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Non-linear sliding mode load frequency control in multi-area power system

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ABSTRACT

This paper addresses non-linear sliding mode controller (SMC) with matched and unmatched uncertainties for load frequency control (LFC) application in three-area interconnected power system. In conventional LFC scheme, as the nominal operating point varies due to system uncertainties, frequency deviations cannot be minimized. These lead to degradation in the dynamic performance or even system instability. In this paper, an effective control law is proposed against matched and unmatched uncertainties.. The proposed controller has ability to vary closed-loop system damping characteristics according to uncertainties and load disturbances present in the system. The frequency deviation converges to zero with minimum undershoot/overshoot, fast settling time, significantly reduced chattering and ensures asymptotic stability. In addition, the controller is robust in the presence of parameter uncertainties and different disturbance patterns. It also guarantees high dynamic performance in the presence of governor dead band (GDB) and generation rate constraint (GRC). Simulations are performed to compare the proposed controller with linear SMC. Using proposed control strategy, undershoot/overshoot and settling time gets reduced by approximately 30% with respect to linear SMC. The computed performance indices and qualitative results establish the superiority as well as applicability of the proposed design for the LFC problem. Further, the proposed controller scheme is validated on IEEE 39 bus large power system.

1. Introduction

Load frequency control (LFC) is one of the important issues in multi-area power systems. The basic objective of the LFC is balanced generation and load demand, such that frequency deviation and tie-line power deviation converges to zero in different control areas defined in a multi-area power system (Bevrani, 2014; Kundur, 1994). Frequency control during load and generation variation in any area is an important operational aspect in a large interconnected power system (Camblong, Vechiu, Etxeberria, & Martínez, 2014; Yinsong, Shizhe, Jingyu, & Zheng, 2016). Conventionally, LFC uses an integral controller. It is well known that a high integral gain may deteriorate the system performance, causing large oscillations and instability. Thus, the integral gain must be set at a level so as to provide a compromise between a desirable transient recovery and low overshoot in the dynamic response of the overall system. The methods to tune the gain of the integral controller have been reported in (Ibraheem, Kumar, & Kothari, 2005). In general, the design approach for load frequency controller is employed on the basis of linearized model with fixed PI parameters (Bevrani & Hiyama, 2005). However, classically tuned PI control strategy results have longer settling time and relatively large overshoots in transient response. Besides, such PI control algorithm provides desired response of the system only in the vicinity of the designed operating point. In other words, these cannot perform over wide range of operating conditions of load changes/disturbances and parameter uncertainties in the multi-area power system.

Recently, several control design approaches have been reported. The application of advanced control methods in both single area and multi-area systems has been found widely during the literature survey such as in (Bevrani, Mitani, & Tsuji, 2004; Ersdal, Imsland, Uhlen, Fabozzi, & Thornhill, 2016; Rerkpreedapong, Hasanovic, & Feliachi, 2003; Zribi, Al-Rashed, & Alrifai, 2005). An optimal fractional order PID controller was designed and tuned using genetic algorithm for LFC (Ismayil, Ramdas Sreerama, & Thiruthimana Krishnan, 2015). The LFC for single area power system has been reported in (Saxena, Hote & Yogesh, 2013) using internal model control and model-order reduction. A direct-indirect adaptive fuzzy controller was developed in (Yousef, AL-Kharusi, Albadi, & Hosseinzadeh, 2014) for multi-area LFC scheme. A H_∞ performance criterion was used to minimize the effect of disturbances. A cooperative control technique was formulated in (Chen, Ye, Wang, & Lu, 2015) to allocate the regulation burden among the control areas.

Due to increase in size and complexity of modern power systems, oscillations are observed when PI control strategy is implemented.

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These system oscillations might propagate into wide area resulting into blackout. So, advanced control methods; optimal control (Fosha, Elgerd); variable structure control (Zribi et al., 2005), (Goshaidas, Sitansu, & Bhattacharyya, 2004); robust control (Bevrani, 2014), (Bevrani et al., 2004), (Lim, Wang, & Zhou, 1996); and adaptive control (Khooban & Niknam, 2015; Zribi et al., 2005) have been applied. The authors (Barisal, 2015) proposed a teaching learning based optimization to tune the parameters of Integral and PID controller in hybrid system following a step change in load. The application of fuzzy PI controllers for LFC is suggested in (Hassan, 2015; Tarkeshwar & Mukherjee, 2015). An adaptive neuro-fuzzy inference system approach for automatic generation control in three area hydro-thermal power system is given in (Prakasha & Sinhab, 2015).

An efficient approach for LFC was formulated and investigated in deregulated environments (Chandra Sekhara, Sahua, Baliarsinghb, & Pandaa, 2016). The decentralized LFC scheme is more practical than the centralized one because it only uses the local area state information to attenuate the frequency deviation (Goshaidas et al., 2004), (Lim et al., 1996), (Tarek Hassan Mohamed et al., 2012). A variable structure control based LFC was formulated in (Goshaidas et al., 2004) in the presence of parameter matched uncertainty. A decentralized LFC scheme was designed using the model predictive control technique for an interconnected power system concerning wind turbines in (Tarek Hassan Mohamed et al., 2012).

The operating characteristic of generating unit changes with time, therefore, parameter uncertainties is an important issue in the controller design (Siaramakrishana, Hariharm, & Srisailam, 1984). Therefore, the designed controller may be suitable for a specific operating point but may not be effective under parameter uncertainties. This necessitates for verification in robustness of designed LFC against the parameter changes. The objective of load frequency control (LFC) action in an area is to compensate against these variations. Several authors (Kundur, 1994), (Goshaidas et al., 2004), (Khodabakhshian & Edrisi, 2008), (Hsu, 1998), (Mi, Fu, Wang, & Wang, 2013) have applied variables structure theory for the design of LFC.

Sliding mode control (SMC) is a form of variable structure control. Mi et al. Mi et al. (2013) has presented decentralized LFC design using SMC strategy for solving matching and unmatched parameter uncertainties. Vrdoljak, Peric, and Petrovic (2010) has proposed a discrete-time sliding mode controller for LFC. The application of SMC for LFC problem has been addressed in references (Mi et al., 2013; Vrdoljak et al., 2010). The non-linear sliding mode control is applied on ship-roll stabilization problem (Fulwani, Bandyopadhyay, & Fridman, 2011) and frequency regulation in power system (Prasad, Purwar, & Kishor, 2016) to improve the system dynamic performance in terms of low overshoot and reduced settling time.

The conventional LFC controllers (Lim et al., 1996; Zribi et al., 2005) are designed with fixed parameters and operated only around the nominal point. Mi Yang (Mi et al., 2013) claimed that SMLFC has improved steady response only in the presence of system matched and unmatched uncertainties, step load disturbance and non-linearities such as generation rate constraint (GRC). This paper addresses the effect of the matched and unmatched uncertainties, different load disturbance patterns and non-linearities such as GRC, governor dead band (GDB) on LFC model for multi-area power system as described in Section 2. The paper objective of this paper is to achieve both minimum overshoot/undershoot and reduced settling time simultaneously with significant reduction in chattering.

The non-linear switching surface is described in Section 3, followed by selection of non-linear function and stability of NLSMLFC under both matched and unmatched uncertainties in multi-area power system. Here, an effective control law is designed for matched as well as unmatched uncertainties in Section 4. Thus, the proposed controller has ability to vary closed-loop system damping characteristics according to present uncertainties and load disturbances in the system. The effectiveness of the proposed controller is evaluated with MATLAB® in Section 5. The proposed; non-linear SMC for LFC (NLSMLFC) is compared with linear SMC design strategy for the same system parameters and various scenarios of three area interconnected power system as reported in (Mi et al., 2013). Mi et al. (2013) has not considered linear SMC performances against random load disturbances and GDB. Further, in this study, the robustness of NLSMLFC is compared with linear SMC (Mi et al., 2013) against random load disturbance. The results have been compared and found better for GRC and GDB conditions of the generating unit. The performance indices are also calculated and compared with linear SMC. The designed control signal provides significantly reduced chattering effect signifying reduced wear-out of actuators (valve) in steam turbine. The overshoot/undershoot and settling time gets reduced by approximately 30% with respect to linear SMC (Mi et al., 2013). Finally, to demonstrate the validation and effectiveness of the proposed NLSMLFC, IEEE 39 bus large power system (Bevrani, 2014) is considered and successfully tested in Scenario 6 of Section 5. The frequency oscillations are reduced to zero and a significant reduction in chattering in the control signal is found with NLSMLFC that enhance the system stability. The results illustrate that the proposed scheme can effectively enhance the frequency stability by improving the damping of the system.

2. LFC scheme for multi-area interconnected power system

2.1. LFC scheme for i-area

For an interconnected system, in addition to primary speed control loop, supplementary control action in secondary loop is

required to schedule the generation. As such, the power network although being a complex non-linear system, can be considered linearized for the study of LFC problem. The linearized model around the operating point of three area power system is referred from (Lim et al., 1996), (Mi et al., 2013). The study model of the i^{th} area of power system is shown in Fig. 1. The generator in each area is assumed to be equipped with non-reheat turbine. The equations that govern the dynamics of ith area are given as (Mi et al., 2013):

$$\Delta\dot{f}_i(t) = -\frac{1}{T_{p_i}}\Delta f_i(t) + \frac{K_{p_i}}{T_{p_i}}\Delta P_{p_i}(t) - \frac{K_{p_i}}{T_{p_i}}\Delta P_{d_i}(t) - \frac{K_{p_i}}{2\pi T_{p_i}}\sum_{j=1, j\neq i}^{N} K_{sij}\{\Delta\delta_i(t) - \Delta\delta_j(t)\} \tag{1}$$

$$\Delta\dot{P}_{g_i}(t) = -\frac{1}{T_{t_i}}\Delta P_{g_i}(t) + \frac{1}{T_{t_i}}\Delta X_{g_i}(t) \tag{2}$$

$$\Delta\dot{X}_{g_i}(t) = \frac{-1}{R_i T_{G_i}}\Delta f_i(t) - \frac{1}{T_{G_i}}\Delta X_{g_i}(t) - \frac{1}{T_{G_i}}\Delta E_i(t) + \frac{1}{T_{G_i}}u_i(t) \tag{3}$$

$$\Delta\dot{E}_i(t) = K_{E_i}\left[K_{B_i}\Delta f_i(t) + \frac{1}{2\pi}\sum_{j=1, j\neq i}^{N} K_{sij}\{\Delta\delta_i(t) - \Delta\delta_j(t)\}\right] \tag{4}$$

$$\Delta\dot{\delta}_i(t) = 2\pi\Delta f_i(t) \tag{5}$$

where, $i = 1, \dots, N$ is the number of areas. Eqs. (1)–(5) can be represented in state space form as:

$$\dot{x}_i(t) = A_i x_i(t) + B_i u_i(t) + \sum_{\substack{j=1 \\ j\neq i}}^{N} E_{ij}x_j(t) + F_i\Delta P_{d_i}(t) \tag{6}$$

where,

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