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Modeling framework and validation of a smart grid and demand response system for wind power integration

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HIGHLIGHTS

- A modeling and simulation framework for a smart grid power system is provided.
- Results of a physical demonstration project are used to validate the model.
- Wind power is then introduced into the power generation mix of the validated model.
- Demand response has the potential to mitigate the impact of wind power variability.
- Traditionally passive loads become responsive and thus an additional resource.

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ABSTRACT

Electricity generation from wind power and other renewable energy sources is increasing, and their variability introduces new challenges to the power system. The emergence of smart grid technologies in recent years has seen a paradigm shift in redefining the electrical system of the future, in which controlled response of the demand side is used to balance fluctuations and intermittencies from the generation side. This paper presents a modeling framework for an integrated electricity system where loads become an additional resource. Agent-based modeling is used to represent a smart grid power system integrating generators, transmission, distribution, loads and market. The model incorporates generator and load controllers, allowing suppliers and demanders to bid into a Real-Time Pricing (RTP) electricity market. The modeling framework is applied to represent a physical demonstration project conducted on the Olympic Peninsula, Washington, USA, and validation simulations are performed using actual dynamic data. Wind power is then introduced into the power generation mix illustrating the potential of demand response to mitigate the impact of wind power variability, primarily through thermostatically controlled loads. The results indicate that effective implementation of Demand Response (DR) to assist integration of variable renewable energy resources requires a diversity of loads to ensure functionality of the overall system.

1. Introduction

Today's electricity grid is a complex system allowing the integrated generation, transmission and distribution of electrical power to consumers. The control of the generation end of the system has been a fundamental operation principle to ensure that demand is met reliably, but with the need to integrate increasing levels of renewable energy generation and reduce reliance on carbon intensive fossil-based electricity generation, an evolution of the grid and new strategies for dispatching power are required. The challenges and impacts of wind power integration, such as power system reliability, reserve requirements and additional costs, have been analyzed and summarized by IEA Wind R&D Task 25 [1]. In particular, the variability of wind power – and of other intermittent Renewable Energy Sources (RES) – is predicated largely by weather and environmental conditions that cannot be controlled. Within a traditional demand-side driven power system, large levels of renewable energy generation therefore require the deployment of additional operational and contingency reserves. In practice such reserves can often only be provided by complementary power generation infrastructures [2]; however, these incur significant additional capital and operational costs, which can reduce the intended environmental benefits [3]. An alternative strategy that offers the prospect of effective integration of renewable generation is to recruit demand side loads as *active* participants. A number of recent studies [4–7] have shown that the active manipulation of loads can support the integration of

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wind power while, at the same time, making the electrical power system more efficient and more reliable.

Broadly, demand side management strategies can be classified as direct load control [8,9] typically implemented as centralized utility-driven, Demand-Side Management (DSM), or price-based control Demand Response (DR) [10,11], where loads independently adjust their power demand in response to market price signals. Thus, the concept changes from utility-driven control to one involving participation of end-use customers in determining prices and clearing the market. Both Demand-Side Management (DSM) and Demand Response (DR) have the ability to provide ancillary service as an alternative to the traditional supply-side management (SSM) approach [12], but both present challenges. Demand-Side Management (DSM) requires robust load aggregation and control strategies and must overcome customers reluctance to relinquish control of their participating appliances. Demand Response (DR) requires effective market pricing and integration of price signals and load controls. The long term motivation for the present work is to assess the effectiveness of Demand Response (DR) in supporting grid integration of large levels of wind generation under different scenarios (generation mix and geographic locations). This requires the development of validated models that resolve appropriately essential characteristics of modern and evolving power grids and the coupling of the grid system model to market pricing models through practical control strategies.

This paper describes a general modeling and simulation framework which integrates and couples generators, transmission, distribution, loads and market comprising a smart grid power system. The model is then specifically applied to represent a field demonstration project conducted on the Olympic Peninsula, Washington, USA. The physical and simulated system relies on the recruitment of selected residential end-use appliances as additional grid resources within a smart grid architecture, and allows examination of how traditionally passive loads can become resources that mitigate the variability of wind energy in the electrical power system. Validation simulations are performed using real performance and temporal data from the Olympic Peninsula Demonstration Project, and results compared with actual system behavior over a period of 1 week. The validated model is then extended to incorporate wind power generation in conjunction with suppliers and demanders who bid into a Real-Time Pricing (RTP) electricity market. The goal of incorporating wind power into the model is to demonstrate that traditionally passive loads can become resources that are capable of mitigating the impacts of wind power variability. This will show that the behavior of thermostatic loads can be changed via a RTP mechanism without affecting the predetermined customers' comfort settings.

2. Power system modeling

An agent-based modeling environment was utilized for modeling a smart grid power system using the "open source" GridLAB-D™ simulation platform [13]. This general modeling framework includes a range of models and sub-models, including load models, market models, distribution and transmission system models, end-use and their coupled interactions within the overall system. The variety of component models within GridLAB-D™ and the array of user determined parameters and variables allows modeling and simulating a variety of complex electric power systems and scenarios, and is particularly well suited to exploring the integration of new energy technologies.

A number of other agent based models have been proposed to investigate electrical power systems in terms of power market interaction, grid congestion and environmental issues and are reviewed in [14]. None of these or other open literature studies [15–18] include detailed load modeling within an overall system context and therefore GridLAB-D™ was selected for the purpose of applying and validating the modeling framework presented in this paper.

The application of the model to solve the power flow problem within a 3-phase unbalanced system utilizing the Three-Phase Current Injection Method (TCIM) [19] for specific transmission and distribution scenarios is discussed in Section 3. This section focuses primarily on two general aspects of the model that have been further developed as part of this work: market modeling and end-use load modeling.

2.1. End-use load modeling

The electric end-use loads of any house can be divided into two major classes: non-thermostatic loads, such as lights and outlets; and thermostatic loads, such as Heating, Ventilation, and Air-Conditioning (HVAC) units, water heaters and refrigerators. Thermostatically controlled loads include some form of intrinsic storage, such as the thermal mass of the home or water in the tank. Therefore the loads service function will be maintained during power interruptions over a limited amount of time, without affecting user comfort.

HVAC systems and water heaters generally have a high potential for demand response, which is dependent on factors such as size of system and house, insulation, location, weather and the recent demand response history. Fig. 1 shows the average energy consumption for a single family residential house in the US, where space heating, air conditioning and water heating together account for 66% of the total energy consumption. Other household appliances, such as lights, have limited or no demand response potential as switching off those appliances would undermine the acceptable level of customer comfort.

The house model in Fig. 2 is based on the Equivalent Thermal Parameter (ETP) model. The ETP model determines the state and power consumption of the HVAC system while also considering the heat gain through the use of other residential appliance, and heat gain/loss to the outside environment as a function of weather. Other household loads were integrated into this model using physical, probabilistic, and time-varying power consumption models. These models are all available within the GridLAB-D development environment [21,22].

2.2. Market

The market model represents a double auction Real-Time Pricing (RTP) electricity market with sellers and buyers bidding into a common market. The basic market interactions are illustrated in Fig. 3.

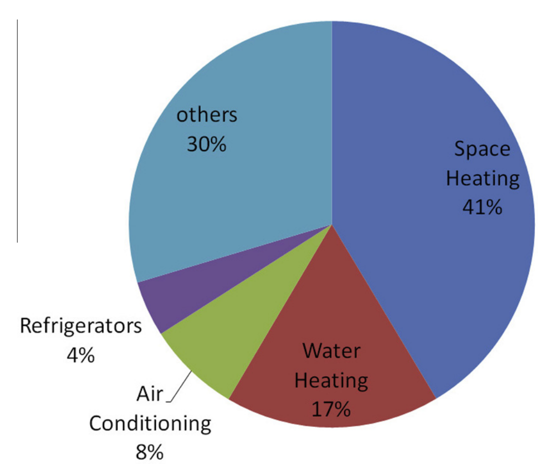

Fig. 1. Average energy consumption for a single family house in the US (data source:[20]).