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Observer based robust integral sliding mode load frequency control for wind power systems

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ABSTRACT

This paper investigates the load frequency control (LFC) for wind power systems with modeling uncertainties and variant loads. Since the system state is difficult to be accurately measured due to perturbation of nonlinear load, an observer is designed for reconstructing a substitution system state. Afterwards, an integral sliding surface is designed and a sliding mode LFC (SMLFC) strategy is proposed for reducing frequency deviations of the overall power system. Remarkably, it has been pointed out that a larger convergence rate of the observer error system has positive influences on the SMLFC performances, while the larger observer gain deteriorates the dynamic behavior. For seeking an acceptable balance so as to determine the optimal controller parameters, a collaborative design algorithm is proposed. The proposed method not only guarantees the asymptotical stability of overall power systems but also capable of improving the system robustness. Numerical examples are provided to demonstrate the effectiveness of the proposed methods.

1. Introduction

The rising consumption of fossil fuel and pollution of natural environment have promoted extensive concerning in integration of clean and sustainable energy sources to traditional power systems. Due to prominent superiorities as inexhaustibility, renewability, cleanability and expandability, some distributed generations (DGs), such as wind power, photo voltaic, etc., are widely conceived as feasible options for alleviating the power supply pressures (Fang, Misra, Xue, & Yang, 2012).

Since the DGs are usually spread in different geographic locations, they are mostly merged to nearby power grid as auxiliary energy sources. However, such integration is not flexible yet because the complementary features of DGs with the utility grid are still not be fully revealed. Due to oscillations and mismatch of generations, inadvertent power exchanges, unexpected events and uncertainties, etc., the power flow frequency often fluctuates and deviates from the nominal value (Pandey, Mohanty, & Kishor, 2013). As a consequence, the power exchange efficiency will be deteriorated even the stability of the overall power grid may be endangered (Alobeidli, Syed, Moursi, & Zeineldi, 2015; Shamsi & Fahimi, 2014). To overcome such defections, a compensational approach is known as the load frequency control (LFC), also called the automatic generation control (AGC). The objective of LFC is to accommodate load demands by maintaining the power flow frequency to the given tolerance and keeping within scheduled limits (Alobeidli et al., 2015; Pandey et al., 2013; Shamsi & Fahimi, 2014). In the past decade, many LFC schemes are proposed from different prospectives. For example, a fractional-order PID controller is researched for single power system with different kinds of turbine in Sondhi and Hote (2014). A sliding mode LFC strategy is proposed for single wind power system in Mi, Fu, Li, Wang, Loh, and Wang (2016). Based on optimal sliding mode Gaussian control theory, an optimal sliding mode LFC scheme is proposed for hydraulic power system in Rittenhouse and Sinha (2013). By coefficient diagram method and a internal model, two different LFC schemes are advocated for single area power system in Ali, Mohanmed, Qudaih, and Mitani (2014) and Saxena and Hote (2013), respectively. Concerning high penetration of wind energy and based on a particle swarm optimization technique, a disturbance rejection LFC scheme is proposed in Tang, Bai, Huang, and Du (2015).

Generally, a multi-area power system can be conceptually separated into several smaller sub-power systems that are interconnected

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by power flows via specific tie-line networks. Since the power flows are exchanged through a network, the dynamics of each subsystem will be inevitably influenced by the connected neighbors. Therefore, concerning to the multi-area power systems, the aforementioned LFC schemes unable to maintain applicability. For probing the intrinsic inter-influence mechanism of the sub power systems, some improved LFC schemes are researched recently. For example, employing direct–indirect adaptive fuzzy control technique, an H_∞ tracking LFC strategy for multi-area power system is researched in Yousef, AL-Kharusi, Albadi, and Hosseinzadeh (2014). Considering tie-line switching topologies and based on a distributed gain scheduling method, a switching LFC strategy is proposed in Liu, Liu, and Saddik (2014). By the coefficient diagram method, a decentralized LFC scheme is advocated for multi-interconnected power systems in Bernard, Mohamed, Qudaih, and Mitani (2014). Considering tie-line communication time-delay, an event-triggered LFC scheme is designed for multi-area power systems in Wen, Yu, Zeng, and Wang (2016). For suppressing the exogenous disturbances, an H_∞ LFC is proposed for multi-area power systems in Dey, Ghosh, Ray, and Rakshit (2012).

In the aforementioned literatures, the system models are mostly assumed to be trustworthy. However, due to parameter changes, errors in modeling and instantaneous load variants, the real power systems usually contain uncertainties in system dynamics. Therefore, the LFC schemes for multi-area power systems should have capability of robustness and adaptiveness to the system uncertainties and load changes. Recently, some robust LFC strategies are gradually proposed. For example, a decentralized robust sliding mode LFC law is designed for multi-area power systems in Mi, Fu, Wang, and Wang (2013). By Kharitonov's theorem, a robust decentralized proportional–integral (PI) LFC scheme is proposed in Toulabi, Shiroei, and Ranjbar (2014). Consider vehicle-to-grid penetration, a robust LFC scheme for multiple wind power systems is proposed in Vachirasricirikul and Ngamroo (2014). Concerning to a multi-area power system in the presence of wind generators with physical constraints of governor inputs and turbine outputs, a model predictive based LFC controller is proposed and the system robustness is improved in Mohamed, Morel, Bevrani, and Hiyama (2012). The dynamic mismatches between nonlinear and linear wind power system is modeled as system uncertainties, a robust RBF neural-network-based sliding mode control law is researched for linear wind power systems in Qian, Tong, Liu, and Liu (2016).

The above discussed literatures give different robust LFC schemes from different viewpoints, however, there still exists many practical issues waiting to be researched. For example, concerning to wind power systems, the system state deviations are difficult or even barely impossible to be explicitly measured due to load variants. Therefore, how to effectively estimate the system state for enclosing a feedback frequency control? In addition, although the power loads appearer as periodical oscillations in a long time-scale, the instantaneous load changes still behave as unpredictably nonlinear dynamics. Therefore, how to design an effective LFC scheme for enhancing system robustness to the nonlinear loads?

With the aforementioned motivations, this paper concerns to further investigate effective LFC for wind power systems with system modeling uncertainties and nonlinear load changes. The contributions of this work are listed as follows. (i) An observer based integral sliding mode LFC (SMLFC) law is proposed for reducing the frequency deviations while enhancing system robustness and adaptiveness to the system uncertainties and the nonlinear loads. (ii) A collaborative design algorithm is proposed for determining the optimal SMLFC parameters. By this method, not only the stability of the power system can be guaranteed but also the SMLFC dynamic performances are greatly improved.

The remainder of the paper is organized as follows. Problem is formulated in Section 2. Main result is presented in Section 3. Section 4 gives simulation examples. A conclusion is provided in Section 5.

The following notations are given which will be used throughout the literature. Let $\mathscr{R}$, $\mathscr{N}$ and $\mathscr{C}$ denote the real, integer and complex numbers, respectively. Given an appropriate dimension matrix A, A^T and $sym(A)$ denote its transpose and $A + A^T$, respectively. Given an square matrix P, $\lambda_{min}(P)$, $\lambda_{max}(P)$ and $tr(P)$ denote the minimal, maximal eigenvalue and the sum of the eigenvalues of P, respectively. The function $\|\cdot\|$, $min(\cdot)$ and $max(\cdot)$ denote the Euclidean norm, the minimal and maximal function, respectively. The notation I denotes an appropriate dimension identity matrix.

2. Problem formulation

The considered overall power system is consisted by N sub wind power systems, where $N \in \mathscr{N}$. Each subsystem includes a doubly-fed induction generator (DFIG) and all of the subsystems are jointly linked with their neighbors by power flows via specific tie-line link(s) (Liu et al., 2014; Vachirasricirikul & Ngamroo, 2014). Although the subsystem is a nonlinear system, the linearized model has been conceived as a permissible description in LFC because relatively slow changes of load and variants during normal operation condition (Mi et al., 2016; Mohamed et al., 2012; Qian et al., 2016). The structure of the ith subsystem, $i \in \{1, 2, \ldots, N\}$, is illustrated as Fig. 1.

In Fig. 1, the dynamic of the ith subsystem can be divided into five sectors as governor deviation, turbine deviation, tie-line power flow, the frequency deviation and wind generator. The corresponding dynamics are given as follows.

(i) The dynamic of the governor can be expressed as:

$$\Delta\dot{p}_{gi}(t) = -\frac{1}{T_{gi}}\Delta p_{gi}(t) - \frac{1}{R_i T_{gi}}\Delta f_i(t) + \frac{1}{T_{gi}}\Delta p_{ci}(t), \tag{1}$$

where $\Delta p_{gi}(t)$, $\Delta f_i(t)$ and $\Delta p_{ci}(t)$ denote the governor value position deviation, frequency deviation and reference load set-point, respectively.

(ii) The dynamic of the turbine is modeled as:

$$\Delta\dot{p}_{mi}(t) = \frac{1}{T_{ti}}\Delta p_{gi}(t) - \frac{1}{T_{ti}}\Delta p_{mi}(t), \tag{2}$$

where Δp_{mi} denotes the generator mechanical power deviation.

(iii) The generator–load dynamic relationship between the incremental power mismatch $(\Delta p_{mi}(t) - \Delta p_{Li}(t))$ between the frequency deviation Δf_i can be expressed as:

$$\begin{aligned}\Delta\dot{f}_i(t) \;=\; & \frac{1}{2H_i}\Delta p_{mi}(t) - \frac{D_i}{2H_i}\Delta f_i(t) - \frac{1}{2H_i}\Delta p_{tie,i}(t) - \frac{X_{3i}\omega_{opt,i}}{2H_i}\Delta i_{qr,i}(t)\\ & - \frac{1}{2H_i}\Delta p_{Li}(t),\end{aligned} \tag{3}$$

where $\Delta p_{Li}(t)$, $\Delta p_{tie,i}(t)$ and $\Delta i_{qr,i}(t)$ denote the grid load deviation, the tie-line power flow of ith subsystem and rotate current of generator i, respectively.

(iv) The tie-line power flow between of ith subsystem is given as:

$$\Delta\dot{p}_{tie,i}(t) = 2\pi\sum_{j=1,j\neq i}^{N} T_{ij}\Delta f_i(t) - 2\pi\sum_{j=1,j\neq i}^{N} T_{ij}\Delta f_j(t). \tag{4}$$

(v) The wind generator is given as:

$$\Delta\dot{i}_{qr,i}(t) = -\frac{1}{T_i}\Delta i_{qr,i}(t) + \frac{X_{2i}}{T_i}\Delta v_{qr,i}(t), \tag{5}$$

where $v_{qr,i}(t)$ is the rotate voltage of generator i.

The rest definitions of the above variables and parameters are listed in Appendix A.1.

For regulating the subsystem frequency, a widely accepted method is to add a frequency deviation with neighbor subsystems for enclosing a feedback loop. Currently, a widely accepted frequency deviation combination method is called the area control error (ACE), i.e.,

$$ACE_i = \Delta p_{tie,i}(t) + E_i\Delta f_i(t), \tag{6}$$

where E_i is a fixed gain, $i = 1, 2, \ldots, N$.

Regarding the ACE as system output, defining vectors and matrices as $x_i(t) = (\Delta p_{gi}, \Delta p_{mi}, \Delta f_i, \Delta p_{tie,i}, \Delta i_{qr,i}, \Delta\omega_i)^T$, $u_i(t) =$