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Providing frequency regulation reserve services using demand response scheduling

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ABSTRACT

During power grid contingencies, frequency regulation is a primary concern. Historically, frequency regulation during contingency events has been the sole responsibility of the power utility. We present a practical method of using distributed demand response scheduling to provide frequency regulation during contingency events. This paper discusses the implementation of a control system model for the use of distributed energy storage systems such as battery banks and electric water heaters as a source of ancillary services. We present an algorithm which handles the optimization of demand response scheduling for normal operation and during contingency events. We use dynamic programming as an optimization tool. A price signal is developed using optimal power flow calculations to determine the locational marginal price of electricity, while sensor data for water usage is also collected. Using these inputs to dynamic programming, the optimal control signals are given as output. We assume a market model in which distributed demand response resources are sold as a commodity on the open market and profits from demand response aggregators as brokers of distributed demand response resources can be calculated. In considering control decisions for regulation of transient changes in frequency, we focus on IEEE standard 1547 in order to prevent the safety shut-off of inverter-based generation and further exacerbation of frequency droop. This method is applied to IEEE case 118 as a demonstration of the method in practice.

1. Introduction

The modern power grid has seen a marked increase in renewable energy generation resources. The intermittent nature of these resources give rise to additional challenges in maintaining grid stability. To design a grid which is secure, a number of factors need to be considered. On a basic level, we define security as the ability of a certain system configuration to continue to function and withstand a wide range of operating parameters, outside influences, or even subsystem failures. One of these security aspects is related to grid frequency which is very important for inverter-based generations [1,2]. In the event of contingencies such as short circuits, large changes in load, or loss of transmission lines, the entire system needs to be able to remain operating long enough for the grid operators to restore stability. Maintaining a balance of power is critical to the continued operation of the grid at these times. In order to increase the capacity to maintain this balance of power, grid operators call upon what are known as ancillary services (AS) to provide these changes in power to the grid quickly. Contingency reserve (CR) is one type of AS which is generally split between spinning and non-spinning reserves and are often based on the largest single hazard (generator or transmission capacity). Contingency events are big (many megawatts) and fast (within a few cycles) [3].

Demand response (DR) resources can provide different types of ancillary services [4,5] or can be used for power resources scheduling [6]. Different types of DR resources that participate in DR programs include industrial [7] and residential [8–10] equipment. Different types of DR resources have been utilized in order to provide various ancillary services such as: using active electric vehicles (EVs) to provide spinning reserves [11], using battery energy storage systems to provide primary control reserves [12], utilizing battery storage systems to provide multi-ancillary services including refrigeration appliances (as dynamic demands) to provide primary frequency regulation through an advanced stochastic control frequency regulation and peak-shaving functions [13], using demand response through pump scheduling to provide balancing services [10], and using domestic algorithm [14]. The use of demand response as a source of AS is a strategy to recover the frequency after the contingencies [15,16]. An

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approach was proposed in [17] which all types of loads can participate in DR programs. This approach considered energy and reserve scheduling, simultaneously. In that study, the energy and reserve scheduling were proposed for day-ahead and real-time. In terms of using DR for voltage stabilization, an approach was presented in [18] for real-time voltage control which uses an emergency DR program that aims at maintaining voltage profile in an acceptable range with minimum cost. This approach is active in emergency conditions where, in real time, the voltages in some nodes leave their permissible ranges. There have been highlights in literature about demonstration projects showing much promise for water heaters (WHs) and battery storage systems as suitable candidates for ancillary services [19]. Energy storage capacity—thermal in the case of WHs and chemical in the case of batteries—allow these systems to delay or anticipate energy consumption. The implementation of suitable optimization and scheduling strategies for these resources becomes a key factor in the successful deployment of these systems as sources of ancillary services. Electric water heaters represent a significant source of energy consumption on the modern grid and have the capacity for energy storage in the form of heat. An important characteristic of these resources is that they tend to cycle on and off randomly [20]. The idea is to use these resources by adding another measure of control to when and how these resources present their loads to the grid. By having the resources work in concert, we are able to optimize and utilize these resources to function as ancillary service providers. For instance, human consumption of thermal energy in the form of hot water comprises 40–60% of the monthly domestic electricity bill in Hawaii. In [21], potential of DRs in Hawaii has been studied in balancing supply and demand on an hourly basis. General Electric, in collaboration with the Hawaii Natural Energy Institute, did a recent study on ancillary services in Hawaii [22]. This study shows that energy storage and DR should be allowed to provide a significant portion of spinning reserve for frequency recovery and mitigation.

Grid-interactive water heaters provide many additional benefits to power grids which are increasing generation by renewables. Control over the timing of these loads can be optimized to enhance power quality and regulate grid frequency. By mitigating the harmful effects of the intermittent nature of renewable generation, greater penetrations can be achieved. Wind farms are able to be utilized during windy low-demand periods. Arbitrage value is added by enabling participants to buy and store low-cost energy and sell demand reduction when energy prices are high. Transmission, distribution, and substation upgrades are able to be deferred by reducing peak demands, and a new resource for spinning reserve is added to supplement existing systems and enable the use of only the most efficient generators.

The management of demand response is considered to be an important factor in the optimization of power systems. Increases in the proportion of renewable energy generation in power systems strain the flexibility of available systems. The use of demand response aggregators (DRAs) as ancillary service providers has become an important strategy for increasing stability. DRA is the entity which aggregates all the bids of DR contributions from houses that have signed up for this service. This entity then will participate in the DR market with the available amount of DR resources. Once the market is cleared and each DRA's contribution is determined, DRAs perform an internal optimization to distribute the specified amount of DR among the houses. Independent system operators (ISOs) and even some governing bodies have incorporated new programs in order to support the participation of consumer side demand flexibility aggregators in order to meet the needs of the modern power grid. As a result, we expect to see the implementation of demand response for ancillary services from large populations of small residential loads very soon. In order to bring these changes, smarter control systems and management approaches must be devised and implemented on a wide scale. With the advent of widespread and reliable communications infrastructure, the interaction of smart appliance networks can be realized and the multitude of devices can act in concert to facilitate the appropriate responses. The bidirectional flow of information and power between utility and customer enables the use of DR components to facilitate crucial services such as peak load shaving, load smoothing, and spinning reserve frequency regulation. With a wide variety of responsive loads at both the utility and residential levels, the pool of resources increases with each step taken toward greater control. When implemented effectively, DR elements can help to improve market efficiency and operational reliability [23].

Models have been shown where DR is used to procure reserve using a short term stochastic security constrained unit commitment (SCUC) [24]. The optimal scheduling of residential appliances and battery storage in consideration of operational and planning constraints has been investigated in [8], where utility goals are considered and integrated into an objective function in order to enhance the approach. In [25], consumer inconvenience is introduced and considered in market-based models. DR can be categorized by price-based and incentive-based types [26]. Different pricing schemes allow flexibility to provide customers with rates which more accurately reflect the price of electricity based on cost of generation and distribution. Price-based DR reacts to fluctuations in real-time prices of electricity to provide the optimum response. Incentive-based DR programs pay the customers to reduce their loads at times requested by the program sponsor. Although the methods are distinct, it would be an interesting question to pose whether qualities and features of both systems may be combined into a hybrid-system with benefits from both sides. Price signaling is based on several different factors such as cost of reserve procurement, reliability studies, operational planning, and load forecasting [27]. Different types of energy storage can be used as DR. These can include thermal storage present in WHs or air conditioners, or chemical storage such as that found in electrochemical cells. Grid-interactive water heaters are able to be controlled by utilities or aggregators in order to perform several grid services such as DR, grid stabilization, and peak load shaving. In experiments conducted in [28], we see that large tank heat pump WHs and electric resistance WHs can be significant sources of DR. The heat-pump type of WH was shown to be at least 10% more available for DR on average while the electric resistance WHs provided a greater degree of dynamic response and power flow when utilized. Data analysis of results and historical data allow for the definition of an improved price signal which considers the attitude of consumers in combination with financial incentives.

Distributed equipment connected to the grid that is capable of participating in demand response can be programmed to process received sensor information and react autonomously based on user-defined policies [29]. Sometimes, these distributed devices are referred to as smart agents. These agents communicate and interact with each other to achieve an optimum aggregate response [29,30]. Multi agent systems (MAS) have been successfully applied to several different power grids [31]. The smart agents respond to sensor data and signals in a way that maximizes profit. The actual sensor data and price signals can be used as direct indicators of current grid conditions. In acting to maximize profits, the smart agents naturally stabilize grid conditions and optimize efficiency. This concept can also be described as power matching [31], which can be a major benefit to power grids with a large presence of intermittent renewable energy generation. Specific price signals can be used to generate a schedule for the switching of home appliances to maximize cost savings [32].

Several different algorithms have been proposed by researchers to generate schedules for controllable resources [33,34] and vary in objective and input, for example: scheduling wind resources and