Available online at www.sciencedirect.com

ScienceDirect

IFAC PapersOnLine 50-1 (2017) 4382–4387

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

Kaihua Xi, Johan L. A. Dubbeldam, Haixiang Lin,
Jan H. van Schuppen

Delft Institute of Applied Mathematics, Delft University of Technology,
Mekelweg 4, 2628CD, Delft, The Netherlands. (e-mail: K.Xi@tudelft.nl,
j.l.a.dubbeldam@tudelft.nl, H.X.Lin@tudelft.nl,
J.H.vanSchuppen@tudelft.nl)

Abstract: To balance the power supply and demand with optimized control cost and nominal synchronized frequency, we propose a secondary frequency control approach, named *Power-Imbalance Allocation Control* (PIAC), for power systems with lossless networks, consisting of synchronous machines, frequency dependent power sources and passive loads. With Proportional-Integral control, the power imbalance is estimated by a coordinator with aggregated frequency deviations and the control inputs are optimally allocated to the controllers after solving an economic power dispatch problem on-line. The advantage of the approach is that the estimated power imbalance converges to the actual power imbalance exponentially with neither overshoot of control inputs nor unnecessary oscillations of the frequency. In addition, the convergence speed only depends on a control coefficient which is independent of any other parameters of the power systems and of the economic power dispatch problem.

Keywords: Power systems, Secondary frequency control, Coordination control, Economic power dispatch, Power imbalance.

1. INTRODUCTION

In daily operation of power systems, the power supply and demand have to be balanced to keep the frequency deviation in a small range to avoid damages to electrical facilities. However, the power demand varies continuously, it depends on many factors such as the weather, working hours or holidays etc. Hence the power demands can neither be modeled accurately nor be predicted precisely. Furthermore, the current transition to a more distributed generation of energy by renewable sources, which are inherently more prone to fluctuations, poses even greater challenges to the functioning of the power grids. As the contribution of renewable energy to the total power being generated is surging, it becomes more challenging to keep the network stable against larger and faster fluctuations. In particular, it is essential to regulate the frequency of power systems to keep the nominal synchronized frequency within the prescribed bounds.

In practice, the frequency control is accomplished by changing the active power injection of generators. Three forms of control can be distinguished from fast to slow timescales, i.e., primary control, secondary control, and tertiary control, see Schavemaker and van der Sluis (2008) and Ilić and Zaborszky (2000).

Primary frequency control balances the power supply and demand rapidly, and synchronizes the system frequency. It is accomplished by droop controllers which are decentralized proportional controllers where the power compensation are proportional to the local frequency deviations. No communication between the controllers is required in the primary frequency control. Even though the power is balanced, the synchronized frequency may deviate from its nominal value.

Secondary frequency control restores the system frequency to its nominal value. Traditionally, the secondary control uses a central controller based on integral control which is operated on a slower time scale than primary control.

Tertiary control determines the economic power dispatch offline without considering the dynamic of power systems. It calculates the operating point stabilized by primary and secondary control from an economic point of view using precise load forecasts. Tertiary control is a kind of centralized control and a communication network is required. Typically, the time scale is much larger than that of secondary frequency control.

In this paper, we focus on secondary control. To decrease the control burden of the central controller, decentralized control becomes a choice to restore the nominal frequency, e.g., Zhao et al. (2015). However, some undesired power injection profiles might happen which violate load sharing and economic power dispatch objectives if there is no coordination between the controllers. Distributed Averaging Integral (DAI), e.g., Dörfler et al. (2016) and Zhao et al. (2015), and Gather-broadcast control, see Dörfler and Grammatico (2017), for secondary frequency control of power system have been proposed, both of which prescribe a form of regulation which involves solving an economic power dispatch problem. However, they actually are based on an integral control method in which the integral gain coefficients must be tuned by considering the parameters of the economic power dispatch problem and of the power system. The drawback of this method is that large integral gain coefficients may result in extra oscillations of the system because of the overshoot problem while small gain results in slow convergence speed to a steady state.

Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2017.08.883

We consider power systems with lossless transmission lines, which comprise traditional synchronous machines, frequency dependent power sources and passive loads. Moreover, assuming that primary controllers are installed in the systems, we propose a secondary control method based on the estimated power imbalance. With the estimated power imbalance, the control inputs of the controllers are determined by solving the economic power dispatch problem. Since the estimated power imbalance converges to the actual power imbalance exponentially, there is no overshoot of control inputs which leads to small frequency deviations and optimal control cost during the transient phase. Furthermore, the economic power dispatch is solved on-line and the marginal costs of all the controllers are always identical during the transient phase.

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

2. THE MODEL

We consider a power system modeled as a graph $G = (\mathcal{V}, \mathcal{E})$ with nodes $\mathcal{V} \in Z^+$ and edges $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$, in which the voltages of buses are constants and the transmission lines are lossless with an adjacency matrix $(\hat{B}_{ij})$. We partition the nodes as $\mathcal{V} = \mathcal{V}_M \cup \mathcal{V}_P \cup \mathcal{V}_F$ corresponding to synchronous machines $\mathcal{V}_M$, passive buses $\mathcal{V}_P$ and frequency dependent devices $\mathcal{V}_F$, e.g., renewable power inverters. Without considering the dynamics of voltage, the associate differential-algebraic models reads as, e.g., Dörfler and Grammatico (2017),

$$
\begin{aligned}
M_i\ddot{\theta}_i + D_i\dot{\theta}_i &= P_i - \sum_{j\in\mathcal{V}} B_{ij}\sin(\theta_i - \theta_j) + u_i,\ i \in \mathcal{V}_M, && (1)\\
D_i\dot{\theta}_i &= P_i - \sum_{j\in\mathcal{V}} B_{ij}\sin(\theta_i - \theta_j) + u_i,\ i \in \mathcal{V}_F, && (2)\\
0 &= P_i - \sum_{j\in\mathcal{V}} B_{ij}\sin(\theta_i - \theta_j),\ i \in \mathcal{V}_P, && (3)
\end{aligned}
$$

where $M_i > 0$ is the moment of inertia of the synchronous machines at node i, θ_i is the phase angle, P_i is the power injection or demand which can be constant or time-varying, and $B_{ij} = \hat{B}_{ij}V_iV_j$ denotes the effective susceptance matrix. Here, $\hat{B}_{ij}$ and V_i denote the susceptance between node i and j and the voltage at node i respectively, $u_i \in [\underline{u}_i, \overline{u}_i]$ and $D_i > 0$ denote the control input and the droop control coefficient at node i, respectively. Note that u_i is the constraint control input of the secondary control of the power system and some of them can be zero, $\underline{u}_i$ and $\overline{u}_i$ are its lower bound and upper bound, 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. The frequency deviation from the nominal frequency, i.e., 50 Hz or 60 Hz, is defined as

$$\omega_i = \dot{\theta}_i,\ i \in \mathcal{V}_M \cup \mathcal{V}_F. \tag{4}$$

We do not model the reactive power and voltage dynamics since they are irrelevant for the control of frequency. More details on decoupling the voltage and frequency control can be found in Kundur (1994),Simpson-Porco et al. (2016) and Trip et al. (2016). For more details of voltage and frequency control for power systems, see Van Cutsem and Vournas (1998) and for Micro-Grids, see, e.g., Guerrero et al. (2011).

3. SECONDARY FREQUENCY CONTROL OF POWER SYSTEMS

3.1 *Problem formulation*

In practice, the frequency deviation should not be too large in order to avoid damages to the synchronous machines. If we assume droop controllers to be installed at some nodes such that $\sum_{i\in\mathcal{V}_M\cup\mathcal{V}_F} D_i > 0$, the explicit synchronized frequency deviation from the nominal frequency with droop control and secondary control is obtained as

$$\omega_{syn} = \frac{\sum_{i\in\mathcal{V}} P_i + \sum_{i\in\mathcal{V}} u_i}{\sum_{i\in\mathcal{V}_M\cup\mathcal{V}_F} D_i}, \tag{5}$$

The necessary and sufficient condition for the existence of the steady state with $\omega_{syn} = 0$ is $\sum_{i\in\mathcal{V}} P_i + \sum_{i\in\mathcal{V}} u_i = 0$. This implies that a system with only droop control, i.e $u_i = 0, i \in \mathcal{V}$, can never converge to a steady state with $\omega_{syn} = 0$ if the power demand and supply is unbalanced such that $\sum_{i\in\mathcal{V}} P_i \neq 0$, This shows the need for secondary control. We want to balance power supply and demand, e.g., Dörfler et al. (2016) and Dörfler and Grammatico (2017).

Problem 1. Compute the inputs $\{u_i, i \in \mathcal{V}\}$ of the power system so as to achieve the *control objective of a balance of power supply and demand* in terms of $\omega_{syn} = 0$ or, equivalently, $\sum_{i\in\mathcal{V}} P_i + \sum_{i\in\mathcal{V}} u_i = 0$.

We use an assumption for a basic feasibility condition to solve Problem 1.

Assumption 1. The total amount of power imbalance can be compensated by the control inputs $\{u_i, i \in \mathcal{V}_K\}$, i.e.

$$-\sum_{i\in\mathcal{V}} P_i \in [\sum_{i\in\mathcal{V}_K} \underline{u}_i, \sum_{i\in\mathcal{V}_K} \overline{u}_i]. \tag{6}$$

Furthermore, to guarantee the existence of a steady state of the power systems, we make a second assumption.

Assumption 2. During a small time interval the value of power supply and demand are constant. In addition, for these values there exist control inputs $\{u_i \in [\underline{u}_i, \overline{u}_i], i \in \mathcal{V}_K\}$, such that $\sum_{i\in\mathcal{V}} P_i + \sum_{i\in\mathcal{V}_K} u_i = 0$.

Assumptions 1 and 2 are realistic since the operating point stabilized by the secondary controls is calculated by tertiary control which guarantees the existence of a steady state and its local stability, see Ilić and Zaborszky (2000), and Wood and Wollenberg (1996).

From the global perspective of the entire network, some objectives might be preferable in the power resource allocation, such as economic power dispatch and stability enhancement. Here we focus on the economic power dispatch problem. For different controllers, the control cost might be different for various reasons such as different device maintenance price. The economic power dispatch is preferable which leads to the following problem.