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Distributed plug-and-play optimal generator and load control for power system frequency regulation

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ABSTRACT

A distributed control scheme, which can be implemented on generators and controllable loads in a plug-and-play manner, is proposed for power system frequency regulation. The proposed scheme is based on local measurements, local computation, and neighborhood information exchanges over a communication network with an arbitrary (but connected) topology. In the event of a sudden change in generation or load, the proposed scheme can restore the nominal frequency and the reference inter-area power flows, while minimizing the total cost of control for participating generators and loads. Power network stability under the proposed control is proved with a relatively realistic model which includes nonlinear power flow and a generic (potentially nonlinear or high-order) turbine-governor model, and further with first- and second-order turbine-governor models as special cases. In simulations, the proposed control scheme shows a comparable performance to the existing automatic generation control (AGC) when implemented only on the generator side, and demonstrates better dynamic characteristics than AGC when each scheme is implemented on both generators and controllable loads. Simulation results also show robustness of the proposed scheme to communication link failure.

1. Introduction

Maintaining power system frequency tightly around its nominal value, e.g., 60 Hz in US, is critical for satisfactory performance of electrical loads, safety of generating equipment, and reliable power delivery [1]. Off-nominal frequency caused by imbalance between power supply and demand is traditionally corrected through primary and secondary frequency control of generators. Primary frequency control stabilizes frequency to a point that may still be off-nominal via decentralized droop response of speed governors [2]. Secondary frequency control, traditionally known as automatic generation control (AGC) [2,3], adjusts generator setpoints in each control area via centralized integral or proportional-integral control, to restore the nominal frequency and the reference inter-area power flows. This work focuses on secondary frequency control and refers to it as frequency regulation [4].[1]

As larger variations in power imbalance arise from the deepening penetration of intermittent renewable generation, AGC may not be adequate to meet the required frequency standards [1,5]. Tackling this challenge requires either increased fast-acting spinning reserves, which incur high operating cost and emissions [5,6], or alternative resources for frequency regulation, such as controllable loads [6–8]. To exploit the full potential of load control, a set of important issues need to be addressed, including: (i) scalability and flexibility of the control system to support autonomous and plug-and-play operations of controllable loads [9]; (ii) coordination between controllable loads, as well as coordination between loads and generators, to ensure a predictable and stable system behavior [7]; (iii) comfort of controllable load users [6,7] optimized jointly with economic efficiency of generators [1]. Addressing these issues calls for the transformation of power systems from a centralized, hierarchical control architecture, which typically features a timescale separation between economic dispatch and AGC, to a distributed, open-access architecture that integrates optimality and stability objectives [9,10]. Towards this transformation, recent endeavors [9,11–24] are dedicated to developing distributed control algorithms, which can stabilize a power network at an equilibrium that solves an appropriate optimization problem and meets the frequency regulation requirements.

It is common for these studies to use simplified power network models to facilitate controller design and stability analysis. For

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[1] In some other literature, frequency regulation includes both primary and secondary frequency control.

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example, [11–18] consider linearized power flow; [21] assumes the power network has a tree topology; [9,11–13,18–20] ignore the generator turbine-governor dynamics, and [14–17,21] use a simplified first-order turbine-governor model. Compared to [9,11,13–21], a more realistic power network model, which includes a nonlinear power flow model and a second-order turbine-governor model, is used in [22–24]. Moreover, stability conditions for a generic (potentially higher-order or nonlinear) turbine-governor model are obtained in [22] with a passivity-based method.

This paper proposes a distributed optimal generator and load control scheme for frequency regulation. In case of imbalance between power supply and demand, the proposed scheme can restore the nominal frequency and the reference inter-area power flows, while minimizing the total cost of control for participating generators and loads. In the proposed scheme, every control agent for a generator or controllable load measures its local frequency and power flows, performs moderate computations, and communicates with its neighboring agents in a communication network with an arbitrary topology (as long as it connects all the agents). Such a distributed scheme is suitable for autonomous and plug-and-play operations. For example, an agent can plug-in and participate in frequency regulation after updating its information with its neighboring agents. This significantly reduces the system operator's burden of interacting with a large number of agents: maintaining their information, communicating with them, and performing centralized computations for all of them. Such a distributed and plug-and-play scheme can also improve robustness of the system against a single-point failure of the communication or computation functions.

This work complements the literature in the following aspects:

(i) Stability is established for a nonlinear power flow model and a generic (potentially nonlinear or high-order) turbine-governor model, and further for first- and second-order turbine-governor models as special cases. This extends all the studies above except [22]. Compared to [22], the stability condition in this paper for the generic turbine-governor model features a simpler supply rate function. Moreover, the proposed control fulfills the inter-area flow requirement, which was ignored in [22].
(ii) By utilizing and extending the concept of virtual flow in [13], we develop a controller with simpler and more flexible communication than [13,24] and a less restrictive stability condition than [24]; see the discussion in Section 4.
(iii) Simulation results on Power System Toolbox [25] show that the proposed control achieves a comparable performance to AGC when implemented purely on the generator side. Moreover, the proposed control demonstrates better dynamic characteristics than AGC when each scheme is implemented on both generators and controllable loads. Robustness of the proposed control to communication link failure is also observed in simulations.

The rest of this paper is organized as follows. Section 2 introduces the power network model. Section 3 formulates an optimization problem which encapsulates the goals of frequency regulation. Section 4 proposes a distributed frequency regulation scheme. Section 5 proves that the proposed scheme can stabilize the power network at an equilibrium that solves the formulated optimization, and thus restores the nominal frequency and the reference inter-area flows while minimizing the total cost of control. Section 6 shows the simulation results. Finally, Section 7 concludes the paper.

2. System setup

2.1. Notation

Number, vector, and matrix: Let $\mathbb{R}$ denote the set of real numbers and $\mathbb{N}$ the set of natural numbers. For a finite set $S \subset \mathbb{N}$, let $|S|$ denote its cardinality. For a set of scalar numbers $\{a_i \mid i \in S\}$, let a_S denote the column vector of the a_i's; the subscript S is dropped when it is clear from the context. The stacked column vector of two vectors $a \in \mathbb{R}^{|S|}$ and $a' \in \mathbb{R}^{|S'|}$ is denoted by (a,a'). Given any matrix A, denote its transpose by A^T, and its i-th row by A_i. Let A_S denote the submatrix of A composed only of the rows A_i for $i \in S$. The diagonal matrix with diagonal entries $\{a_i \mid i \in S\}$ is denoted interchangeably by $\mathrm{diag}(a_i, i \in S)$, $\mathrm{diag}(a_S)$, and a_S (when it can be distinguished from the vector a_S by the context). Let $\mathbf{1}_S$ ($\mathbf{0}_S$) denote the $|S|$-dimensional column vector of all ones (zeros), which is often simplified as 1 (0) when its dimension is obvious from the context.

Power network: Consider a power transmission network represented by a *directed*, connected graph $(\mathscr{N},\mathscr{E})$, where $\mathscr{N}$ is the set of buses, and $\mathscr{E}$ is the set of transmission lines. A transmission line indexed the e-th in $\mathscr{E}$ and directed from buses i to j is denoted interchangeably by $e \in \mathscr{E}$ and $ij \in \mathscr{E}$. The symbol $i \sim j$ means either $ij \in \mathscr{E}$ or $ji \in \mathscr{E}$ without distinguishing the direction of the link. The set $\mathscr{N}$ of buses is partitioned as $\mathscr{N} = \mathscr{G} \cup \mathscr{L}$ where $\mathscr{G}$ and $\mathscr{L}$ are the sets of generator and load buses, respectively. A generator bus connects to a generator with large inertia. A load bus represents the aggregate of a substation and the distributed energy resources and loads connected to it. The power network $(\mathscr{N},\mathscr{E})$ is divided into a set $\mathscr{K}$ of subgraphs, called control areas.

Communication network: Each bus $i \in \mathscr{N}$ has an agent which decides its local control actions by measuring local frequency and power flows, performing moderate computations, and communicating with its neighboring agents in an *undirected* (two-way), connected graph $(\mathscr{N},\mathscr{E}')$. The topology of the communication network $(\mathscr{N},\mathscr{E}')$ can be arbitrary, and in particular can be different from the power network $(\mathscr{N},\mathscr{E})$, as long as it connects all the buses in $\mathscr{N}$. Notations $ij \in \mathscr{E}'$ and $i \leftrightarrow j$ are used interchangeably to indicate that the agents at buses i and j communicate with each other. A positive constant weight $B'_{ij} = B'_{ji}$ is assigned to every communication link $ij \in \mathscr{E}'$. The choice of B'_{ij} is also arbitrary; see a further comment in Section 4. Although the proposed controller in Section 4 and its optimality and stability analysis in Section 5 assume that every bus has a control agent that can compute and communicate, in the simulations in Section 6 the control agents are only installed at a subset of buses which have controllable generators and loads.

Other frequently used notations are listed below:

	Variables
θ_i, $i \in \mathscr{N}$	bus voltage phase angles
ω_i, $i \in \mathscr{N}$	*deviations* of bus frequencies from the nominal value
r_i, $i \in \mathscr{N}$	frequency-insensitive uncontrollable power injections
p_i^{m}, $i \in \mathscr{G}$	mechanical power outputs of generators
p_i, $i \in \mathscr{G}$	generation control commands
d_i, $i \in \mathscr{N}$	real power consumption of controllable loads
P_{ij}, $ij \in \mathscr{E}$	transmission line power flows. Define $P_{ji} := -P_{ij}$
	Constants
M_i, $i \in \mathscr{G}$	positive generator inertia constants
D_i, $i \in \mathscr{N}$	positive load-damping constants
B_{ij}, $ij \in \mathscr{E}$	positive constant line parameters. Define $B_{ji} := B_{ij}$
C_{ie}, $i \in \mathscr{N}$, $e \in \mathscr{E}$	$C_{ie} = 1$ if $e = ij$ for some bus j, $C_{ie} = -1$ if $e = \ell i$ for some bus ℓ, and $C_{ie} = 0$ otherwise. $C \in \mathbb{R}^{|\mathscr{N}| \times |\mathscr{E}|}$ is the incidence matrix of $(\mathscr{N},\mathscr{E})$
E_{ki}, $k \in \mathscr{K}$, $i \in \mathscr{N}$	$E_{ki} = 1$ if bus i is in control area k, and $E_{ki} = 0$ otherwise

2.2. Power network model

Consider the standard power network model [2,3]: