Variable Structure Load Frequency Control of Power System

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Abstract. Power-system load-frequency control by variable structure controller is proposed. To ease the design effort and improve the performance of the controller, second order variable structure control combine with integral sliding is developed. Overall system is asymptotically stable, for all admissible system parametric uncertainties, when all the local load frequency controllers are working together. Simulations confirm that the proposed second order variable structure control can rebalance power and resynchronize bus frequencies after a disturbance with significantly improved transient performance.

Keywords: Power system control · Power system dynamics · Load frequency control

1 Introduction

Generally, the load frequency control is accomplished by two different control actions of the primary speed control and supplementary speed control in an interconnected power system. The primary speed control performs the initial readjustment of the frequency. By its actions, the various generators in the control area track a load variation and share it in proportion to their capacities. The speed of the response is only limited by the natural time lags of the turbine, governor and the system itself. The supplementary speed control takes over the fine adjustment of the frequency by resetting the frequency error to zero through an integral action (the PI controller) [1].

Various types of load frequency control schemes have been developed recently [2–14]. A survey of different control schemes of load frequency control and strategies of automatic generation control (AGC) can be found in [2]. The authors of [3] proposed the two-degree-of-freedom internal model control design method for tuning PID load frequency controller. The study in [4] presented a PID optimised by the lozi map-based chaotic algorithm to solve the load-frequency control problem. Design and performance analysis of differential evolution algorithm based parallel 2- degree freedom of proportional-integral-derivative controller for load frequency control of interconnected power system is presented in [5]. By using a modified traditional frequency response

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mode, an intelligent solution for load-frequency control in a restructured power system is presented in [6]. Based on two-degree-of-freedom, internal model control scheme and modified internal model control filter design, the approach to load frequency control design for the power systems is proposed in [7]. In [8], cooperative control by using differential games is proposed for load frequency control of interconnected power systems. In [9], a load frequency control for multi-area power systems is developed based on the direct–indirect adaptive fuzzy control technique. The shortening of time periods in which each level of frequency regulation must finish could be also expected in the future.

Variable structure control is another method to solve load frequency control problem. Generally, variable structure control is a robust control technique that shows very good behavior in controlling systems with external disturbances and parameter variations [10]. Recently, the variable structure control frequency controller has been applied to solve the problems of power systems with uncertainties [10–14]. In [11], the variable structure load frequency controller was proposed for interconnected power systems. In [12], a robust sliding surface design method was proposed for load frequency control of interconnected power systems, which decreases the influence of unmatched uncertainties to system behavior. In [13], the discrete-time sliding mode controller for load-frequency control in control areas of a power system. Based on the decentralized variable structure control, a load frequency controller is designed for multi-area interconnected power systems [14]. However, the main obstacle to its implementation was chattering. Such chattering has many negative effects in practical applications since it may damage the control actuator and excite the undesirable unmodeled dynamics, which probably leads to unforeseen instability.

In this paper, a second order variable structure controller is proposed for load-frequency control of multi-area interconnected power systems. The stability of the multi-area interconnected power systems is guaranteed and the multi-area interconnected power systems is invariant on the sliding surface. In addition, the chattering in the control input is also reduced considerably. Simulation results show that the developed second order variable structure controller is able to achieve the load frequency control objectives in terms of zero steady-state frequency and tie-line deviations.

2 Two-Area LFC System

One typical multi-area interconnected power system [8] is used in this paper. Here, the disturbance/uncertainties are considered as $\Delta P_d(t)$, and the dynamic model can be obtained with the following state-space form

$$\dot{x}(t) = Ax(t) + Bu(t) + E\Delta P_d(t) \tag{1}$$

where $x(t) = \left[\Delta f_1 \ \Delta \mathrm{P}_{g1} \ \Delta X_{g1} \ \Delta f_2 \ \Delta \mathrm{P}_{g2} \ \Delta X_{g2} \ \Delta P_{tie} \ \Delta \mathrm{P}_{c1} \ \Delta P_{c2}\right]^T \in R^n$ is the state vector; $u(t) \in R^m$ is the input vector linked to the control-output signals of second order sliding mode control; $\Delta P_d(t) = [\Delta P_{d1}(t) \quad \Delta P_{d2}(t)]^T$ is the disturbance vector that reflects load variation, model/parameter uncertainties; the state matrix is

$$A = \begin{bmatrix} \frac{-1}{T_{p1}} & \frac{K_{p1}}{T_{p1}} & 0 & 0 & 0 & 0 & \frac{-K_{p1}}{T_{p1}} & 0 & 0 \\ 0 & \frac{-1}{T_{t1}} & \frac{1}{T_{t1}} & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{-1}{R_1 T_{g1}} & 0 & \frac{-1}{T_{g1}} & 0 & 0 & 0 & 0 & \frac{1}{T_{g1}} & 0 \\ 0 & 0 & 0 & \frac{-1}{T_{p2}} & \frac{K_{p2}}{T_{p2}} & 0 & \frac{K_{p2}}{T_{p2}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{-1}{T_{t2}} & \frac{1}{T_{t2}} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{-1}{R_2 T_{g2}} & 0 & \frac{-1}{T_{g2}} & 0 & 0 & \frac{1}{T_{g2}} \\ \mathrm{T}_{12} & 0 & 0 & -\mathrm{T}_{12} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}; \tag{2}$$

the input matrix is

$$B = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}^T; \tag{3}$$

and the disturbance matrix is

$$E = \begin{bmatrix} \frac{-K_{p1}}{T_{p1}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{-K_{p2}}{T_{p2}} & 0 & 0 & 0 & 0 & 0 \end{bmatrix}^T \tag{4}$$

with subscript i representing the i th control area, $\Delta f_i, \Delta \mathrm{P}_{gi}, \Delta X_{gi}, \Delta P_{tie}, \Delta \mathrm{P}_{ci}$ are the deviation of frequency, generator mechanical output, valve position, tie-line power, and requested generator output, respectively; T_{gi},T_{ti},K_{pi},T_{pi},T_{12} and r_i are the time constant of the governor, the time constant of the turbine, the electric system gain, the electric system time constant, the tie-line synchronizing coefficient, and the speed drop, respectively.

3 Variable Structure Load Frequency Control Design

Let us consider an integral sliding surface

$$\sigma(t) = B^+ x(t) - B^+ (A - BK) \int_0^t x(\tau) d\tau \tag{5}$$

where $B^+ = (B^T B)^{-1} B^T \in R^{m \times n}$ is the Moore–Penrose pseudoinverse of B. The design matrix $K \in R^{m \times n}$ is chosen satisfying the inequality condition

$$\mathrm{Re}[\lambda_{\max}(A - BK) < 0] \tag{6}$$

By taking the time derivative of $\sigma(t)$, we obtain

$$\dot{\sigma}(t) = B^{+}[Ax(t) + Bu(t) + E\Delta P_d(t)] - B^{+}(A - BK)x(t) \tag{7}$$

The second time derivative of $\sigma(t)$ can be expressed as

$$\ddot{\sigma}(t) = B^{+}\left[A\dot{x}(t) + B\dot{u}(t) + E\Delta\dot{P}_d(t)\right] - B^{+}(A - BK)\dot{x}(t) \tag{8}$$

Assumption 1. The above design procedure assumes that the load disturbance is continuous, bounded and its derivatives exist. The derivative of the load disturbance in system (1) is bounded and satisfies

$$\Delta\dot{P}_d(t) < \delta \tag{9}$$

where δ is known constant.

If it is possible to bring $\sigma(t)$ and $\dot{\sigma}(t)$ to zero in finite time by using a discontinuous control signal $\dot{u}(t)$, then the actual input to the system, $u(t)$, can be obtained by integrating the discontinuous signal and thus $u(t)$ becomes continuous. Hence the undesired high frequency oscillations in the control signal $u(t)$ present in the first order variable structure control are eliminated.

Let the sliding manifold be considered as

$$\theta(t) = \dot{\sigma}(t) + \varepsilon\sigma(t) \tag{10}$$

where $\varepsilon > 0$ is a positive constant.

Differentiating Eq. (10) and using Eq. (8), we have

$$\begin{aligned}\dot{\theta}(t) = B^{+}&\left[A\dot{x}(t) + B\dot{u}(t) + E\Delta\dot{P}_d(t)\right] \\ &-B^{+}(A - BK)\dot{x}(t) + \varepsilon\dot{\sigma}(t)\end{aligned} \tag{11}$$

Using Eq. (10) and Eq. (11), the control law is obtained as

$$\dot{u}(t) = -[B^{+}A\dot{x}(t) + \|B^{+}E\|\delta - B^{+}(A - BK)\dot{x}(t) + \varepsilon\dot{\sigma}(t)] + \beta sign(\theta(t)) \tag{12}$$

where $\beta > 0$ is a positive constant.

Theorem 1. Let us consider the system (1) with the double integral sliding surface given by (5). The trajectory of the closed loop system (1) can be driven onto the sliding manifold $\theta(t)$ in finite time by using the controller given by Eq. (12).

Proof. Choose a Lyapunov function candidate as

$$V(t) = \frac{1}{2}\theta^{T}(t)\theta(t) \tag{13}$$

By taking the time derivative of $V(t)$, we obtain

$$\dot{V}(t) = \theta^T(t)\dot{\theta}(t) \tag{14}$$

Substituting the Eq. (11) into Eq. (14), we have

$$\dot{V}(t) = \theta^T(t)\left\{B^+\left[A\dot{x}((t)) + B\dot{u}((t)) + E\Delta\dot{P}_d((t)\right] - B^+(A - BK)\dot{x}(t) + \varepsilon\dot{\sigma}(t)\right\} \tag{15}$$

Using the controller (12) and Eq. (15), we obtain

$$\dot{V}(t) \leq -\mu\|\theta(t)\| - \beta sign(\theta(t)) \tag{16}$$

From Eq. (16) and according to the Lyapunov stability theorem, the second order variable structure controller in (12) can stabilize system (1), and $\Delta f(t)$ arrives to zero along the designed sliding manifold $\theta(t)$.

4 Simulation Tests

In order to verify the proposed method for load frequency controller design, a typical two-area four-machine system [8] is selected as the test system. In the simulations, the step changes of the load demand occur in Areas 2 at $t = 0$ s, $\Delta P_{d2} = 0.01$ pu (Table 1).

Table 1. Parameters of two-area interconnected power system [8]

Area	T_{Pi}	K_{Pi}	T_{Ti}	T_{Gi}	R_i	K_{Ei}	K_{Bi}	K_{sij}
1	20	120	0.3	0.08	2.4	10	0.41	0.55
2	25	112.5	0.33	0.072	2.7	9	0.37	0.65

In this case, the responses of the generator frequencies and the tie-line power to the load demand changes are tested. The results are shown in Figs. 1 and 2 for frequencies, Fig. 3 for tie-line power, and Fig. 4 for control input. From the responses of the generator frequencies in Figs. 1 and 2, it is known that, with the help of the proposed second order variable structure controller, the frequencies of all generators return to the normal value in about 14 s after load disturbances happen. Figure 3 shows that the tie-line power is restored to its scheduled value as well. The settling time and transient deviations comparison between the proposed method and the method given in [8] indicate that the proposed method obtains a shorter settling time and smaller transient deviations than the given in [8] in terms of load disturbances.

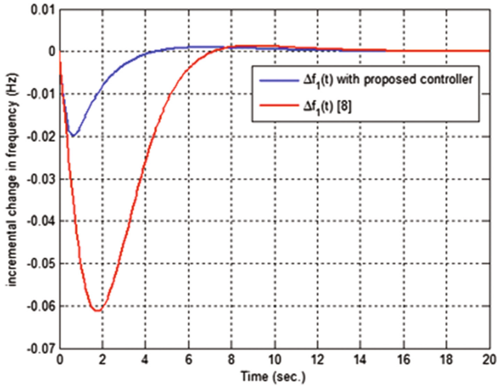

Fig. 1. Frequency deviation of control area 1

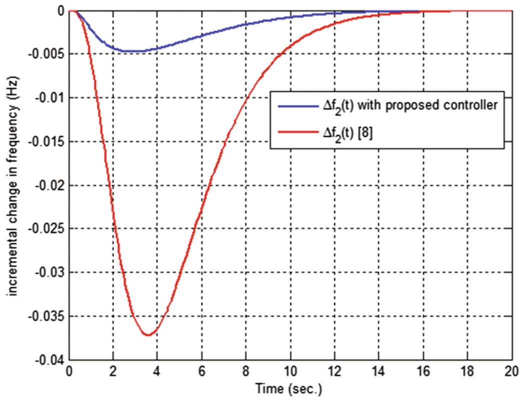

Fig. 2. Frequency deviation of control area 2

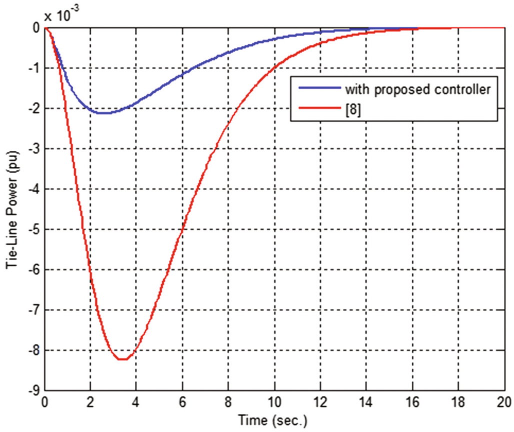

Fig. 3. Tie-line power

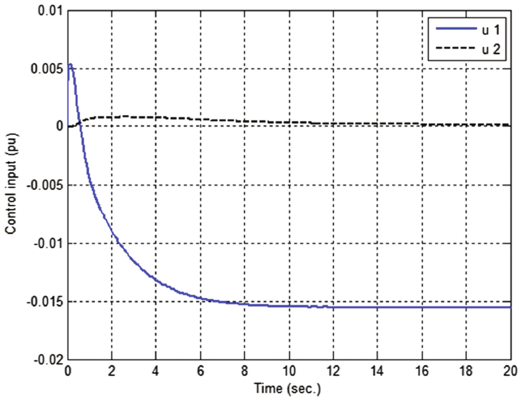

Fig. 4. Control input of two control areas

5 Conclusions

In this article, a new second order variable structure control approach is proposed to design the controllers to solve the problem of active power balance. The stability of the multi-area interconnected power systems is guaranteed and the chattering in the control input is also reduced considerably. The priority of the proposed approach is clarified by using different disturbances, indices and parameter variations. Simulation results demonstrate the effectiveness of the proposed second order variable structure controller, and robustness against parameter uncertainties. It also shows that the load frequency controller based on second order variable structure controller can provide better dynamic performance in comparing with the conventional controller.

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