Primary Control by ON/OFF Demand-Side Devices

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***Abstract*—We consider an aggregator managing a portfolio of ON/OFF demand-side devices. The devices are able to shift consumption in time within certain energy limitations; moreover, the devices are able to measure the system frequency and switch ON and OFF accordingly. We show how the aggregator can manage the portfolio of devices to collectively provide a primary reserve delivery in an unbundled liberalized electricity market setting under current regulations. Furthermore, we formulate a binary linear optimization problem that minimizes the aggregator's cost of providing a primary reserve delivery of a given volume, and demonstrate this method on numerical examples.**

***Index Terms*—Demand response, liberalized electricity market, primary reserve, smart grids.**

I. Nomenclature

A. Indices

i	Index of devices.
j	Index of frequency deviation.
k	Index of time sample number.

B. Parameters

a	[W/Hz] Droop curve slope;
J_{prim}	[−] Cost of act. devices $\mathcal{I}_{\mathrm{prim}}$.
$f_{\mathrm{db}}, f_{\max}, f_{\mathrm{tol}}$	[Hz] Droop curve parameters;
f_{nom}	[Hz] Nominal system frequency;
$f_{\mathrm{sys}}(k)$	[Hz] System frequency;
K	[−] Samples in a delivery period;
m	[−] Number of frequency intervals;
n	[−] Number of devices
p	[W] Nominal power consumptions
$p_{\mathrm{ctrl}}(k)$	[W] Primary control reference;
$p_{\mathrm{prim}}(k)$	[W] Primary reserve volume;
$p_{\mathrm{prim}}^{\max}, p_{\mathrm{prim}}^{\min}$	[W] Up./lower primary res. limit;
T	[s] Duration of delivery period;
t_i	[Hz] Trigger frequency of device i;
$t_i^{\min}, t_i^{\max}$	[Hz] Min/max trig. freq. for dev. i;
$\overline{t}, \underline{t}$	[Hz] Frequency interval vectors;
T_s	[s] Sampling time;
$u(k)$	[W] Device power consumptions;
v	[W] Device drain rates;
$x(k)$	[J] Device energy storage levels;
$x^{\min}, x^{\max}$	[J] Up./lower energy limits;
$x_0(k)$	[J] Initial device energy levels;
$\Delta f(k)$	[Hz] Frequency deviation;
π	[−] Device activation costs.

C. Sets

$\mathcal{I}$	Devices index set.
$\mathcal{I}_{\mathrm{prim}}$	Devices activated for primary reserve.
$\mathcal{I}_{\mathrm{up}}, \mathcal{I}_{\mathrm{up}}$	Upward/downward regulation devices.
$\mathcal{J}$	Frequency deviation index set.
$\mathcal{K}$	Sample number index set.

D. Variables

$\overline{X}$	Frequency allocation matrix for upward reg.
$\underline{X}$	Frequency allocation matrix for downward reg.

Throughout the nomenclature, the notation [−] is used to denote a dimensionless parameter. Notice that the costs are assumed normalized and hence described as dimensionless.

II. Introduction

With an increasing focus on climate-related issues and rising fossil fuel prices, the penetration of renewable energy sources is likely to increase in the foreseeable future throughout the developed world [1]. Many actions have been taken from a political point to increase the penetration of renewables: in the US, almost all states have renewable portfolio standards or goals that ensure a certain percentage of renewables [2]. Similarly, the commission of the European Community has set a target of 20% renewables by 2020 [3], while China has doubled its wind power production every year since 2004 [4].

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In Denmark, the 2020 goals are 35% sustainable energy over all energy sectors and 50% wind power in the electrical energy sector [5].

A major challenge arises when replacing central power plants with renewable energy sources: the central power plants do not only deliver power but also provide ancillary services to ensure a reliable and secure electrical power system. This includes frequency stability support, power balancing, voltage control, etc. When the conventional power plants are replaced with renewables such as wind turbines and photovoltaics, the ability to provide ancillary services in the classical sense disappears; the renewable energy sources will often fully utilize the available power and thus not be able to provide balancing ancillary services. Furthermore, conventional fossil fuel power plant generators are synchronous with the grid and therefore provide rotating inertia that supports the system frequency against changes [6]. As renewable energy sources typically interface with the grid via power electronics, they do not directly provide inertia to the grid as the conventional synchronous generators [7], which further increases the balancing challenges. Although recent works suggest that wind turbines can provide synthetic and artificial inertia by regulating the active power output of the generator according to the system frequency [8], [9], this type of control is generally not implemented in the wind power plants of today. Moreover, many renewable sources are characterized by highly fluctuating power generation: they can suddenly increase or decrease production depending on weather conditions. These rapid production changes are not always predictable and can therefore imply severe consequences for grid stability [10].

It is therefore evident that in a grid with high penetration of renewables, the need for balancing ancillary services will increase [11], [12]. As conventional power plants are phased out gradually, alternative sources of ancillary services must be established. One of the approaches to obtaining alternative ancillary services is the *smart grid* concept, where demand-side devices with flexible power consumption take part in the balancing effort [13], [14]. The basic idea is to let an *aggregator* manage a portfolio of flexible demand-side devices and utilize the accumulated flexibility in the unbundled electricity markets on equal terms with conventional generators [15].

Flexible demand-side devices have significantly different characteristics than conventional generators: while conventional generators are able to provide more or less energy by adjusting the fuel consumption, demand-side devices will on average roughly consume the same amount of energy. An electrical vehicle may for example be able to consume energy in one hour and deliver the energy back in the following hour; however, over the course of a year, the net energy consumption will roughly be the same independent of how the flexibility is utilized. On the other hand, many demand-side devices can be switched ON and OFF almost instantaneously enabling them to react faster than most conventional generators. These characteristics make demand-side devices ideal for primary frequency control, as this type of reserve demands rapid up and down power regulation abilities but generally does not require actual energy deliveries.

Another benefit of primary frequency control in this context is that the delivery of reserves depends on local system frequency measurements; hence, no expensive near real-time communication from aggregator to devices is necessary. Furthermore, primary reserves are generally the most expensive deliveries, as they require fast control action. This increases the attractiveness of enabling demand-side devices to participate in the primary reserve market.

Demand-side management by controlling smaller appliances to support grid stability has been discussed as early as the 1980s [16]. Since, the topic of demand-side management has received much attention from a research perspective. See, e.g., [17]–[19]. Currently, demand-side programs are in operation in many systems, for example in the UK and the US systems [20]–[22]; moreover, a growth is seen in the volume of these programs. As an example of this growth, New England has experienced an increase in demand-side programs from contracts on 200 MW in 2003 to more than 2,000 MW in 2009 [23].

Recent works have discussed the use of demand-side management to provide primary reserve. A few examples are: refrigeration systems that adjust the power consumption according to the system frequency deviation [24], [25], thermal systems that respond when the system frequency drops below a certain value [26], and primary frequency control of flexible domestic consumption devices activated through a local smart meter [27]. While these works discuss methods for providing primary reserves, they do not consider these services sold through the current liberalized market system. In other words: the cited works show how to deliver primary reserve for grid support but do, however, not design the control strategies such that the accumulated response of the demand-side devices satisfy the regulatory requirements for primary reserve deliveries.

The main contribution of this work is to show how an aggregator can manage a portfolio of ON/OFF demand-side devices to collectively provide a delivery of primary reserve that comply with the current regulations in the European electric power system. This allows the aggregator to enter the primary frequency control market and thus compete with the conventional generators as is desired in a liberalized market setting [15].

The paper is structured as follows. In Section III, we present a system architecture where an aggregator manages a portfolio of ON/OFF device. Following, in Section IV, we describe how these ON/OFF devices can be managed to provide frequency reserves complying with current regulations. In Section V, we present a method for minimizing the cost of a reserve delivery, and in Section VI this method is applied to a numerical example. Finally, in Section VII, we conclude the work.

III. System Architecture

In this section, we describe the overall relation between consumers, aggregator and the primary reserve market.

A. Aggregator as Player in the Electricity Markets

We consider an unbundled liberalized electricity system architecture. In this setup, the Transmission System Operators (TSOs) are responsible for secure and reliable system operation and must consequently ensure balance between production and consumption. Generally, in an unbundled electricity system, TSOs do not own production units and must therefore procure