Design and Stability of Load-Side Primary Frequency Control in Power Systems

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***Abstract*—We present a systematic method to design ubiquitous continuous fast-acting distributed load control for primary frequency regulation in power networks, by formulating an optimal load control (OLC) problem where the objective is to minimize the aggregate cost of tracking an operating point subject to power balance over the network. We prove that the swing dynamics and the branch power flows, coupled with frequency-based load control, serve as a distributed primal-dual algorithm to solve OLC. We establish the global asymptotic stability of a multimachine network under such type of load-side primary frequency control. These results imply that the local frequency deviations on each bus convey exactly the right information about the global power imbalance for the loads to make individual decisions that turn out to be globally optimal. Simulations confirm that the proposed algorithm can rebalance power and resynchronize bus frequencies after a disturbance with significantly improved transient performance.**

***Index Terms*—Decentralized control, optimization, power system control, power system dynamics.**

I. Introduction

A. Motivation

FREQUENCY control maintains the frequency of a power system tightly around its nominal value when demand or supply fluctuates. It is traditionally implemented on the generation side and consists of three mechanisms that work at different timescales in concert [1]–[4]. The primary frequency control operates at a timescale up to low tens of seconds and uses a governor to adjust, around a setpoint, the mechanical power input to a generator based on the local frequency deviation. It is called the droop control and is completely decentralized. The primary control can rebalance power and stabilize the frequency but does not in itself restore the nominal frequency. The secondary frequency control (called automatic generation control) operates at a timescale up to a minute or so and adjusts the setpoints of governors in a control area in a centralized fashion to drive the frequency back to its nominal value and the inter-area power flows to their scheduled values. Economic dispatch operates at a timescale of several minutes or up and schedules the output levels of generators that are online and the inter-area power flows. See [5] for a recent hierarchical model of these three mechanisms and its stability analysis. This paper focuses on load participation in the primary frequency control.

The needs and technologies for ubiquitous continuous fast-acting distributed load participation in frequency control at different timescales have started to mature in the last decade or so. The idea however dates back to the late 1970s. Schweppe *et al.* advocated in a 1980 paper [6] its deployment to "assist or even replace turbine-governed systems and spinning reserve". They also proposed to use spot prices to incentivize the users to adapt their consumption to the true cost of generation at the time of consumption. Remarkably it was emphasized back then that such frequency adaptive loads would "allow the system to accept more readily a stochastically fluctuating energy source, such as wind or solar generation" [6]. This point is echoed recently in, e.g., [7]–[13], that argue for "grid-friendly" appliances, such as refrigerators, water or space heaters, ventilation systems, and air conditioners, as well as plug-in electric vehicles to help manage energy imbalance. For further references, see [12]. Simulations in all these studies have consistently shown significant improvement in performance and reduction in the need for spinning reserves. The benefit of this approach can thus be substantial as the total capacity of grid-friendly appliances in the U.S. is estimated in [8] to be about 18% of the peak demand, comparable to the required operating reserve, currently at 13% of the peak demand. The feasibility of this approach is confirmed by experiments reported in [10] that measured the correlation between the frequency at a 230 kV transmission substation and the frequencies at the 120 V wall outlets at various places in a city in Montana. They show that local frequency measurements are adequate for loads to participate in primary frequency control as well as in the damping of electromechanical oscillations due to inter-area modes of large interconnected systems.

Indeed a small scale demonstration project has been conducted by the Pacific Northwest National Lab during early 2006 to March 2007 where 200 residential appliances participated in primary frequency control by automatically reducing their

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consumption (e.g, the heating element of a clothes dryer was turned off while the tumble continued) when the frequency of the household dropped below a threshold (59.95 Hz) [14]. Field trials are also carried out in other countries around the globe, e.g., the U.K. Market Transformation Program [15]. Even though loads do not yet provide second-by-second or minute-by-minute *continuous* regulation service in any major electricity markets, the survey in [16] finds that they already provide 50% of the 2,400 MW contingency reserve in ERCOT (Electric Reliability Council of Texas) and 30% of dispatched reserve energy (in between continuous reserve and economic dispatch) in the U.K. market. Long Island Power Authority (LIPA) developed LIPA Edge that provides 24.9 MW of demand reduction and 75 MW of spinning reserve by 23,400 loads for peak power management [17].

While there are many simulation studies and field trials of frequency-based load control as discussed above, there is not much analytic study that relates the behavior of the loads and the equilibrium and dynamic behavior of a multimachine power network. Indeed this has been recognized, e.g., in [7], [14], [15], as a major unanswered question that must be resolved before ubiquitous continuous fast-acting distributed load participation in frequency regulation will become widespread. Even though classical models for power system dynamics [2]–[4] that focus on the generator control can be adapted to include load adaptation, they do not consider the cost, or disutility, to the load in participating in frequency control, an important aspect of such an approach [6], [12]–[14].

In this paper we present a systematic method to design ubiquitous continuous fast-acting distributed load control and establish the global asymptotic stability of a multimachine network under this type of primary frequency control. Our approach allows the loads to choose their consumption pattern based on their need and the global power imbalance on the network, attaining with the generation what [6] calls a *homeostatic equilibrium* "to the benefit of both the utilities and their customers." To the best of our knowledge, this is the first network model and analysis of load-side primary frequency control.

B. Summary

Specifically we consider a simple network model described by linearized swing dynamics on generator buses, power flow dynamics on the branches, and a measure of disutility to users when they participate in primary frequency control. At steady state, the frequencies on different buses are synchronized to a common nominal value and the mechanic power is balanced with the electric power on each bus. Suppose a small change in power injection occurs on an arbitrary subset of the buses, causing the bus frequencies to deviate from their nominal value. We assume the change is small and the DC power flow model is reasonably accurate. Instead of adjusting the generators as in the traditional approach, how should we adjust the controllable loads in the network to rebalance power in a way that minimizes the aggregate disutility of these loads? We formulate this question as an optimal load control (OLC) problem, which informally takes the form

$$\min_{d} \; c(d) \quad \text{subject to} \quad \text{power rebalance}$$

where d is the demand vector and c measures the disutility to loads in participating in control. Even though neither frequency nor branch power flows appear in OLC, we will show that frequency deviations emerge as a measure of the cost of power imbalance and branch flow deviations as a measure of frequency asynchronism. More strikingly the swing dynamics together with local frequency-based load control serve as a distributed primal-dual algorithm to solve the dual of OLC. This primal-dual algorithm is globally asymptotically stable, steering the network to the unique global optimal of OLC.

These results have four important implications. First the local frequency deviation on each bus conveys exactly the right information about the global power imbalance for the loads themselves to make local decisions that turn out to be globally optimal. This allows a completely decentralized solution without explicit communication to or among the loads. Second the global asymptotic stability of the primal-dual algorithm of OLC suggests that ubiquitous continuous decentralized load participation in primary frequency control is stable, addressing a question raised in several prior studies, e.g. [6], [7], [14], [15]. Third we present a "forward engineering" perspective where we start with the basic goal of load control and derive the frequency-based controller and the swing dynamics as a distributed primal-dual algorithm to solve the dual of OLC. In this perspective the controller design mainly boils down to specifying an appropriate optimization problem (OLC). Fourth the opposite perspective of "reverse engineering" is useful as well where, given an appropriate frequency-based controller design, the network dynamics will converge to a unique equilibrium that *inevitably* solves OLC with an objective function that depends on the controller design. In this sense any memoryless frequency adaptation implies a certain disutility function of the load that the control implicitly minimizes. For instance the linear controller in [7], [10] implies a quadratic disutility function and hence a quadratic objective in OLC.

Our results confirm that frequency adaptive loads can rebalance power and resynchronize frequency, just as the droop control of the generators currently does. They fit well with the emerging layered control architecture advocated in [18].

C. Our Prior Work and Structure of Paper

In our previous papers [19]–[21] we consider a power network that is tightly coupled electrically and can be modeled as a single generator connected to a group of loads. A disturbance in generation causes the (single) frequency to deviate from its nominal value. The goal is to adapt loads, using local frequency measurements in the presence of additive noise, to rebalance power at minimum disutility. The model for generator dynamics in [21] is more detailed than the model in this paper. Here we study a network of generator and load buses with branch flows between them and their local frequencies during transient. We use a simpler model for individual generators and focus on the effect of the network structure on frequency-based load control.

The paper is organized as follows. Section II describes a dynamic model of power networks. Section III formulates OLC as a systematic method to design load-side primary frequency control and explains how the frequency-based load control and the system dynamics serve as a distributed primal-dual algorithm to