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Hierarchical market integration of responsive loads as spinning reserve

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ABSTRACT

In this paper, a new market integration approach for responsive loads is proposed. Large, spatially-distributed populations of heat pumps, electric vehicles, and electrolyzers are integrated into the conventional security constrained economic dispatch formulation using a hierarchical load management policy. Regional pockets of responsive loads are aggregated into models that describe population dynamics as an equivalent virtual power plant. This demand-side virtual power plant is then integrated into the market as a new source of spinning reserves. The potential impact of reserve capacity supported by responsive loads on the operating characteristics of the power system is investigated using a bottom-up modeling framework. Results indicate that by supplying spinning reserve, responsive loads can increase the flexibility of existing resources within the active power portion of the market. The hierarchical market integration policy enhances both the technical and economic efficiency of the power system, reduces operating costs and emissions, and supports increasing levels of variable generation on the grid.

1. Introduction

Electric power is one of the most ubiquitous and reliable end-use services in the developed world. This is an impressive feat, considering the complexity and sheer size of power systems that deliver electricity to consumers. Robust security protocol enables this high-level of reliability. If an unforeseen contingency occurs, the power system operator (PSO) must have a coordinated set of operating reserves continuously available in order to guarantee the system can maintain required service levels. Typically denoted as spinning reserve, online capacity must be kept synchronized to the grid to provide system security, but results in the need to leave valuable capacity idle that could otherwise contribute to actual power supply.

Complicating the issue of this missed opportunity is the increasingly pressing need to develop low carbon energy systems, particularly through the large-scale integration of renewable generation technology such as wind farms and solar power plants. When these technologies are employed at large-scales, the short-term production variability inherent to generating wind and solar power begets the need for increased access to online reserve capacity [1,2].

With the increasing prevalence of information technology and distributed computing, advanced power system configurations are offering alternative avenues to needed flexibility. Particularly appealing is the prospect of enabling loads that have historically been passive with the technology that promotes responsiveness to power system conditions. This could provide an alternative pathway to the provision of power system ancillary services, such as spinning reserve [3]. Many modeling and simulation studies have examined various aspects of using loads to provide spinning reserve, but there remains a disconnect between many of the market-integration studies and the actual load control formulations. This prevents a unified description of the technical, economic, and environmental benefits associated with pursuing these types of system configurations.

In order to address some of the system integration questions, this paper investigates the impact of loads as spinning reserve on the complete system using a bottom-up modeling framework. A regional load aggregation scheme is used in order to optimally manage spatially-distributed load groups that consist of disparate load types. A novel approach is then proposed, wherein each regional load aggregator is assigned the task of defining a virtual power plant (VPP) that encapsulates the available flexibility that exists inside its region. This VPP is integrated within a joint energy-reserve market as spinning reserve. A model of the hierarchical load management policy is developed to assess the impacts of VPP reserve on dispatch order. This model is capable of capturing the physical constraints of loads in conjunction with the economic and environmental impacts of electricity markets.

1.1. Previous work

Typically, market-based studies assume that responsive loads represent an elastic quantity within the market, with no consideration

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of the actual load dynamics occurring on the demand-side or how these loads are in fact to be controlled. These studies instead rely on penalties to be paid out by the PSO for violating the unperturbed demand trajectory [4–8]. These studies have provided valuable insight into the possible benefits of involving responsive demand within electricity markets, but the underlying top-down, or aggregated descriptions can be insufficient in describing the true behavior of the system. An alternative approach is to explicitly model groups of individual loads in terms of their end-use functionality. These characteristics drive the actual load on the grid, and therefore hold the true potential for groups to be controlled and perform in the market [9].

In order to define the control strategies needed to manipulate individual loads into providing services such as spinning reserve, physical load modeling has been utilized to develop a plethora of different methods. In [10], a system identification approach has been proposed to design an open-loop direct load control strategy. A state-queueing model of thermostatically controlled appliances is developed in [11] to describe the aggregated response to price control signals. In [12], a method based on the Nash certainty equivalence principle is used to develop a novel decentralized charging control algorithm for large populations of electric vehicles. In general, these studies have indicated that thermal or charging loads, in either residential or industrial areas, can potentially be controlled at a high-level of accuracy.

A common theme among these load control studies (and others) is the development and potential benefit of a load aggregator (LA) as an intermediary that offers the services of large groups of loads within the electricity market. This type of aggregation process is beneficial, as markets typically require participating resources to have a minimum capacity that is well beyond that available from a single load. If these intermediaries can balance the needs of both the PSO and end-user within an economically viable package, load aggregation may represent an attractive new business opportunity within electricity markets. Understanding the potential for LAs to perform in the market will require the coupling of resilient load control strategies and conventional market constructs.

From the perspective of the PSO, the desired characteristic of the LA is its ability to make groups of loads look like generation. This is because the PSO can then control these groups using conventional resource allocation schemes [13]. Such a description of load behavior can be achieved by treating the grid-loading dynamics associated with a population of responsive loads in a format equivalent to conventional generation. This means prescribing capacity and ramp-limitations to the controllable aggregate load. The model development can further entail inclusion of other small-scale distributed generation encompassed within the LA's management area. As the resultant model's capacity is of similar order to that seen in other transmission-level supply resources, it is typically referred to as a virtual power plant (VPP) [14]. When the VPP is called upon to provide a certain level of capacity, the LA is tasked with allocating the objective amongst its managed resources. This type of hierarchical control allows the power system operator to dispatch loads without the need to consider the device-level constraints, and further enables small-scale resources to penetrate into a market conventionally dominated by utility-scale plants.

A hierarchical control policy will require that the LA determine a robust policy capable of ensuring the interactions proceed as desired. From the perspective of the end-user, the main concerns lie in the tradeoffs between possible forfeits in end-use functionality and potential gains in acting as an energy resource. Two separate management policies have emerged in the literature: price-based control, which relies on the consumer reacting accordingly to price changes conveying the PSO's objective, and direct load control, which relies on the explicit manipulation of targeted loads in order to meet the PSO's objective. While intriguing in terms of the seamless market-integration, price-based control strategies are subject to uncertainties in customer behavior, which may compromise the reliability of load control actions. The second problem with price-based approaches is that consumers may need to forfeit end-use functionality of targeted devices, or alternatively be penalized for attempting to maintain typical service-levels.

Some studies have indicated that deployment of automation at the device-level can allow users to define demand curves that autonomously allow the user to participate in the market [11,15]. However, this process may be ill-suited for end-users who have little experience or knowledge of how the electricity market operates. Finally, as electricity prices are intrinsically linked to levels of demand on the system (i.e. peak demand usually corresponds to peak prices), price-based control can be seen as an attempt to charge customers more for services over periods when they need it most. It may therefore be unappealing from the viewpoint of individuals constrained to specific electricity use patterns by their daily schedules.

As overviewed in [16], direct load control actions may provide a more resilient approach for two reasons. First, directly controlling loads removes the possibility of user behavior compromising load control reliability. Secondly, direct load control can act over relatively short timeframes (price-based approaches must wait for the market to update). While in the direct control case there may be issues with customers relinquishing control to an outside party, they are to be rewarded accordingly for doing so, based on the value of their resource within the electricity market. Hence, they should be willing to participate if the benefits out-weigh those associated with maintaining control authority. Thus, if direct load control strategies can remain non-disruptive, customers may readily allow recruitment of suitable end-use devices, as they will likely incur reduced costs of energy-related services.

As was demonstrated in [10], by making small, continuous changes to a thermostat's set-point, the aggregate demand associated with a large population of thermostatically controlled loads can be ramped up or down over relatively short periods. Such temperature changes would be small and remain unnoticed by the end-user, and therefore customers should be willing to participate given associated auxiliary benefits. Building on this idea [17], developed an adaptable method capable of aggregating the dynamics occurring in loads controlled via set-point control to models equivalent to a comfort-constrained VPP, and applied it to provide regulation-based ancillary services to the grid. In [18], the comfort-constrained VPP is integrated within a novel online voltage security assessment. It is demonstrated that when dispatched, the VPP can respond accurately and quickly, thus promoting its efficacy as a reserve resource. An important question that remains and which this paper addresses, is how the use of demand-side VPPs for system security reserve impacts the economic and environmental operating qualities of the power system.

Although an array of bottom-up strategies for load control have been proposed, most of these strategies remain decoupled from the electricity market. These studies therefore offer limited scope for an integrated description and analysis of the possible systemic impacts. In this paper, an optimal hierarchical management framework that explicitly treats actual customer load dynamics is proposed. Small-scale residential load-types (heat pumps and electric vehicles) and a commercial/industrial load-type (electrolyzers) are considered to exist within regional pockets. The disparate load groups are aggregated using the method described in [17] to form the region's equivalent VPP. The VPP ramping constraints are then defined as available online reserve capabilities, which is integrated into a conventional energy-reserve joint market based on optimal power flow (OPF). The benefits of VPP reserve accessibility is investigated within a multi-zone electricity network with high reserve requirements that is impacted by a large internal wind farm.