Decentralized Demand-Side Contribution to Primary Frequency Control

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***Abstract*—Frequency in large power systems is usually controlled by adjusting the production of generating units in response to changes in the load. As the amount of intermittent renewable generation increases and the proportion of flexible conventional generating units decreases, a contribution from the demand side to primary frequency control becomes technically and economically desirable. One of the reasons why this has not been done was the perceived difficulties in dealing with many small loads rather than a limited number of generating units. In particular, the cost and complexity associated with two-way communications between many loads and the control center appeared to be insurmountable obstacles. This paper argues that this two-way communication is not essential and that the demand can respond to the frequency error in a manner similar to the generators. Simulation results show that, using this approach, the demand side can make a significant and reliable contribution to primary frequency response while preserving the benefits that consumers derive from their supply of electric energy.**

***Index Terms*—Decentralized control, demand-side response, load frequency control, primary frequency control.**

I. Introduction

IMBALANCES between load and generation must be corrected within seconds to avoid frequency deviations that might threaten the stability and security of the power system. Routine deviations from this balance are usually corrected by adjustments in the output of conventional generating units driven by their governor in what is called primary frequency response [1]. The load is used explicitly to restore this balance only when the imbalance is severe and cannot be remedied quickly enough using fast acting generation. In such cases, blocks of loads are interrupted following the action of underfrequency relays. This control philosophy may need to be revised in the coming years as the demand side may take a more active role in the control of the system. As their relative size increases, intermittent and variable output renewable energy sources such as wind farms will contribute larger random fluctuations to the load/generation balance [2]. At the same time, the number of conventional generating plants that have the flexibility required to take part in primary frequency control is likely to decrease as coal-fired plants are decommissioned. One possible scenario would see the bulk of the electrical energy being produced by a combination of renewable sources and nuclear power plants [3]. Under such conditions, performing primary frequency control using only supply-side resources may become not only prohibitively expensive but also technically difficult; see, for example, [4]. It is therefore important to explore how a sufficient proportion of the loads could assume a routine role in primary frequency control to maintain the stability of the system at an acceptable cost, considering this load participation as an example of the contribution that consumers could make to ancillary services [5], [6].

The obvious challenge in including loads in frequency control is the large increase in the number of potential participants. Even in the largest control areas, at most a few hundred large generators contribute to frequency control. On the other hand, participation from the demand side might involve tens of thousands if not millions of consumers. Though this may appear technically daunting and economically unrealistic, it has to keep in mind that conventional primary frequency control is a distributed control system that relies on the availability of the frequency as a measure of imbalance between load and generation. Indeed, the response of each generating unit is determined by its droop characteristic and a local frequency measurement, not by a signal sent from a control center. Communication to and from the control center is used only in the slower secondary and tertiary control loops for better economic optimization and network security. A load or consumer thus does not have to be plugged into a communication network to take part in primary frequency control. Schweppe *et al.* originally proposed this idea in 1980 and patented this concept as the Frequency Adaptive Power Energy Rescheduler (FAPER) [7].

In the last few years, research effort on the design and application of FAPER-like controllers applied to primary frequency control gained significant momentum. The Grid Friendly Appliance controller [8] developed by the Pacific Northwest National Laboratory has shown great promise as a means to modulate load in response to certain trends in the system frequency. This controller is to be fitted into individual appliances which are essentially *energy* users rather than *power* users. Energy users are appliances which can modulate their power consumption over time as long as the final energy consumption is sensibly the same. These include primarily heating, ventilation and air conditioning equipment, tumble dryers, immersion water heaters, etc. Lu and Hammerstrom in [9] discuss, simulate, and test in a laboratory environment the effect of the triggering frequency

Manuscript received July 16, 2009; revised November 06, 2009. First published May 24, 2010; current version published January 21, 2011. This work was supported in part by the Spanish Fundación Séneca, 08747/PI/08 Reference. Paper no. TPWRS-00538-2009.

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Digital Object Identifier 10.1109/TPWRS.2010.2048223

and duration of interruption on the behavior of residential appliances. They consider that 61% of such appliances are compatible with the proposed Grid Friendly™ appliances (GFAs) that can detect frequency excursions and turn on or off according to a certain control logic. Due to the high penetration of cooling and heating loads, about 20% of the load in the U.S. comes from consumer appliances that cycle on and off [10] and which could make a contribution to frequency control during a normal state operation.

Taylor in [11] and [12] and Taylor *et al.* in [13] developed another distributed load controller for autonomous renewable energy systems, which uses the frequency and the rate of change of frequency as inputs to a fuzzy logic load control system. This approach was tested in an island power system with a small number of water-heating loads. Infield *et al.* have developed a low-cost load distributed frequency controller as an improvement to solutions for regulation of a wind-diesel system based on storage devices [14]. Kondoh *et al.* [15] compare independent and cooperative control techniques as applied to frequency regulation using electric water heaters. Shokooh *et al.* [16] applied a similar concept to an islanded industrial system where load shedding is a viable proposition and where, due to the characteristics of the generation capacity, fairly wide frequency excursions are acceptable. Trudnowski *et al.* [17] assume that these frequency responsive appliances will make possible a linear modulation of the load as a function of the frequency error. They then explore how this load response would improve the stability of the system. Hirst [18] proposed a more sophisticated flavor of the FAPER whose control behavior is modulated by the magnitude of the sensed frequency deviation. These devices are currently being tested in Italy and the United Kingdom. A recent demonstration showing that it is not only feasible to provide spinning reserve using demand-side resources but that it may also be preferable to rely on these resources can be found in [19], where practical experiences based on a centralized system coordinated to minimize customer confusion and process applications and installations efficiently are described from an international perspective.

Notwithstanding the significant effort in designing the algorithms for these load control devices, little systematic attention has be given 1) to power system operation and operations planning in grids with significant proportions of demand controlled by FAPER-like devices; and 2) to establish bounds on the amount of frequency-sensitive demand response which could be achieved in such power systems. The work of Short *et al.* [20] looks carefully at the first aspect. These authors demonstrate how real-time operation could be like with a significant amount of active frequency-sensitive fridge/freezer load for the National Grid system in Great Britain. They also provide evidence of the usefulness of increasing the proportion of these types of loads when power systems have to integrate large penetrations of wind generation.

This paper attempts to look at the latter aspect. In this work, we establish the general shape and bounds on the relationship between the aggregated demand responses provided by active loads with respect to the system frequency deviation. Obtaining this information will prove to be of critical importance to transmission system operators in the future (as the penetration of such loads becomes more widespread) when determining the amount of primary frequency reserves needed. In addition, and from the decentralized frequency sensitive load controller over Schweppe's FAPER [7] and Hirst's Grid Stabilizing System [18], we also consider a time-dimension grading for frequency deviations analogous to an inverse time over-current protection characteristic and extend the control logic to overfrequency situations.

Primary frequency control is so critical in keeping power systems from collapsing in the initiating moments of a major disturbance. Therefore, it requires coordinated and robust, yet economical, scheduling of frequency responsive generation and active demand. Increasing levels of frequency-responsive demand should reduce the cost of providing primary frequency response because less part loaded thermal generation is needed. However, the fact that the demand-side response will always remain uncertain—in magnitude and rate of response—requires the system operator to use caution when replacing generation-based primary reserve with active demand-side primary reserve. In so doing, the operator will need the information on the aggregated frequency-sensitive demand response characteristic. In this paper, we obtain this information from empirical simulation studies. These studies demonstrate, among other things, that the aggregated active load response characteristic is akin to the droop characteristic of a thermal generating unit with a finite power output.

The paper is organized in the following way. Section II describes the operation of a generalized frequency-sensitive load controller. Section III provides a detailed analysis of how participation from the demand side might affect the overall control of the frequency in the system. Specifically, we show how one can establish the general shape of the aggregate active frequency load response and its upper and lower bounds. We finally conclude in Section IV.

II. Generalized Frequency-Responsive Load Controller

A. Context

Neglecting local differences caused by electromechanical transients and oscillations, the angular frequency ω of a power system is determined by Newton's 2nd Law of Motion. Expressing this law in terms of small deviations around the nominal angular frequency of the system gives

$$M\frac{d\Delta\omega}{dt} + D\Delta\omega = \Delta P_g - \Delta P_l \tag{1}$$

where

$M = I\omega_0$ nominal angular momentum of the rotating masses in the system;

I total inertia of the rotating masses of the system;

ω_0 nominal angular frequency of the system;

D damping factor representing the natural frequency dependence of the load alongside the damping provided by synchronous generator damper windings;