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Agent-Based Simulation for Interconnection-Scale Renewable Integration and Demand Response Studies

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ABSTRACT This paper collects and synthesizes the technical requirements, implementation, and validation methods for quasi-steady agent-based simulations of interconnection-scale models with particular attention to the integration of renewable generation and controllable loads. Approaches for modeling aggregated controllable loads are presented and placed in the same control and economic modeling framework as generation resources for interconnection planning studies. Model performance is examined with system parameters that are typical for an interconnection approximately the size of the Western Electricity Coordinating Council (WECC) and a control area about 1/100 the size of the system. These results are used to demonstrate and validate the methods presented.

KEYWORDS interconnection studies, demand response, load control, renewable integration, agent-based simulation, electricity markets

1 Introduction

Climate change concerns are driving electric utilities to find ways to reduce greenhouse gas emissions while continuing to meet the demand for reliable electricity. Primary among these methods is the adoption of renewable generation as a major component in the generation resource portfolio. The growth of renewable resources has reached a level in some electricity interconnections such that existing frequency regulation resources are being called upon to react to deviations more often than in the past [1]. In response, utilities are sometimes forced to schedule and dispatch more costly reserves and/or curtail less costly renewables. This response increases the effective cost of renewables by requiring the purchase of additional reserves at prices that are higher than the marginal cost of the intermittent resources [2].

An alternative to employing additional reserve and regulation resources is to enable load to respond to frequency deviations in a manner that is similar to generation. This general approach was originally proposed more than 30 years ago [3]. Simulation studies [4] and demonstrations [5, 6] have shown the potential for loads to serve as short-term fast-acting virtual generators and act as a frequency regulation resource that can contribute to primary regulation.

Conventional direct load control has focused primarily on the use of load as an under-frequency load shedding resource. The control models of this type of resource are primarily based on the impulse response of loads to large deviations in frequency [7]. However, for the purposes of frequency regulation, load control design must examine the small signal stability of the system [8]. The latter approach considers more than just the magnitude of the total installed base of controllable load [9, 10]; it also considers the aggregate load control gain, closed-loop control feedback effects, and any load state diversity impacts arising from resource utilization.

The lack of participation by load in organized energy markets is an important barrier to demand response technology [11]. In addition, the cost, capacity, and reliability of the communication systems for controllable loads undermine the confidence utilities have in using loads as a reliable substitute for dispatchable generation [12]. There can also be significant uncertainty regarding the amount of load that will be available to respond, the duration with which it will respond, and the magnitude of the rebound when it is released [13]. Finally, changes in the allocation of generation resources can impact transmission capacity and *N*–1 contingency reliability resource selection, and can lead to additional operational costs [14].

There is a long history of using load as a resource, beginning with demand-side management (DSM) programs and time-of-use (TOU) rates. DSM programs exploited seasonal long-term demand elasticity through energy efficiency measures in order to defer capacity additions by holding down peak loads as load-growth rates waned in industrialized nations. TOU programs were an effective strategy for obtaining the sustained price-based control of peak load using diurnal

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mid-term demand elasticity. Some of this capability has been transferred to short-term elasticity by using the pseudo-storage potential of thermostat loads [15]. Peak-time rebates, critical-peak prices, and real-time price signals have been used to more directly reveal the short-term elasticity of demand [16].

In the case of real-time price (RTP) demand response systems, price-discovery is an important challenge [17] that has been addressed through the development of so-called "transactive control." In these bi-directional systems, information about the available resources and their reservation prices※ is collected from demand resources and included in a double-auction market where both the supply curve and demand curve are used to discover the price at which supply will equal demand. This mechanism has been used to solve real-time resource capacity allocation problems at the utility scale [18] but has yet to be carefully studied for regulation resource allocation [19].

The main purpose of this paper is to review and synthesize design requirements, implementation considerations, and validation approaches for agent-based simulations that can assist in the design of load control strategies. The simulations can then help address the renewable integration challenges that utilities confront as they try to mitigate the greenhouse gas emissions of their conventional generation fleets. Such simulation environments must capture all the salient features of the electromechanical dynamics of the interconnection, the dispatchable and renewable generation resources, the market designs and market participants, control area and balancing authority operations, and both the unresponsive and responsive loads. At the same time, it must remain computationally tractable in order to study large interconnected regions where inter-jurisdictional interactions are important.

This paper is structured as follows. In Section 2, we review the agent-based methods used to solve quasi-steady models of interconnections, generation resources, and markets, with particular attention to the sub-hourly behavior of the system. Section 3 focuses on the problem of modeling individual and aggregated loads and load control at this time scale. Validation challenges and preliminary results loosely based on the Western Electricity Coordinating Council (WECC) planning model are discussed in Sections 4 and 5.

2 System model

Modeling the composite behavior of highly complex interconnected systems has been a challenge for engineers since the early days of digital simulators [7]. Recent advances in agent-based computing have helped overcome many of the barriers to simulation, particularly with respect to finding the solution to multiple systems of differential equations where the subsystem models are fundamentally incompatible [20]. GridLAB-D™ is an example of a simulation environment that overcomes some of these challenges, in spite of the fact that its implementation raises issues regarding validation [21]. In particular, the lack of analytic solutions and proofs of stability continue to impair the usability of agent-based time-domain simulation as a control system design tool. Nonetheless, agent-based simulations are very useful as an environment in which to experiment, gain experience and insight, and quickly demonstrate by modus tollens when a particular proposition or strategy fails to work as intended.

It has been previously observed that the bandwidth of renewable intermittency, short-term demand response, and frequency regulation coincide, as shown in Figure 1. This particular alignment between the primary operating bandwidth of demand response and wind intermittency presents both an opportunity and a challenge for system planners. The possible coupling of demand response and intermittent resources means that any feedback mechanisms and delays can give rise to instabilities if controls are not properly designed. However, for the same reasons, well-designed control can give rise to highly efficient performance, both from an economic and a control performance perspective.

2.1 Markets

Generating units cannot be started, stopped, or moved through their operating

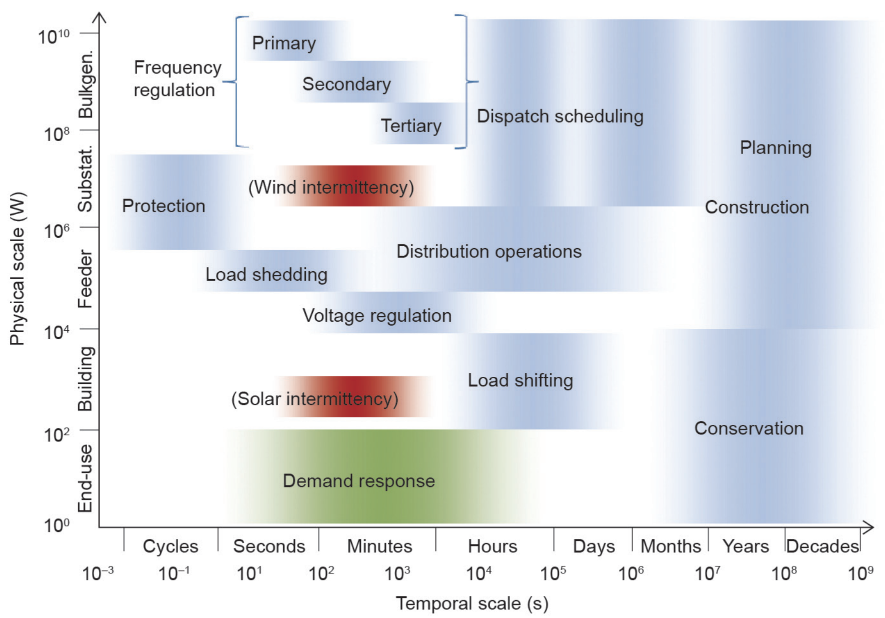

Figure 1. Temporal-scales for various electricity system processes.

※ A reservation price is defined as the price at which a resource will decline to participate. For a producer, this is a lower price constraint; and for a consumer, it is an upper price constraint.