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Agent-based modeling and simulation of a smart grid: A case study of communication effects on frequency control

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ABSTRACT

A smart grid is the next generation power grid focused on providing increased reliability and efficiency in the wake of integration of volatile distributed energy resources. For the development of the smart grid, the modeling and simulation infrastructure is an important concern. This study presents an agent-based model for simulating different smart grid frequency control schemes, such as demand response. The model can be used for combined simulation of electrical, communication and control dynamics. The model structure is presented in detail, and the applicability of the model is evaluated with four distinct simulation case examples. The study confirms that an agent-based modeling and simulation approach is suitable for modeling frequency control in the smart grid. Additionally, the simulations indicate that demand response could be a viable alternative for providing primary control capabilities to the smart grid, even when faced with communication constraints.

1. Introduction

A smart grid is the envisioned more flexible electricity network of the future. One motivation for the smart grid is the increase in distributed energy resources (DER), such as wind and solar power, which increase the power generation volatility (ENTSO-E, 2012). The increased volatility in power generation can lead to imbalances in produced and consumed energy, which causes frequency deviations in the grid. Large frequency deviations can subsequently lead to grid instability, which should be avoided at all costs. Future smart grid technologies are planned to enable managing inefficiencies in consumption and production of energy. However, appropriate control strategies must be devised and implemented in order to avoid adverse effects from communication latencies (US Department of Energy, 2010) and possible synchronization effects involved (Ramchurn et al., 2011).

One technique for countering this volatility is demand response (DR), meaning the ability to adjust the customer electricity consumption based on control signals. With smart grid-enabled DR, customers can participate in maintaining the balance between produced and consumed energy. This helps to ensure grid stability with the addition of DER (Finnish Energy Industries and Fingrid Oy, 2012), but can also be useful in mitigating other issues in power generation and distribution, such as line failures (ENTSO-E, 2012).

The purpose of this paper is to evaluate agent-based modeling and simulation (ABMS) as a method for studying balancing control in the smart grid. In addition to the producers of energy and the consumers, the communication infrastructure responsible for relaying the control signals and relevant information between the actors in the grid, is an important element which is integrated into the model. With a simulator based on the model, the effects of the communication latencies involved in controlling the frequency of the grid are investigated. The paper is structured as follows. Section 2 reviews related research concerning frequency control, communication, and agent-based modeling and simulation of the smart grid. Section 3 describes the agent-based model of the frequency control problem. Section 4 presents the results from simulations, followed by discussion and conclusions in Sections 5 and 6.

2. Related research

2.1. Frequency control of the smart grid

Frequency stability requires that the electricity grid is able to maintain a steady frequency even when the power production and consumption become imbalanced (Kundur et al., 2004). Without frequency control the grid may become unstable, as large frequency deviations can lead to generating units disconnecting and further imbalancing the system. This instability can eventually

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lead to large blackouts and damage to the physical equipment. Small variations in the frequency are dampened by the kinetic energy of the rotating motors connected to the grid (Rebours et al., 2007), but greater imbalances need to be compensated with the regulation of supply or demand.

Primary control is the mechanism used to limit the short-term deviation of the grid frequency and sustain the stability by varying the production of the generators dedicated to primary control (UCTE, 2004). The ENTSO-E (European Network of Transmission System Operators for Electricity) standards (UCTE, 2004) dictate that primary control reserves react to the grid frequency deviation by varying the generated power proportionally to the frequency deviation Δf according to the formula

$$\Delta P_P = K_P \Delta f, \tag{1}$$

where ΔP_P is the change in the generated power and K_P is the generator specific coefficient. However, this proportional primary control leaves a constant steady-state error to the system frequency. The constant power imbalance is removed with subsequently activated integral secondary and tertiary controls. According to the ENTSO-E standards, the primary control reserves must be fully activated in 30 s, where a 0.2 Hz deviation leads to a full activation. The correcting secondary controlled reserves are then activated within 15 min (UCTE, 2004).

With the communication and demand-side capabilities of the smart grid, at least a portion of the primary control can be realized by controlling the demand instead of the supply (Callaway and Hiskens, 2011). Demand side load balancing could enable faster, more efficient and more reliable balancing of the power grid compared to traditional primary control using large generators.

The basic control architectures for DR are the centralized and decentralized approaches. In centralized control, primary frequency control is provided by centrally controlling customer loads as a function of the grid frequency. An example of centralized control approach is presented by Shimizu et al. (2010), where electric vehicle charging rates are synchronized centrally to manage the grid frequency. Alternatively, in decentralized control, the loads measure the grid frequency independently and act according to their individual frequency thresholds, as presented by Molina-García et al. (2011). Some quality of service requirements for the required communication technologies has already been suggested (Gungor et al., 2013; Bouhafs et al., 2012), but more convenient models could be used to further inspect the effects of communication latencies on frequency control.

2.2. Communication in the smart grid

Extensive communication is a distinguishing factor between the smart grid and the traditional electric grid. Providing this communication is a significant technical challenge (Bouhafs et al., 2012). Communication in the smart grid is generally conceived as a heterogenous communication infrastructure utilizing existing networks and technologies (Gungor et al., 2011; Zaballos et al., 2011). Particularly in centralized control, all these communication media are relied on to transmit the control signals between the central controller and the associated energy resources. Thus, the properties of the communication infrastructure, such as latency or potential packet loss, are a significant constituent in centralized frequency control of smart grids (Lu et al., 2013). Furthermore, the use of existing networks and particularly the Internet, for communication, raises security concerns which must be addressed in smart grids (Wang and Yi, 2011).

Simulations of smart grids generally include some simulation of the communication infrastructure. Communication can be modeled at various levels of authenticity, spanning from constant zero delays to statistical modeling of individual communication technologies. These statistical models can take into account such features as latency, network congestion, packet loss, or packet duplication. For the most comprehensive and accurate simulation of communication, a specialized communication network simulator may be integrated to the smart grid simulation (Mets et al., 2011).

2.3. Agent-based modeling and control of the smart grid

A popular approach for modeling smart grids is to build upon existing electric and communication simulation frameworks, such as PSCAD/EMTDC (Hopkinson et al., 2006), OpenDSS (Godfrey et al., 2010), OMNeT++ (Mets et al., 2011) or NS2 (Nutaro et al., 2008). This allows existing simulation libraries and algorithms to be employed, and thus possibly reduces the effort needed for model implementation. For example, Lin et al. (2011) present a versatile co-simulation model that takes into account the synchronization of both the electric and communication dynamics.

In contrast, agent-based models have recently been applied for modeling smart grids (Conzelmann et al., 2005; Karnouskos and De Holanda, 2009; Lin et al., 2011). Likely because the decentralized and potentially co-operative nature of the consumers in DR highlights the potential of ABMS as a method to model and simulate the smart grid (Zhou et al., 2011). In addition, the communication framework with sophisticated varying latencies is naturally suited for ABMS (Borshchev and Filippov, 2004). Agent-based modeling of smart grids has however been mostly limited to electricity markets (Weidlich and Veit, 2008; Zhou et al., 2011; Conzelmann et al., 2005) and control strategies related to load shifting in long time scales (Callaway and Hiskens, 2011). In addition to the modeling and simulation of smart grids, agents have been introduced to control algorithms, e.g. in self-healing control under fault situations (Liu et al., 2012).

Simulating and modeling DR using ABMS have seen various efforts, including PHEV (plug-in hybrid electric vehicles) (Galus and Andersson, 2008) and residential appliances (Ramchurn et al., 2011; Karnouskos and De Holanda, 2009). However, agent-based modeling and simulation have not been thoroughly investigated in smaller time-scale frequency stabilizing control scenarios. In addition, the frequency control and demand response simulations presented in the literature have very simplistic models of communication dynamics, such as discrete packet delays (Bhowmik et al., 2004). This is likely because they are mainly focused on load shedding during daily power demand peak moments, where the time scales are such that the effects of communication tend to be negligible. However, in short-term outage management scenarios when following the ENTSO-E primary control standards, the varying delays in the communication infrastructure between the loads and central control stations are a significant part of the total response time (Moslehi and Kumar, 2010) and may become an issue for the performance (US Department of Energy, 2010).

3. Agent-based modeling of frequency control

3.1. Modeling approach

ABMS is a paradigm suited for modeling systems with multiple decision-makers that interact with each other (Macal and North, 2010). These kinds of systems are referred to as complex adaptive systems (CAS) (Miller and Page, 2010). CAS often exhibit complex behavior arising from the low-level interactions and behaviors of the decision-makers, which makes them generally difficult to model using traditional methods. ABMS allows this complex behavior to be reproduced without having to construct explicit models of the system.

In ABMS, agents are used to represent the decision-makers in the smart grid, such as plant operators or intelligent control