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Power-Imbalance Allocation Control of Power Systems-Secondary Frequency Control ☆

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ABSTRACT

The traditional secondary frequency control of power systems restores nominal frequency by steering *Area Control Errors* (ACEs) to zero. Existing methods are a form of integral control with the characteristic that large control gain coefficients introduce an overshoot and small ones result in a slow convergence to a steady state. In order to deal with the large frequency deviation problem, which is the main concern of the power system integrated with a large number of renewable energy, a faster convergence is critical. In this paper, we propose a secondary frequency control method named *Power-Imbalance Allocation Control* (PIAC) to restore the nominal frequency with a minimized control cost, in which a coordinator estimates the power imbalance and dispatches the control inputs to the controllers after solving an economic power dispatch problem. The power imbalance estimation converges exponentially in PIAC, both overshoots and large frequency deviations are avoided. In addition, when PIAC is implemented in a multi-area controlled network, the controllers of an area are independent of the disturbance of the neighbor areas, which allows an asynchronous control in the multi-area network. A Lyapunov stability analysis shows that PIAC is locally asymptotically stable and simulation results illustrate that it effectively eliminates the drawback of the traditional integral control based methods.

1. Introduction

Rapid expansion of the contribution of distributed renewable energy sources has accelerated research efforts in controlling the power grid. In general, frequency control is implemented at three different levels distinguished from fast to slow timescales (Ilić & Zaborszky, 2000; Schavemaker & van der Sluis, 2008). In a short time scale, the power grid is stabilized by decentralized droop control, which is called *primary control*. While successfully balancing the power supply and demand, and synchronizing the power frequency, the primary control induces frequency deviations from the nominal frequency, e.g., 50 or 60 Hz. The *secondary frequency control* regulates the frequency back to its nominal frequency in a slower time scale than the primary control. On top of the primary and secondary control, the *tertiary control* is concerned with global economic power dispatch over the networks in a large time scale. Consequently it depends on the energy prices and markets.

The secondary frequency control is the focus of this paper. An interconnected electric power system can be described as a collection of subsystems, each of which is called a control area. The secondary control in a single area is regulated by *Automatic Generation Control* (AGC), which is driven by *Area Control Error* (ACE). The ACE of an area is calculated from the local frequency deviations within the area and power transfers between the area and its neighbor areas. The AGC controls the power injections to force the ACE to zero, thus restores the nominal frequency. Due to the availability of a communication network, other secondary frequency control approaches have recently been developed which minimize the control cost on-line (Dörfler, Simpson-Porco, & Bullo, 2016), e.g., the Distributed Average Integral Method (DAI) (Zhao, Mallada, & Dörfler, 2015), the Gather-and-Broadcast (GB) method (Dörfler & Grammatico, 2017), economic AGC (EAGC) method (Li, Zhao, & Chen, 2016), and distributed real time power optimal power control method (Liu, Qu, Xin, & Gan, 2017). These methods suffer from a common drawback, namely that they exhibit overshoot for large gain coefficients and slow convergence for small gain coefficients (Berger & Schweppe, 1989; Elgerd & Fosha, 1970; Ibraheem, Kumar, & Kothari, 2005). This is due to the fact that they rely on integral control which is well-known to give rise to the two phenomena mentioned above. Note that the slow convergence speed results in a large frequency deviation which is the main concern of power systems integrated with a large amount of renewable energy.

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The presence of fluctuations is expected to increase in the near future, due to weather dependent renewable energy, such as solar and wind energy. These renewable power sources often cause serious frequency fluctuations and deviation from the nominal frequency due to the uncertainty of the weather. This demonstrates the necessity of good secondary frequency control methods whose transient performance is enhanced with respect to the traditional methods. We have recently derived such a method called *Power Imbalance Allocation Method* (PIAC) in Xi, Dubbeldam, Lin, and van Schuppen (2017b), which can eliminate the drawback of the integral control based approach. This paper is the extended version of the conference paper (Xi et al., 2017b) with additional stability analysis and the extension of PIAC to multi-area control.

We consider power systems with lossless transmission lines, which comprise traditional synchronous machines, frequency dependent devices (e.g., power inverters of renewable energy or frequency dependent loads) and passive loads. We assume the system to be equipped with the primary controllers and propose the PIAC method in the framework of Proportional–Integral (PI) control, which first estimates the power imbalance of the system via the measured frequency deviations of the nodes of the synchronous machines and frequency dependent power sources, next dispatches the control inputs of the distributed controllers after solving the economic power dispatch problem. Since the estimated power imbalance converges exponentially at a rate that can be accelerated by increasing the control gain coefficient, the overshoot problem and the large frequency deviation problem are avoided. Hence the drawback of the traditional ACE method is eliminated. Furthermore, the control gain coefficient is independent of the parameters of the power system but only relies on the response time of the control devices. Consequently the transient performance is greatly enhanced by improving the performance of the control devices in PIAC. When implemented in a multi-area power network, PIAC makes the control actions of the areas independent, while the controllers of each area handle the power imbalance of the local area only.

The paper is organized as follows. We introduce the mathematical model of the power system in Section 2. We formulate the problem and discuss the existing approaches in Section 3, then propose the secondary frequency control approach, *Power-Imbalance Allocation Control* (PIAC), based on estimated power imbalance in Section 4 and analyze its the stability invoking the Lyapunov/LaSalle stability criterion in Section 5. Finally, we evaluate the performance of PIAC by simulations on the IEEE-39 New England test power system in Section 6. Section 7 concludes with remarks.

2. The model

A power system is described by a graph $G = (\mathcal{V}, \mathcal{E})$ with nodes $\mathcal{V}$ and edges $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$, where a node represents a bus and edge (i, j) represents the direct transmission line connection between nodes i and j. We consider a power system as a lossless electric network with constant voltage (e.g., transmission grids where the line resistances are neglected) and an adjacency matrix $(\hat{B}_{ij})$ where $\hat{B}_{ij}$ denotes the susceptance between node i and node j. The system consists of three types of nodes, synchronous machines, frequency dependent devices and passive loads, the sets of which are denoted by $\mathcal{V}_M$, $\mathcal{V}_F$ and $\mathcal{V}_P$ respectively. Thus $\mathcal{V} = \mathcal{V}_M \cup \mathcal{V}_P \cup \mathcal{V}_F$. The frequency dependent devices are for example frequency dependent loads, inverters of renewable energy, buses equipped with droop controllers. Denote the number of the nodes in $\mathcal{V}, \mathcal{V}_M, \mathcal{V}_F, \mathcal{V}_P$ by n, n_M, n_F, and n_P respectively, hence $n = n_M+n_F+n_P$. The model is described by the following *Differential Algebraic Equations* (DAEs), see e.g., Dörfler, and Grammatico (2017),

$$\dot{\theta}_i = \omega_i,\ i \in \mathcal{V}_M \cup \mathcal{V}_F, \tag{1a}$$

$$M_i\dot{\omega}_i + D_i\omega_i = P_i - \sum_{j\in\mathcal{V}} B_{ij}\sin(\theta_i - \theta_j) + u_i,\ i \in \mathcal{V}_M, \tag{1b}$$

$$D_i\omega_i = P_i - \sum_{j\in\mathcal{V}} B_{ij}\sin(\theta_i - \theta_j) + u_i,\ i \in \mathcal{V}_F, \tag{1c}$$

$$0 = P_i - \sum_{j\in\mathcal{V}} B_{ij}\sin(\theta_i - \theta_j),\ i \in \mathcal{V}_P, \tag{1d}$$

where θ_i is the phase angle at node i, ω_i is the frequency deviation from the nominal frequency, i.e., $\omega_i = \overline{\omega}_i - f^*$ where $\overline{\omega}_i$ is the frequency and $f^* = 50$ Hz or 60 Hz is the nominal frequency, $M_i > 0$ denotes the moment of inertia of a synchronous machine, $D_i > 0$ is the droop control coefficient, P_i is the power injection or demand, $B_{ij} = \hat{B}_{ij}V_iV_j$ is the effective susceptance of line (i, j), V_i is the voltage at node i, $u_i \in [\underline{u}_i, \overline{u}_i]$ is a secondary frequency control input. Note that u_i is a constrained input of the secondary frequency control, $\underline{u}_i$ and $\overline{u}_i$ are its lower and upper bounds, respectively. Furthermore, the set of nodes equipped with the secondary controllers is denoted by $\mathcal{V}_K \subseteq \mathcal{V}_M \cup \mathcal{V}_F$ and $u_i = 0$ for $i \notin \mathcal{V}_K$. Here, we have assumed that the nodes that participate in secondary control are equipped with primary controllers. Note that the loads can also be equipped with primary controllers (Zhao, Topcu, Li, & Low, 2014). The dynamics of the voltage and reactive power is not modeled, since they are irrelevant for control of the frequency. More details on decoupling the voltage and frequency control in the power system can be found in Kundur (1994), Simpson-Porco, Dörfler, and Bullo (2016), and Trip, Bürger, and De Persis (2016). The model with linearized sine functions in (1) is also widely studied to design primary and secondary frequency control laws, e.g., Andreasson, Dimarogonas, Sandberg, and Johansson (2014), Li et al. (2016) and Zhao, Mallada, Low, and Bialek (2016). For the validity of the linearized model with lossless network, we refer to Ilić and Zaborszky (2000), and Van Hertem (2006).

3. Secondary frequency control of power systems

3.1. Problem formulation

In practice, the frequency deviation should be in a prescribed range in order to avoid damage to the devices in the power system. We assume droop controllers to be installed at some nodes such that $\sum_{i\in\mathcal{V}_M\cup\mathcal{V}_F} D_i > 0$. When the power supply and demand are time-invariant, the frequencies of all the nodes in $\mathcal{V}_M \cup \mathcal{V}_F$ synchronize at a state, called *synchronous state* defined as follows,

$$\theta_i = \omega_{syn}t + \theta_i^*,\ i \in \mathcal{V}, \tag{2a}$$

$$\omega_i = \omega_{syn},\ i \in \mathcal{V}_M \cup \mathcal{V}_F, \tag{2b}$$

$$\dot{\theta}_i = \omega_{syn},\ i \in \mathcal{V}, \tag{2c}$$

$$\dot{\omega}_i = 0,\ i \in \mathcal{V}_M \cup \mathcal{V}_F, \tag{2d}$$

where ω_{syn} is the synchronized frequency deviation, and the phase angle differences at the steady state, $\{\theta_i^* - \theta_j^*,\ (i, j) \in \mathcal{E}\}$, determine the power flows in the transmission lines. The explicit synchronized frequency deviation ω_{syn} of the system is obtained by substituting (2) into (1) as

$$\omega_{syn} = \frac{\sum_{i\in\mathcal{V}} P_i + \sum_{i\in\mathcal{V}_K} u_i}{\sum_{i\in\mathcal{V}_M\cup\mathcal{V}_F} D_i}. \tag{3}$$

If and only if $\sum_{i\in\mathcal{V}}P_i + \sum_{i\in\mathcal{V}_K}u_i = 0$, the frequency deviation of the steady state is zero, i.e., $\omega_{syn} = 0$. This implies that a system with only droop control, i.e., $u_i = 0$, for $i \in \mathcal{V}_K$, can never converge to a steady state with $\omega_{syn} = 0$ if the power demand and supply are unbalanced such that $\sum_{i\in\mathcal{V}}P_i \neq 0$. This shows the need