kW. The rated wind speed is 7.25m/s. This section describes a simulation performance that tests the proposed controller. The augmented system state $\tilde{x}(t)$ is defined as

$$\tilde{x}(t) = \begin{bmatrix} x_{r,1}(t) & x_{r,2}(t) & x_1(t) & x_2(t) \end{bmatrix}^T \tag{13}$$

where $x_1$and x_2 stand for voltage and frequency, respectively.

Three linear models are obtained from (5) applying L=0.5 and H=1.5 for both V_b and f. For controller design parameters, the diagonal matrix $\boldsymbol{Q}$ is with $Q_{11}=Q_{33}=2000$ and $Q_{22}=Q_{44}=4000$, and the diagonal matrix $\boldsymbol{\xi}$ is with $\xi_{11}=\xi_{22}=80$. The rest of the terms equal zero. The tuned PI controller gains are P_{gov}=20, I_{gov}=60, and P_{efd}=30, I_{efd}=90.

4.2 Wind-Dump Load Control

Wind speed is shown in Fig. 7. For the simulation task, a step load change is applied at 5 seconds from the initial loading of 35kW to 27kW. In the following figures, the proposed fuzzy-robust controller is referred to as SMLQR for comparison with the PI controller. Fig. 8 shows the power in the IG, the load, and the dump load. In this case, when the load decreases, the dump load dissipates the excess power in the network. The proposed control scheme improves the bus frequency performance compared to the PI controller as shown in Fig. 9. In this system, the SG is used as a synchronous condenser. By controlling the field excitation, the SG can be made to either generate or absorb reactive power to maintain its terminal voltage. Fig. 10 shows the reactive power from the SG. Fig. 11 shows the bus voltage performance.

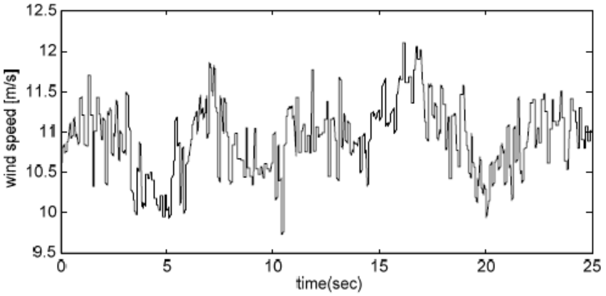

Fig. 7. Wind speed

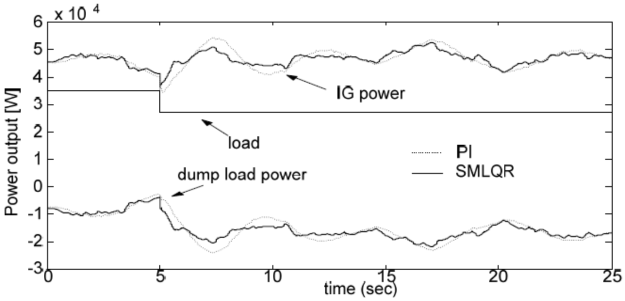

Fig. 8. Power outputs of IG, load, and dump load

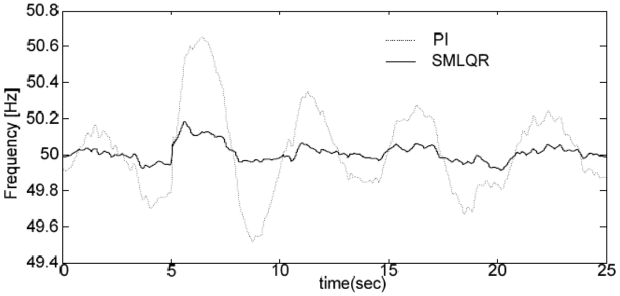

Fig. 9. Frequency performance

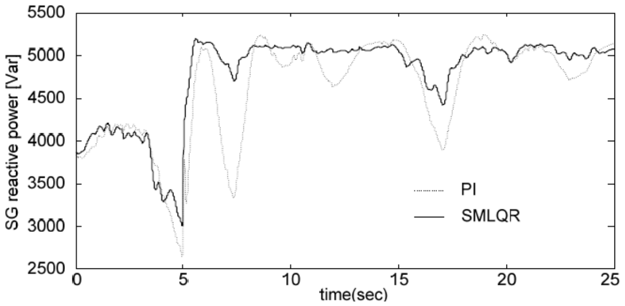

Fig. 10. Reactive power output from the SG

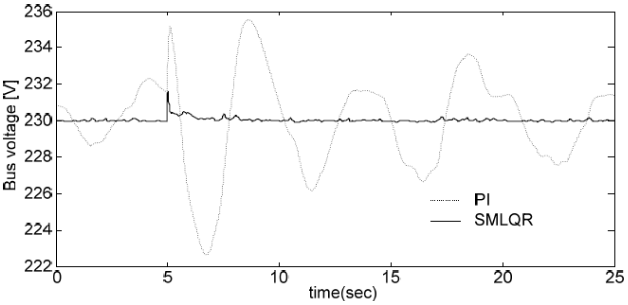

Fig. 11. Bus voltage performance

In SMLQR, the improvement of frequency and voltage with respected to the PI controller is 51.922% and 52.511% in per unit, respectively. The fuzzy-robust controller achieves better performance compared to the PI controller. The maximum voltage and frequency deviations are less than 1%. However, the voltage performance of the PI controller shows slow damping. Such poor performance is caused by the neglect of the interaction of variables between the PI controller loops [7]. Clearly, a control method is required that handles a multi-input-multi-output system. In the proposed controller, all performances are smooth and damped. Therefore, the fuzzy-robust controller provides more effective mechanism for multi-input-multi-output nonlinear system.

5 Conclusions

In this paper, the modeling of a wind-dump load system has been presented for power quality analysis, and the proposed control scheme is derived based on the Takagi-Sugeno (TS) fuzzy model and the sliding mode control. The proposed state-space model provides a new means for a controller design, especially when system states are not fully measurable or a non-zero final state. By employing the TS fuzzy model that represents a nonlinear system with several linear sub-systems, combined by linguistic rules, and by using the sliding mode control for each sub-system, the TS fuzzy model based controller can be designed taking into account model imperfections and uncertainties even though the reduced-order model is used to design a controller. The proposed controller provides more effective control for the system to achieve good power quality, which is demonstrated by smooth transition of bus voltage and frequency.

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