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Sliding mode based load-frequency control in power systems

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ABSTRACT

The paper presents a new discrete-time sliding mode controller for load-frequency control (LFC) in control areas (CAs) of a power system. As it uses full-state feedback it can be applied for LFC not only in CAs with thermal power plants but also in CAs with hydro power plants, in spite of their non-minimum phase behaviors. To enable full-state feedback we have proposed a state estimation method based on fast sampling of measured output variables, which are frequency, active power flow interchange and generated power from power plants engaged in LFC in the CA. The same estimation method is also used for the estimation of external disturbances in the CA, what additionally improves the overall system behavior. Design of the discrete-time sliding mode controller for LFC with desired behavior is accomplished by using a genetic algorithm. To the best of our knowledge, proposed controller outperforms any of the existing controllers in fulfilling the requirements of LFC. It was thoroughly compared to the commonly used PI controller by extensive simulation experiments on a power system with four interconnected CAs. These experiments show that the proposed controller ensures better disturbance rejection, maintains required control quality in the wider operating range, shortens the frequency's transient response avoiding the overshoot and is more robust to uncertainties in the system.

1. Introduction

Power systems are composed of interconnected subsystems or control areas (CAs). Most of European countries are members of "Union for the Co-ordination of Transmission of Electricity" (UCTE) interconnection [1]. It is assumed that each CA consists of a coherent group of generators. CAs are interconnected by the tie-lines. Because of the differences in generation and load in a power system, system's frequency deviates from its nominal value and active power flow interchanges between areas deviate from their contracted values. The purpose of load-frequency control (LFC) in each CA is to compensate for those deviations. That is obtained by changing power outputs of certain generators within the CA. To test LFC algorithms, an example power system is usually modeled as an interconnection of a few CAs. Since all generators in one CA are coherent, all power plants engaged in LFC in a CA can be replaced with one substitute power plant [2]. In some CAs that power plant is of thermal type and in some CAs of hydro type. When modeling a CA, power imbalance and losses can be seen as external disturbances.

Nowadays, in the majority of CAs PI type controllers with constant parameters are used for LFC [3–6]. However, systems with PI control have long settling time and relatively large overshoots in frequency's transient responses [7]. Besides, PI control algorithm provides required behavior of the system only in the vicinity of the nominal operating point, for which it is designed. But, operating point of a power system usually changes a lot, which is primarily caused by the amount and characteristic of power consumption, characteristics of power plants and the number of power plants engaged in LFC in a CA. Future power systems will rely on large amounts of distributed generation with large percentage of renewable energy based sources, what will further increase system uncertainties and thereby induce new requirements to the LFC system [8]. The shortening of time periods in which each level of frequency regulation must finish could be also expected in the future [9].

Therefore, an advanced controller should be developed and used instead of the PI controller in order to: (1) ensure better disturbance rejection, (2) maintain required control quality in the wider operating range, (3) shorten the frequency's transient responses avoiding the overshoots and (4) be robust to uncertainties in the system. Additionally, a new control algorithm for a CA should enable decentralized LFC of interconnected CAs, i.e. its structure and parameters must not depend on applied controllers in neighboring CAs. It should also be a discrete-time control algorithm with sampling time in the range 1–5 s as required in UCTE interconnection [1]. Finally, it should be relatively simple to implement,

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in order to be accepted as adequate replacement of PI control algorithm.

Recently, many different control algorithms have been proposed for LFC [10,11] in order to overcome limitations of the PI controller. Among them, the most immanent are based on: robust control, [5,12], fuzzy logic [13–15], neural networks [16–18], model predictive control [19,20], optimal control [21–23], adaptive control [24–26] and sliding mode control (SMC) [27–31] algorithms. Some drawbacks present in the above algorithms can be listed as follows: (1) measurements from neighbor CAs are required for controller synthesis, but obtaining them could be impractical in real power system [25,27]; (2) control signal is computed in continuous-time [5,15,27–32] although in real power system the signal should be sent to the power plants in discrete-time; (3) controllers are based on full system state, but with no estimator present [14,22,27–31]; (4) controllers are complex and of high order [20]; (5) there is a requirement for on-line parameters identification [24,30]; (6) the choosing of appropriate controller parameters is problematic [23,29,32]. Listed drawbacks clearly indicate that none of the abovementioned controllers fulfills all requirements for LFC.

In this paper we propose a discrete-time sliding mode controller that at best of our knowledge outperforms any of the existing controllers in fulfilling the requirements for LFC. Generally, SMC is a robust control technique that shows very good behavior in controlling systems with external disturbances and parameter variations [33]. In SMC, system closed-loop behavior is determined by a sub-manifold in the state space, which is called a sliding surface. The goal of the sliding mode control is to drive the system trajectory to reach the sliding surface and then to stay on it. When the trajectory is on the surface, system invariance to particular uncertainties and parameter variations is guaranteed.

Ideal sliding of the system trajectory along the sliding surface can be achieved only by the continuous-time SMC with very high (theoretically infinite) switching frequency of the control signal. But, real power plants are unable to respond to so fast changes of the control signal, and that is the reason why we propose a discrete-time sliding mode controller which changes control signal periodically in discrete-time instants. Of course, with the usage of discrete-time SMC the system trajectory can't be kept on the sliding surface but inside a small band around the surface. That behavior is known as quasi sliding mode [34]. Two main problems in designing discrete-time SMC for LFC are appropriate choices of sliding surface which defines desired system behavior, and of reaching law which must be chosen to ensure convergence of the trajectory from any point in the state space towards the surface [35]. An optimization method based on genetic algorithm (GA) is proposed for finding optimal parameters of the sliding surface and of the reaching law.

If only thermal power plants are used for LFC in a CA then stable sliding mode controller can be also designed using only measured output signals, which are frequency, active power flow interchange and generated power from each power plant in that CA. But, if hydro power plants are used for LFC then full-state feedback is needed because of their non-minimum phase behaviors. We have developed a full-state sliding mode controller, which can be applied in either cases. The usage of the state estimation method based on fast output sampling (FOS) [36] is proposed, what is possible due to availability of multiple measurements of output signals in each sampling period of the controller. FOS estimation method is also used for the estimation of external disturbances, what additionally improves the overall system behavior.

The brief outline of the paper is as follows: Section 2 presents power system model, Section 3 describes state and disturbance estimation technique. Section 4 gives an overview of discrete-time SMC and its application to LFC. Section 5 presents a GA used for the purpose of finding optimal sliding mode algorithm parameters, while Section 6 contains simulation results.

2. Mathematical model of a power system

An example mathematical model of a power system used in this paper consists of four interconnected CAs, each represented with one substitute thermal or hydro power plant. Each CA has its own load frequency controller, as it is shown in Fig. 1. Power system is modeled as continuous, while control signals are sent to the plants in discrete-time.

It is supposed that power plants in CA1 and CA4 are thermal power plants, while power plants in CA2 and CA3 are hydro power plants. Furthermore, power plants in CA1 and CA2 have less generating capacity then those in CA3 and CA4. Sliding mode based LFC, described in Section 4, will be applied to CA1 and CA3, while LFC in other CAs will be based on conventional PI type control algorithm.

Linearized mathematical model of each of four CAs can be described with the following equation:

$$\dot{\mathbf{x}}_i(t) = \mathbf{A}_i\mathbf{x}_i(t) + \sum_j \mathbf{A}_{ij}\mathbf{x}_j(t) + \mathbf{B}_i\mathbf{u}_i(t) + \mathbf{F}_i\mathbf{d}_i(t) + \boldsymbol{\xi}_i(\mathbf{x}, \mathbf{u}, t), \qquad (1)$$

where $\mathbf{x}_i \in \mathbb{R}^n$ is the system state vector, $\mathbf{x}_j \in \mathbb{R}^p$ is a state vector of the neighbor system, $\mathbf{u}_i \in \mathbb{R}^m$ is the control signal vector, $\mathbf{d}_i \in \mathbb{R}^k$ is the disturbance vector, $\boldsymbol{\xi}_i$ is a vector of uncertainties and $\mathbf{y} \in \mathbb{R}^l$ is the output vector. Matrices in (1) have appropriate dimensions: $\mathbf{A}_i \in \mathbb{R}^{n\times n}$, $\mathbf{A}_{ij} \in \mathbb{R}^{n\times p}$, $\mathbf{B}_i \in \mathbb{R}^{n\times m}$, $\mathbf{F}_i \in \mathbb{R}^{n\times k}$ and $\mathbf{C}_i \in \mathbb{R}^{l\times n}$.

Linearized model of CAs are used instead of the nonlinear ones because proposed SMC is based on such a linear model, where linearization error is included in the uncertainty term $\boldsymbol{\xi}_i(\mathbf{x}, \mathbf{u}, t)$. Simplified linearized continuous-time models of CAs with one substitute hydro or thermal power plant are shown in Figs. 2 and 3, respectively.

For the model shown in Fig. 2 state and disturbance vectors from (1) are (see Table 1):

$$\mathbf{x}_i(t) = \begin{bmatrix} \Delta f_i(t) \\ \Delta P_{tiei}(t) \\ \Delta P_{gi}(t) \\ \Delta x_{gi}(t) \\ \Delta x_{ghi}(t) \end{bmatrix}, \mathbf{d}_i(t) = \Delta P_{di}(t). \qquad (2)$$

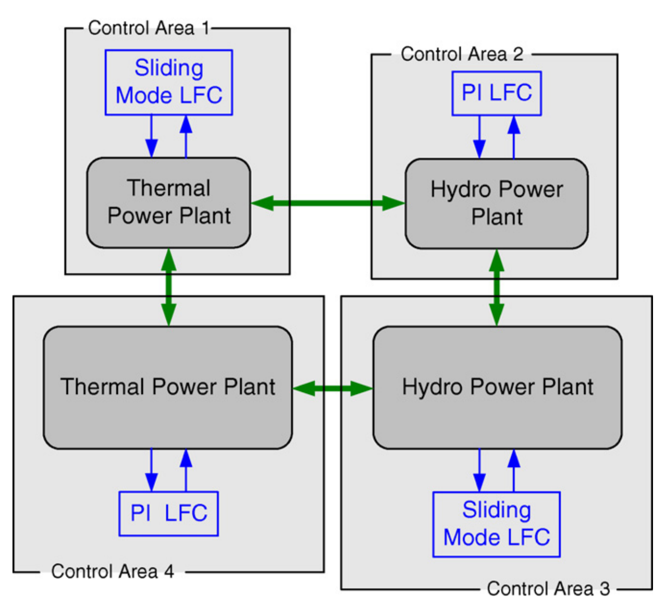

Fig. 1. Four interconnected control areas.