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The sliding mode load frequency control for hybrid power system based on disturbance observer

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ABSTRACT

Penetration of wind and solar power are increasing in power systems. Intermittent characteristics of renewable sources and random load variation result in system voltage and frequency fluctuation. A load frequency control (LFC) strategy based on sliding mode control (SMC) theory and disturbance observer is proposed for the single area power system. In order to reduce the frequency deviation caused by the unmatched parameter uncertainties such as the renewable source and different load disturbance, the sliding mode load frequency controller is constructed by selecting the appropriate proportional and integral switching surface and the reaching law condition. Furthermore, the sliding mode load frequency controller is reconstructed based on the designed disturbance observer (DOB) to improve the dynamic performance and suppress the chattering. The proposed method is compared with the conventional sliding mode LFC and the robust adaptive LFC (RALFC) by using the matlab software, the simulation results show that the designed LFC has faster response speed and better robust performance.

1. Introduction

Wind power generation is increasing tremendously worldwide due to global warming and the scarcity of fossil fuels [1–3]. But the wind power fluctuation is varied by weather condition, which may cause large frequency and voltage deviation. Load variation can also have the same problem [4]. So it is necessary to maintain the power quality through designing the load frequency control [5–10].

Different control methods have been applied to construct load frequency controller [8,11]. Proportional and integral (PI) control method [12–14] is widely applied for speed-governor system in normal operation mode [12]. However, there are many uncertainties such as parameter uncertainties, modelling error, renewable source fluctuation and random load disturbance in the practical power systems, so the PI LFC may be designed together with the advanced control techniques to improve the controller [13,14]. Many control methods such as optimal control [5,6], sliding mode control (SMC) [9,15–19], adaptive control [10,20], intelligent control [21] and robust control [22–24] have been used to design the LFC in recent years. The energy storage devices are also used to dispose of the hybrid power system LFC problem [25]. However, the cost and maintenance of batteries is a barrier for application.

The SMC [26] is utilized to design the load frequency control because of its strong robustness. The automatic generation control for single-area non-reheat systems is investigated [9] by using sliding mode control through the pole assignment method. The novel switching surface is constructed [19] to improve the dynamic performance for single area power system according to the integral load frequency controller. The optimized sliding mode load frequency controller is presented [18] for multi-area power systems. However, in many research results, the generation rate constraint, unmatched uncertainty and resource variation are not studied. A discrete SMC LFC is proposed [15] for multi-area power system with generation rate constraint, but the parameter uncertainties are not considered. The decentralized sliding mode load frequency control is designed [26] for multi-area power systems with matched and unmatched uncertainties, but there is no renewable resource in the power system.

Based on the above analysis, the novel sliding mode LFC is designed in this paper. Here, the power system model is constructed including unmatched parameter uncertainty, different

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load disturbance and fluctuating wind power which is more realistic and complex according to the power system only with step load disturbance. In order to design controller conveniently, all the uncertainties are aggregated into one item. The generation rate constraint (GRC) is also considered for simulation analysis. Furthermore, the sliding mode load frequency controller is reconstructed by using the disturbance observer [27] to reduce the chattering. The equality reaching law is applied to solve the controller and the frequency deviation convergence is proved by using the Lyapunov theorem. The rest of this paper is organized as follows. The power system model is defined in Section 2. The composite sliding mode control and disturbance observer for LFC are presented in Section 3. In Section 4, the proposed sliding mode LFC is simulated by matlab software for different cases. The conclusion can be drawn in Section 5.

2. Model of power system

A power system is a complex non-linear dynamic system with various uncertainties. Since a power system is usually exposed to slow changes of load and resource during normal operation, the linearized model can be used to represent the power system dynamics around the normal operating point. Therefore the control laws of a LFC are usually developed based on the linearized model. Due to load and resource variation, a controller based on the fixed-parameters may not work properly for actual systems. Therefore, the system model should be developed with considering uncertainties and parameter variations. The control block diagram of the linearized system model is shown in Fig. 1.

The state-space equations of the system model as shown in Fig. 1 can be written as follows,

$$\Delta\dot{f}(t) = -\frac{1}{T_p}\Delta f(t) + \frac{K_p}{T_p}\Delta P_G(t) - \frac{K_p}{T_p}\Delta P_d(t) + \frac{K_p}{T_p}P_{WF}(t) \tag{1}$$

$$\Delta\dot{P}_G(t) = -\frac{1}{T_T}\Delta P_G(t) + \frac{1}{T_T}\Delta X_G(t) \tag{2}$$

$$\Delta\dot{X}_G(t) = -\frac{1}{RT_G}\Delta f(t) - \frac{1}{T_G}\Delta X_G(t) - \frac{1}{T_G}\Delta E(t) + \frac{1}{T_G}u(t) \tag{3}$$

$$\Delta\dot{E}(t) = K_E\Delta f(t) \tag{4}$$

where $\Delta f(t)$, $\Delta P_G(t)$, $\Delta X_G(t)$, $\Delta E(t)$ and $\Delta P_d(t)$ are the variation of frequency, generator output, governor valve position, integral control and load disturbance respectively. T_G, T_T and T_P are time constants of governor, turbine and plant respectively. K_P is plant gain, R is the speed regulation due to governor action, K_E is integral control gain. $P_{WF}(t)$ is the output power of WTG. $u(t)$ is the designed sliding mode load frequency controller.

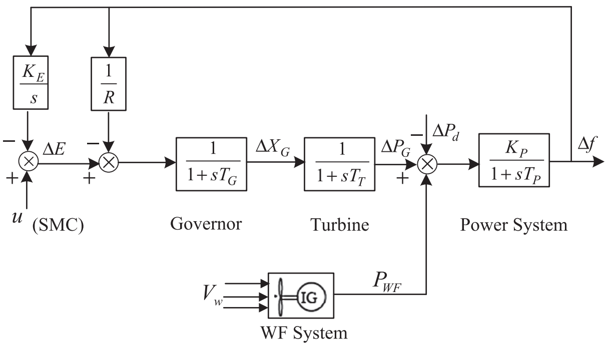

Fig. 1. Control block diagram of power system.

The matrix form of (1)–(4) can be rewritten as

$$\dot{x}(t) = Ax(t) + Bu(t) + H\Delta P_d(t) - HP_{WF}(t) \tag{5}$$

where $x(t)$ is state vector, matrix $A \in R^{4\times4}$, matrix $B \in R^{4\times1}$ and matrix $H \in R^{4\times1}$ are constant matrix with appropriate dimensions.

$$x(t) = \begin{bmatrix} \Delta f(t) \\ \Delta P_G(t) \\ \Delta X_G(t) \\ \Delta E(t) \end{bmatrix}, \quad A = \begin{bmatrix} -\frac{1}{T_P} & \frac{K_P}{T_P} & 0 & 0 \\ 0 & -\frac{1}{T_T} & \frac{1}{T_T} & 0 \\ -\frac{1}{RT_G} & 0 & -\frac{1}{T_G} & -\frac{1}{T_G} \\ K_E & 0 & 0 & 0 \end{bmatrix},$$

$$B = \begin{bmatrix} 0 \\ 0 \\ \frac{1}{T_G} \\ 0 \end{bmatrix} \text{ and } H = \begin{bmatrix} -\frac{K_P}{T_P} \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

In practical power system, the operation point vary constantly induced by load disturbance and fluctuating resource. Considering the uncertainties and parameter variations, the power system model can also be described as

$$\begin{aligned}\dot{x}(t) = {} & (A + \Delta A(t))x(t) + Bu(t) + (H + \Delta H(t))\Delta P_d(t) \\ & - (H + \Delta H(t))P_{WF}(t)\end{aligned} \tag{6}$$

where $\Delta A(t)$ and $\Delta H(t)$ are time varying parameter uncertainties with appropriate dimensions.

Defining $g(t) = \Delta A(t)x(t) + (H + \Delta H(t))\Delta P_d(t) - (H + \Delta H(t))$, the system model (6) can also be expressed as

$$\dot{x}(t) = Ax(t) + Bu(t) + g(t) \tag{7}$$

where the continuous function $g(t)$ represents the uncertainties with the matched part and mismatched part.

2.1. Wind power generation model

The output power of wind turbine generator depends upon the wind speed and other weather conditions, the output power can be expressed as follows [2].

$$P_{WF} = \frac{1}{2}\rho\alpha V_W^3 C_p(\lambda, \beta) \tag{8}$$

where V_W is wind speed, ρ is the air density, α is swept area of blades, $C_p(\lambda, \beta)$ is power coefficient which is a function of tip speed ratio λ and pitch angle β, $C_p(\lambda, \beta)$ is approximated by the following equation,

$$C_p(\lambda, \beta) = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\right)e^{\frac{-C_5}{\lambda_i}} + C_6\lambda \tag{9}$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{10}$$

where $\lambda_i = 1\Big/\left(\frac{1}{\lambda+0.08\beta} + \frac{0.035}{\beta^3+1}\right)$, C_1–C_5 are constants represented by performance characteristic of the windmill. The curve of $C_p(\lambda, \beta)$ according to the pitch angle β and the tip speed ratio λ is shown as

2.2. Load model

In the practical power system, the load is variable constantly [28]. In order to test the robustness of the designed SMLFC in this paper, we consider three kinds of load disturbance for the power system, the load model are as follow.

The load disturbance models are used to represent the abnormal change of load, such as generator tripping, suddenly lost a lot of load or power system splitting, the load disturbance of the second frequency control and so on.