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Dynamic demand control for system frequency regulation: Concept review, algorithm comparison, and future vision

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ABSTRACT

The increasing penetration of renewable energy resources brings a number of uncertainties to modern power system operation. In particular, the frequent variation of wind power output causes a short-term mismatch between generation and demand, which causes system frequency fluctuation. The traditional approach to deal with this problem is to increase the amount of system spinning reserve. In recent years, researchers are actively exploring the utilization of residential and commercial loads in frequency regulation without affecting customers' life quality. This paper first reviews the theoretical basis and application background of the dynamic demand control. Then, the paper summarizes the technical features and advantage/disadvantages of three types of dynamic demand control algorithms, namely centralized control, decentralized control and hybrid control. The technical and economic concerns of this research field are also discussed, which can be future research directions.

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1. Introduction

One essential requirement for power system operation is to ensure the balance between power generation and demand in real time. As a result of a considerable unbalance between generation and demand, frequency instability is usually associated with poor coordination of control and protection equipment, insufficient generation reserves, and inadequacies in equipment responses [1]. In recent years, however, the increasing penetration of renewable energy resources and the development of power market bring three challenges to frequency stability, increasing the need for frequency regulation for both long-term (hourly) and short-term (minute to second timescale):

- The intermittent nature of renewable energy causes a mismatch between power generation and demand [2,3], therefore, frequency fluctuation is more likely to happen than ever before;
- Some synchronous generators are replaced by converter-based energy sources, which may decrease the mechanical inertia of the present system [3,4]; and
- The hourly-based electricity market or system operation (like Union for the Coordination of Transmission of Electricity (UCTE) and Western Electricity Coordinating Council (WECC)) is likely to cause a mismatch between generation and load in the first few minutes of an hour [5].

In regard to the aforementioned problems, the conventional thought suggests that the generation side should always be prepared to satisfy all the required generation-demand mismatch, while some new ideas state that the system will be the most efficient if the large mismatch, mainly due to wind power fluctuation in recent years, is minimized by suitable demand control [6,7]. Demand Response (DR) has been introduced to adjust demand-side power consumption whenever necessary. For the power system operation perspective, the essential purpose of DR is to reduce the amount of spinning reserve while maintaining the frequency stability to improve the system. A wide variety of DR programs have been designed for peak load shaving and valley load filling, which can be regarded as mitigating long-term (usually 24 h) frequency fluctuation. Based on its objective, DR programs can be divided into three categories: the incentive-based program that is focused on utility's welfare [8,9], the price-based program that is focused on customers' welfare [10], and the hybrid program that is focused on both [11]. In all, the study on the DR application in economic-related issues was started in 1980s with many established research works.

To mitigate the short-term frequency fluctuation, turbine governor control and automatic generation control (AGC) are designed to automatically adjust the output power of generation units in order to compensate power shortfalls or to avoid power surplus. At the demand side, underfrequency load shedding (UFLS), as a protection approach, is activated when system frequency falls under a particular threshold (e.g., 59.50 Hz) [12,13]. In 2007, Short proposed a new frequency regulation approach, named as *dynamic demand control* (DDC) [14]. If compared with conventional frequency regulations, DDC is superior for the following reasons:

- *Fast response*: If compared with the generator-side control, DDC can capture sudden frequency drop and restore it faster than AGC which is typically in several minutes [15].
- *Flexibility*: If compared with UFLS that is activated at a large frequency drop, DDC is more flexible since it is activated at a relatively small frequency drop with multiple frequency thresholds (e.g., 59.85–59.95 Hz) [5,16].
- *Economic efficiency*: A large number of controlled loads can emulate the frequency droop characteristic of a generation unit in order to mitigate the frequency fluctuation, which is caused by short-period wind power shortage or generator outage [16,17]. Therefore, we can expect that the wide application of DDC helps reduce the capacity requirement of spinning reserves and further reduce the system operation costs [18,19].

In summary, DDC can be a useful compensation for conventional power system frequency regulation approaches. Therefore, this review paper provides a comprehensive survey on DDC including its theoretical basis, application background, and newly-proposed control algorithms.

The remaining parts of the paper are organized as follows. Section 2 describes the power-frequency dynamic characteristic and general principle of power system frequency regulation. Section 3 investigates the characteristic of responsive loads and the uncertainty of load availability for frequency regulation reserves. Section 4 presents a comparison of the advantages and disadvantages of various control strategies including the centralized control, decentralized control, and hybrid control. Section 5 discusses practical techno-economic concerns and future research directions of DDC. Finally, Section 6 concludes this review paper.

2. Brief description of frequency regulation

The mission of frequency regulation is to quickly respond to system frequency deviation by increasing or decreasing the power generation or load demand to bring frequency back to nominal value (50 or 60 Hz). This section first introduces the so-called load-frequency control (LFC) model to illustrate the relationship between frequency and power unbalance, then discusses the concept of frequency regulation in the industry. The model and concept are the theoretical basis of various DDC strategies that will be discussed in Section 4.

2.1. Power system frequency response

Neglecting local frequency differences caused by electromechanical transients and oscillations, we consider that the system frequency is governed by the 2nd Newton Law. Expressing this law in terms of small deviations around the nominal frequency gives Eq. (1) [20],

$$\Delta P_g(t) - \Delta P_d(t) = 2H\frac{d\Delta f(t)}{dt} + D\Delta f(t) \tag{1}$$

where $\Delta P_g(t)$ is the generator mechanical power deviation, $\Delta P_d(t)$ is the load demand deviation, and $\Delta f(t)$ is the system frequency deviation (= $f(t) - 60$), all at time t. Note: power and frequency variables are in per-unit values here. H is the inertia constant, denoting the kinetic energy at the rated speed divided by the rated power base. D is the system load damping coefficient which is expressed