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Switched distributed load-side frequency control of power systems

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ABSTRACT

This paper presents a frequency control scheme for transmission networks with multiple control areas using load-side controllers in cooperation with automatic generation control (AGC) to regulate the system frequency and the tie-line powers between control areas. In transmission networks, a switched consensus-based distributed controller is proposed for each load bus. Once the frequency violates a pre-defined threshold, load-side controllers will start to work in a frequency regulation mode (FRM) in which each controller communicates with neighboring controllers to discover the power imbalance of the corresponding control area. The control centre in each control area will send the tie-line power information to all the buses in the area, which together with the power imbalance of the area determines the control output of each load-side controller. After the frequency goes back to a satisfactory range, load-side controllers will switch to a load recovery mode (LRM) and shift their duties to the generators. Case studies involving a contingency of load increase and wind farm power fluctuation in the IEEE 118-bus multi-area system show that the performance of frequency and tie-line power regulation is improved significantly by the proposed control scheme compared with AGC and with minimized impacts on end-users.

1. Introduction

Frequency control is traditionally carried out on the generation side by making generation follow demand, and is composed of three levels operating at different timescales [1]. Primary frequency control, also called droop control, operates on a timescale up to tens of seconds to rebalance the supply with demand after disturbances and stabilizes the system to a new equilibrium point in a decentralized way. However, it will result in a steady-state frequency deviation. Secondary frequency control, also known as AGC, is accomplished by adjusting load reference setpoints of selected generators on a timescale of 10 min in a centralized way [1]. Consequently, the frequency can be restored to the nominal value (50 or 60 Hz) and the tie-line powers between control areas can be maintained at the scheduled values. Tertiary frequency control, or economic dispatch, aims to minimize operating costs by scheduling outputs of generators and tie-line power between control areas on a timescale of 15 min or more.

However, traditional generation-side frequency control alone may not be able to maintain the system frequency at its nominal value due to the uncertainty and intermittency of renewable power [2]. The situation becomes even worse as penetration of renewable power increases to higher levels. Further, extra spinning reserves will be required [3], which will produce increased operation costs and higher emissions.

To solve these issues, efforts have been made from two different aspects. On one hand, various control methods such as distributed model-based control [4], fuzzy logic control [5] and decentralized model predictive control [6] have been proposed to enhance traditional generation-side frequency control. Also, the stability of the AGC over cognitive radio networks has been investigated in [7]. On the other hand, the adoption of controllable loads on frequency control has been proposed due to its advantages such as fast response, low emission and highly distributed availability throughout the power grid [3,8]. It has been shown in experimental [9] and simulation results (e.g., [10,11,3,12–20]) that load-side frequency control is able to regulate the system frequency effectively. Since there may be large numbers of loads dispersed in the grid, it is infeasible to use centralized control for demand-side control. In contrast, distributed control [21,10–13,22,23] and decentralized control [17,18] can deal with this issue effectively. In [17], a decentralized control method is proposed for controllable loads which can stabilize the frequency, however, it cannot regulate the frequency to the nominal value. An improved decentralized control scheme is proposed [18] based on the DC power flow model, which may not be feasible when it is adopted to the AC power flow model. Therefore, in this paper distributed control is adopted in which communication only exists between neighbors.

As pointed out in [8], two goals have to be achieved by load-side

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controllers when taking part in frequency control schemes, i.e., be fully responsive and non-disruptive. However, most of the prior works emphasize the first goal and do not directly take the second goal into precise account. Recently in [10], some theoretical analysis was given for a scheme which achieves both goals. Designs for a switched consensus-based distributed controller for each load bus to achieve the dual goals are presented and tested on the IEEE 118-bus system in this paper.

The proposed load-side controllers help AGC restore the frequency after disturbances, and recover controllable loads to their nominal values (i.e., original values before disturbances take place) after the frequency goes back to a satisfactory region. The consensus mechanism [24] is adopted for each load-side controller to acquire the average power imbalance of the area by communicating with neighbors. Then, this active power mismatch is compensated by controllable loads and generators so the frequency can be restored back to the satisfactory region. After this, controllable loads recover to their nominal values and let the generators take over reduction of the power mismatch. Therefore, the controllable loads have two operation modes, i.e., the frequency regulation mode (FRM) and load recovery mode (LRM) [10], which can be achieved by using switching control [25]. Different from the idea in [10] where only load buses are involved in the consensus mechanism, and an auxiliary variable is adopted and shared with neighbors by each load-side controller, in this paper, all buses are involved in the average power imbalance discovery (APoID) process and the power imbalance at each bus is used as local information to communicate with neighbors. Further, the dwell-time method introduced in the switched system theory [25] is used to enhance the stability of the system with the designed load-side controllers. Moreover, a new controllable load recovery strategy is designed for proposed load-side controllers in the multi-area system.

To maintain the tie-line power between control areas at scheduled values is one of the objectives of frequency control in the multi-area system, and hence load-side control should also take it into account when participating in frequency control. In this paper, based on the distributed load-side control method mentioned above, an improved control strategy is proposed for a multi-area system. In the multi-area system we assume that communication between neighbors only exists in the same control area such that controllable loads will be responsible for the power imbalance in their own control area. When detecting the frequency exceeding the pre-defined range, the control centre in each control area computes the tie-line power changes between its own area and other adjacent areas, and then sends to all the buses in its area, according to which the control output of each load-side controller will be adjusted.

The main contributions of this paper are threefold. First, switching control is adopted for the proposed load-side controllers which consequently have two work modes. These load-side controllers cooperatively provide a system-level power support in the FRM when disturbances occur, which reduces the burden of generators (i.e., traditional load frequency control (LFC)) significantly. Further, each controllable load will share the total power imbalance in proportion to its capacity in the FRM such that any single controllable load will not be influenced severely. Moreover, load-side controllers will restore controllable loads to their nominal values in the LRM to minimize the disruption on end-users when the frequency recovers. Second, a new controllable load recovery strategy is proposed which together with the adopted dwell-time method ensures that the proposed load-side controllers can switch to the LRM smoothly without causing new disturbances when the frequency is restored. Third, both the system frequency and tie-line power between control areas are considered in the proposed control scheme. Consequently, it can restore the frequency to the nominal value and tie-line power to the scheduled value much faster than adopting traditional LFC.

In the following, Section 2 introduces the structure-preserving model with controllable loads and the traditional frequency control method. Section 3 gives the designed load-side control method for the multi-area system. The topology of the communication network and strategy to deal with communication failures are given in Section 4. Case studies are given and analyzed in Section 5. The conclusion of this paper is made in Section 6.

2. System model and traditional frequency control review

2.1. System model

In this paper, the following assumptions are made [1]:

(1) The transmission network is connected in which transmission lines are lossless and characterized by reactances $x_{ij} = x_{ji}$.
(2) In the transmission network, the magnitude of each bus voltage $|V_i|$ is fixed such that the voltage will not affect active power flows between buses.

These assumptions allow the structure-preserving model for power systems [26] interpreted with controllable loads to be adopted

$$\dot{\delta}_i = \omega_i, \quad i \in \mathcal{G} \tag{1a}$$

$$M_i\dot{\omega}_i = -D_i\omega_i + P_{m_i} - \sum_{j=1}^{N} b_{ij}\sin(\delta_i-\delta_j), \quad i \in \mathcal{G} \tag{1b}$$

$$D_i\dot{\delta}_i = u_i - \sum_{j=1}^{N} b_{ij}\sin(\delta_i-\delta_j) - P_{D_i}, \quad i \in \mathcal{L} \tag{1c}$$

where the index set of all the buses is denoted by $\mathcal{N} = \{1, 2, ..., N\} = \mathcal{G}\bigcup\mathcal{L}$. The index sets of generator buses and load buses are denoted by $\mathcal{G} = \{1, 2, ..., N_G\}$ and $\mathcal{L} = \{1, 2, ..., N_L\}$, respectively.

For each generator $i \in \mathcal{G}$, variables and parameters δ_i, ω_i, M_i, D_i and P_{m_i} are the phase angle, angular velocity, inertia constant, damping coefficient and mechanical power input, respectively. For each load $i \in \mathcal{L}$, parameters and variables D_i, P_{D_i} and u_i are the frequency-dependent coefficient, uncontrollable constant load and controllable load with capacity limits $\underline{u}_i \leqslant u_i \leqslant \overline{u}_i$, respectively. For all $i \in \mathcal{N}$, the coefficient $b_{ij} = \frac{|V_i||V_j|}{x_{ij}}$ is calculated based on assumptions (1) and (2).

It should be noted that inverter-based generators such as a wind farm or PV can also be described by Eq. (1c) [27]. Differently to the load bus, the parameter D_i represents the frequency-dependent coefficient introduced by droop control for inverter-based generators, and the time-varying power output of the inverter-based generator can be modeled as a negative load by replacing P_{D_i} with $P_{w_i}(t)$. The controllable load u_i can be zero or not which depends on if any local load is connected to the corresponding bus. For the case studies, only wind farms are considered in this paper, and more intermittent sources such as PV will be considered in the future work.

Remark 2.1. In this paper we focus on frequency control issues for transmission networks in which it is common to neglect line losses as reactances of lines are much greater than resistances [1]. For simplicity, we assume active power flows mainly affect power angles and the frequency, and bus voltages are mostly impacted by reactive powers which can be regulated by some fast voltage control. However, line losses cannot be ignored in lower voltage systems such as subtransmission networks and distribution networks due to the higher R/X ratio, and consequently both the frequency and bus voltage will be affected by active power mismatches. In this situation, a control scheme has been proposed [28] for subtransmission networks which implements both frequency and voltage control and also takes line losses into account.