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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

$$\Delta P_P = K_P \Delta f, \qquad (1)$$

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

Table 1
A taxonomy of entities in an ABMS model of the smart grid.

Entity	Properties and functionality	Examples
Agent	Communicates with other agents, affects the environment, makes control decisions	System operator, consumer, power plant
Electrical device	Electrical dynamics	Generator, relay, electrical appliance
Communication link	Deliver messages between communicating agents, includes communication dynamics (especially latency)	Powerline communication, 3G, Ethernet
Grid	Connects electrical devices, transmits electricity	Transport link, abstract grid (non-spatial)
Environmental influences	Outside sources which affect the environment and the behavior of the agents	Weather, demand patterns

programs. The purpose of the agents is to reproduce the behaviors of real world decision-makers in the smart grid. In order for the agents to have a realistic operating environment, the relevant dynamics of the system are replicated by a different part of the model called the environment entities. These entities represent the environment of the agents, for example, the electric grid, communication channels and electric devices belonging to the smart grid.

According to ABMS, a model is constructed by describing the types of agents and environment entities in the system and how they interact with each other. When the model is executed, each agent and environment entity act in turn according to the behavior rules defined by the modeler.

3.2. Model structure

The ABMS model of smart grid defined in this paper consists of the agents and the environment, which is affected by the agents and various environmental influences. An example of how the smart grid can be described using these model entities is shown in Table 1. The first column of the table identifies the organization of the model entities that constitute the smart grid. The second column identifies the prominent properties and functionalities that characterize each of these entities. The third column lists some concrete examples of each entity.

The model consists of three types of agents, their decision logic and the environment which they affect. The model entities are illustrated in Fig. 1. The grid environment is represented by a grid entity, which calculates the grid frequency based on the power production and consumption of all the electrical devices in the model. The model is designed to cover studying of frequency control scenarios with different control approaches. The control approaches are studied in a situation where a large generator unexpectedly disconnects from the grid, leaving a large imbalance in generated and consumed power. The frequency can be stabilized using either a smaller generator, centralized DR or decentralized DR, which are scaled to represent equally large power reserves. The stabilizing generators are modeled using power plant agents, which contain a generator entity and a simple decision logic that operates them.

The demand response is modeled using a virtual power plant (VPP) agent that provides a number of consumer agents with additional information. The VPP represents a centralized control system that has a communication link to all the consumer agents and a decision logic that induces the desired control behaviors in the consumers. The consumer agents model the control of house temperature control systems, and they comprise a controllable electric heater, a house temperature model and a control logic. The control logic is used to influence the environment through the electric heater. The heater affects the house temperature and the grid frequency, respectively. In the centralized control scenario, the VPP is responsible for controlling the power consumption of the consumers. Alternatively in the decentralized scenario, the VPP allocates the separate control parameters to each consumer so that their combined behavior is similar to the centralized control situation.

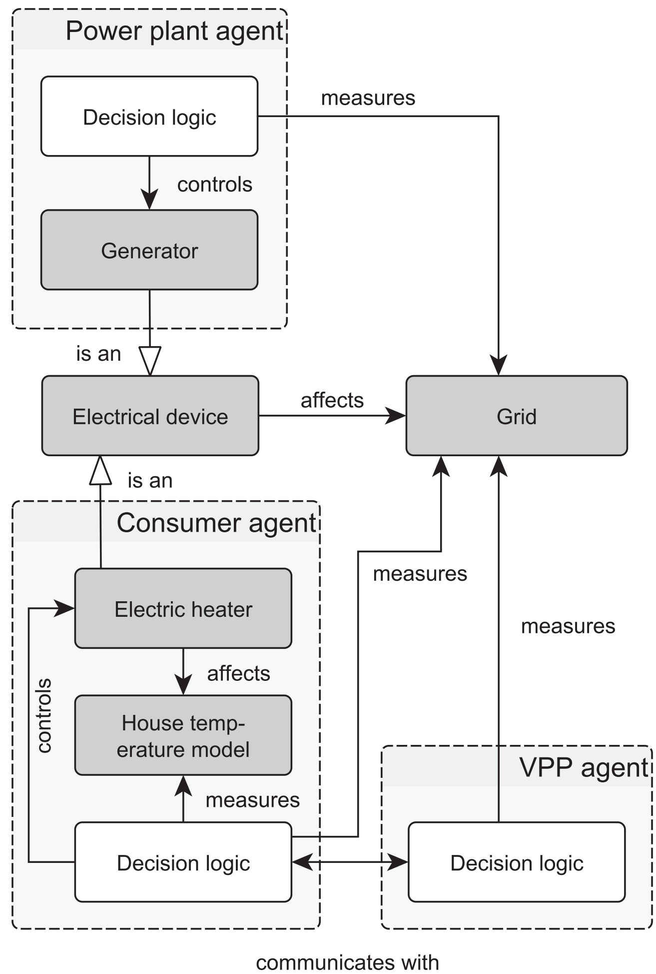

Fig. 1. A class diagram illustrating the most relevant model entities and their interconnections.

Simulations with the model are run with the help of an underlying discrete-event scheduler that schedules the order of simulation events, such as updating the grid frequency, arrival of a message or action made by an agent. The scheduling logic in the developed simulator is similar to the one presented by Lin et al. (2011). Agents react to messages by determining appropriate control actions according to their control behaviors. These are modeled as procedures of decision logic which are different for each agent type, i.e. VPP, power plant and consumer agents. Control behaviors also require communication with other agents. Details of modeling agent behaviors and their effects on environment entities are presented in subsequent sections.

3.3. Thermal and electrical effects

The electrical devices in the model consist of electric heaters and power generators. The heater is either fully on or fully off, and is primarily controlled by a simple thermostat that aims to maintain the house temperature within set limits. However, the consumer decision logic can override this control and set the heater to either state if needed. The consumer agent is a model of the thermostat decision logic and through its electrical device affects the grid frequency.

The house temperature is modeled using discretized first-order dynamics, adapted from Mortensen and Haggerty (1988),

$$T_t = e^{-(dt/\tau)}T_{t-1} + (1-e^{-(dt/\tau)})(T_a + G_h P_h) + \nu_t, \tag{2}$$

where T_t is the internal temperature at time t, dt is the simulation timestep, τ is the time constant of the house, T_a is the ambient temperature, G_h is the heater temperature gain per unit of power, P_h is the heater power and ν_t is a Gaussian white noise process. In practice, the house thermal dynamics contribute marginally to the simulation results due to the short simulation runs conducted in this study. In this model, the time constant of a house was approximated to be 24 h and the temperature gain was approximated to be 10 °C/kW.

Likewise, the generators are simplified and modeled also using discretized first-order dynamics

$$P_t = e^{-(dt/\tau)}P_{t-1} + (1-e^{-(dt/\tau)})P_{ref}, \tag{3}$$

where P_t is the generator power at time t, dt is the simulation timestep, τ is the time constant of the generator and P_{ref} is the power reference value given by the proportional control. In this model, only the dynamics of the primary control generator are relevant, as the failing generator is cut down from the grid instantaneously. The time constant τ of the primary control generator is approximated to be 8 s.

The electric grid is the environment in which the electric devices interact with each other. The composite frequency dynamics of the whole grid are taken into account with the simplified model:

$$\frac{2W_k}{f_n}\Delta f'(t) + K_\nu \Delta f(t) = \Delta P_G + \Delta P_{DR} - \Delta P_L, \tag{4}$$

which includes the kinetic energy W_k, the nominal frequency f_n and the self-regulation of the loads K_ν in the grid (Elovaara and Haarla, 2011). The system under consideration is the Nordic power grid for which the values for the factors involved are $W_k = 110$ GWs (Fingrid, 2012), $f_n = 50$ Hz and $K_\nu = 1000$ MW/Hz (Elovaara and Haarla, 2011). Additionally, the model includes the power generation and demand in the form of change in power generation ΔP_G, change in demand response ΔP_{DR} and ΔP_L as the change in load power. The resulting deviation of the grid frequency is denoted by Δf.

3.4. Communication behaviors

Fig. 2 illustrates communication between agents. Agents are connected through unidirectional communication channels that are instances of a communication technology. The communication technology consists of the sending and receiving devices and the network connecting them. Each communication technology has a model for channel reliability, permitting the modeling of packet loss as latency or total loss, and a model for channel and communication base latency. These models reflect the stochastic nature of latencies and packet loss in real-world communication networks, and can cover congestional, as well as, computational latencies. Messages sent over the communication channel are turned into scheduled events, notwithstanding possible packet loss. Scenarios comparable to packet loss could occur in the case of communication channel outages, and the resulting communication link switching. The message incurs a delay drawn from the latency model of the communication channel. After the delay, a message event is invoked in the receiving agent. In addition to the stochastic properties of the communication channels, most scheduled events include a slight, for example, 5% inaccuracy, in their delay. Hence, on consecutive simulation runs, two events with an equal delay are eventually invoked in a non-deterministic order. Furthermore, latencies other than the actual propagation of the packets, such as related to the processing and queuing of packets have been augmented to the communication channel.

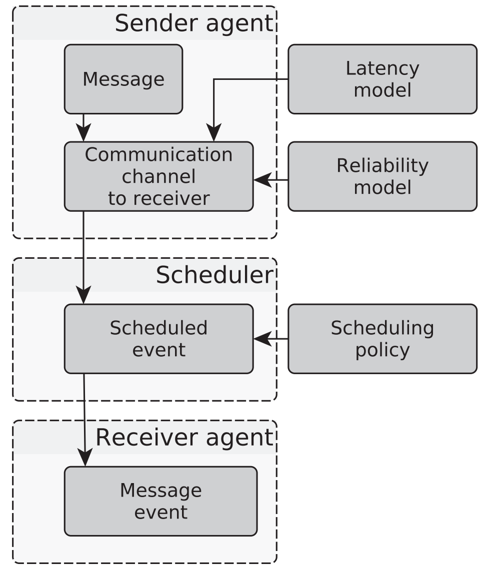

Fig. 2. Message transmission between agents through their shared communication channel and scheduler by the scheduler.

The communication channels support comprehensive modeling of latency. With unidirectional channels, bidirectional communication can be symmetric or asymmetric, for example, broadcast over the electric grid and response over the Internet. Low latency reliable communication channels, such as local Ethernet connections, have practically zero latency with very little variation. On the other hand, unreliable wireless communication can exhibit highly variable latencies and possible retransmissions. For simulating reliable communication, such as that over the TCP protocol, latencies can be drawn from two or more distributions to cover the possible retransmission of packets.

3.5. Control behaviors

In the examined system, the VPP governs a set of consumers and keeps a list of their nominal power, operation state (on or off) and willingness to change state. The willingness is indicated by a real number ranging from 0 to 1, where '1' indicates the device is very willing to change to 'disabled' and vice versa. To implement frequency control, the VPP measures the grid frequency and communicates to a required amount of loads to turn on or off proportionally to the frequency deviation. The loads are controlled in the order of their reported willingness. In case the decentralized control approach is used, the VPP distributes a randomized set of frequency thresholds to the loads. These thresholds are linearly distributed so that the combined shedded load is equivalent to the proportional control defined by ENTSO-E (UCTE, 2004). The randomization is implemented to avoid synchronized reaction to frequency fluctuations.

The control behavior of the electric heaters in consumer residences is modeled as consumer agents, as seen in Fig. 1. The heater can be controlled remotely by the operating VPP or in a decentralized manner by the consumer. In centralized control, the consumer agent receives control and query messages from the VPP agent, which models the aggregating virtual power plant. The control messages can force the device 'enabled' or 'disabled', or change the frequency threshold used in decentralized DR. The query messages are responded with a message that includes the agents' operation state and willingness to change it. The willingness is determined based on the proximity of the thermostat temperature to the upper temperature threshold. In decentralized control, the electric device agents locally sense the grid performance and act on it independently. When the individual frequency threshold is exceeded, the consumer switches the operation state of its heater correspondingly.

4. Simulations

The feasibility of the previously presented agent-based modeling and simulation method was analyzed through simulations based on the model presented in the previous section. Four different experiments were conducted on the model. The investigated scenarios cover different control alternatives under several communication and simulation parameter variations:

Case A compares traditional primary control reserve activation from a power plant, DR and lack of control.

Case B covers centralized DR with two different communication parameters and decentralized control.

Case C examines the sensitivity analysis performed on the communication channel parameters.

Case D demonstrates the effect of the number of consumer agents used for DR.

4.1. Simulation setup

The simulation platform to evaluate the detailed agent-based model was coded from the ground up in C++. The implementation includes simultaneously the scheduling of the thermal and communication dynamics of the system. The main investigated scenario with the simulation framework is the detachment of the largest allowed power plant in the Finnish grid (1650 MW (Fingrid, 2012)). The power generator is detached at $t=2$, which activates the primary frequency control. The effects of secondary and tertiary control are omitted in this short-term simulation. This drastic step response is used to evaluate the possible problems due to communication dynamics when stabilizing the frequency with DR.

The primary reserves are modeled with a single plant able to activate 1400 MW of primary reserves in response to the deviation of 0.2 Hz in the system frequency. The plant follows first-order dynamics with a time constant of 8 s and thus the proportional control gain K_P is defined as 7617 MW/Hz.

Alternatively, the primary control is fully handled by controlling the demand side consumer loads. The combined maximal power of controllable loads is set to 2000 MW for studying the feasibility of providing primary control using the consumer loads. In practice, most of the primary control would be dedicated to the traditional reserves. In the beginning of the simulation, the power grid is assumed to be balanced. Each consumer agent is connected to the VPP by a communication link with individual parameters drawn from a suitable normal distribution. The thermal loads are initialized with randomized values, averaged at their equilibrium state assuming constant weather conditions.

4.2. Simulation results

Case A compares the centralized DR to traditional control and control failure. The simulated grid frequency deviations are shown in Fig. 3. Without any correction in production or load shedding when the power generator is disconnected, the frequency deviation soon falls below acceptable levels (-0.8 Hz (UCTE, 2004)), and settles at -1.6 Hz. In case a traditional power plant is used for proportional control, the system frequency deviation settles after some slight oscillation at the expected -0.2 Hz. Using demand response with similar proportional control, the system reaches the settling frequency faster due to the more immediate nature of the devices.

Case B compares the decentralized DR control to two implementations of centralized DR control using GPRS communications with and without packet loss. In the case of packet loss, 20% of the sent messages never reach the recipient. The frequency deviations illustrated in Fig. 4 show that decentralized control exhibits the best behavior with no oscillation, whereas with centralized control the frequency tends to oscillate. This can be explained by the delays incurred in centralized control. The particularly good behavior of the system under decentralized control can be explained by the fact that the sensing and response to the frequency variations can be implemented without any of the latency involved with communicating the control or measurement signals over various channels. With packet loss or similar long reception delay, the frequency can be seen to oscillate slightly more and settle at a slightly lower frequency. The frequency deviation is explained by the fact that the control algorithm is based on the assertion that each control message is always

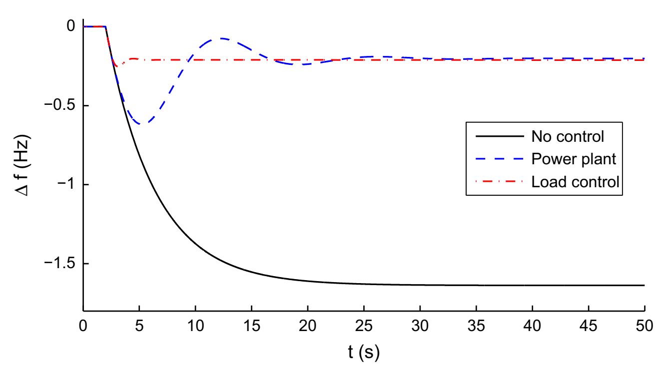

Fig. 3. *Case A*: Power grid frequency behavior without control, with a conventional power plant and demand side load control.

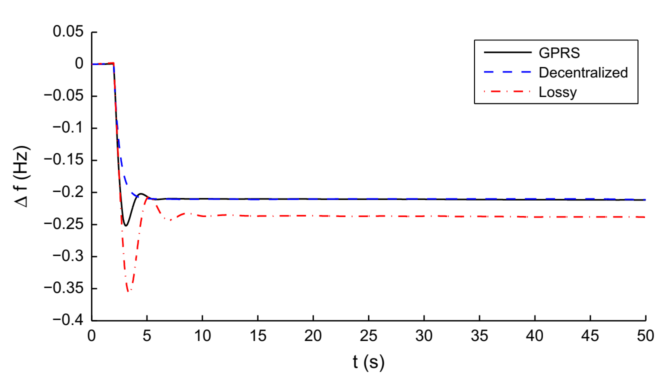

Fig. 4. *Case B*: Power grid frequency behavior with demand side load control using GPRS for communication and using decentralized control.

delivered, which is now not the case in the surveyed time frame. It should be noted that the grid is not unstable in any of the presented configurations. The 200 mHz deviation is later compensated with secondary and tertiary control.

Case C considers the sensitivity analysis with respect to the communication channel parameters. As the parameters used for the communication channels are only approximations, it is interesting to know how the results would vary with slightly different parameter values. This was studied by running 1000 simulations, where all the parameters for each communication link were varied randomly between $\pm 50\%$ of their nominal values. The resulting distribution of frequency deviation curves is shown in Fig. 5. Apart from different levels of oscillation, varying the parameters beyond their approximated values does not result in radically different behavior.

Case D demonstrates the effect of the number of consumer agents used for DR. In these simulations, a VPP with 100, 1000 and 10,000 consumers is used for control with an aggregate control potential scaled to a same value, and simulated 1000 times with different initial seeds used for random processes. The results in Fig. 6 show that the number of oscillations, and especially variation between individual simulations diminishes, when the number of load agents is increased. While using only 100 simulated loads (Fig. 6(a)), there is significant variation between the simulations but the grid is not driven unstable. When the number of loads is increased to 10,000 (Fig. 6(c)), the system exhibits unified behavior, even though the individual agents may experience, for example, varying communication delays. Thus, the results indicate increasing predictability of control when the number of loads is increased.

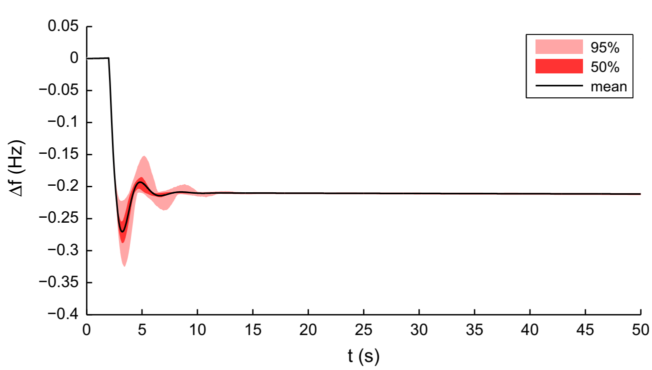

Fig. 5. *Case C*: Power grid frequency behavior when varying the GPRS communication channel parameters $\pm 50\%$.

5. Discussion

The main purpose of this research was to evaluate the method of agent-based modeling and simulation, for studying the balancing control of the smart grid. This study differed from the previous related studies, such as by Lin et al. (2011), in the aspect that the model was constructed without relying on external modeling frameworks. This approach was motivated by the independence of this model from any particular modeling framework and the possibility to choose exactly which aspects are included in the model and how they are simulated. Furthermore, this study focused on presenting a feasible agent-based model for simulating smart grids, instead of solving issues with framework integration. Nevertheless, it should be possible to integrate external frameworks into the model presented in this paper, as many successful comparable integration projects have already been reported in the literature (Hopkinson et al., 2006; Godfrey et al., 2010; Mets et al., 2011; Nutaro et al., 2008).

As the model is constructed in a modular way, it could be expanded in the direction of, for example, electricity market simulation. Many of the existing features could remain intact, such as the electrical and communication dynamics, whereas new dynamics would have to be introduced for marketplaces and bidding logic.

In addition, the supplementary objective of simulating effects of communication latencies was explored. The simulation cases cover a variety of communication scenarios which indicate that communication dynamics with realistic worst-case parameters have only a minimal effect on the grid frequency transients. The large number of interacting agents can be seen as a factor resulting in unified and composed behavior, as seen in Fig. 6. In addition, the kinetic energy of the grid resists the faster oscillations and decline of the grid frequency. However, to further investigate the effect of communication dynamics on frequency control, more simulation studies with different scenarios and possibly more refined models could be required.

The electric and communication dynamics were approximated with rather simple equations. This was because highly accurate dynamics were not deemed necessary for demonstrating the feasibility of the modeling approach itself, or the most prominent features of the system under study. The dynamic models could be changed into more complicated ones if necessary. This was considered to be an important feature in the implemented model as the DR is likely to cause several challenges requiring further research. From the electric grid point of view, voltage stability, component overloading, and the DR effect on the grid losses are relevant issues requiring more complicated models. In addition, the frequency stability focused in this paper could be studied with

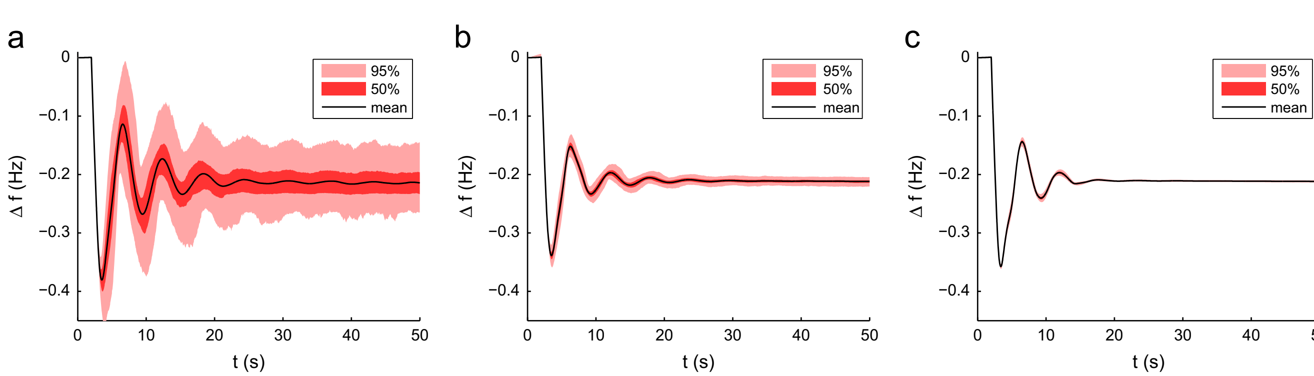

Fig. 6. *Case D*: Effect of number of simulated loads on the frequency behavior with 1000 simulations in varying communication conditions. (a) $N=100$, (b) $N=1000$, (c) $N=10{,}000$.

more detailed grid dynamics. However, the primary control has relatively slow performance requirements, which is why the approximate grid dynamics was considered to be sufficient for the purposes of this study. Including load-shedding and other supportive procedures, would mitigate the role of the DR as the frequency controlled reserve.

In practice, the DR specified in the paper can be realized by implementing the intelligent electronic devices capable of controlling the loads either remotely using communication with a central controller or locally using frequency measurements. Currently, the DR programmes in progress are mainly limited to industrial loads but consumer participation is expected to be increasing in the near future (Torriti et al., 2010). Some consumer devices already exist in the market, which have the ability to react to price or other control signals in order to offer more optimized performance for all parties involved.[1]

Some practical issues with DR were not considered in this study. For example, when controlling consumer loads directly, the effect on customer satisfaction should be taken into account. However, as in this study the house thermal dynamics are slow compared to the simulation case duration, the effects of this kind of control should be negligible. From DR control perspective, further research would be required to study the limitations caused by a limited and varying amount of total controllable power and the possible effects of a postcontrol “recovery peak”.

6. Conclusion

This paper presented an agent-based model that can be used for modeling frequency control scenarios in the smart grid. The model is designed for reproducing system-level behaviors in the smart grid by implementing sufficiently accurate models of the relevant bottom-level behaviors. The main components of the model were presented and the function of the model was studied through four separate simulation case examples, where frequency control efficiency was studied after an unexpected power plant failure. The simulation model could be used to derive clear and understandable results that can be used to analyze the control system under study. These results indicate that the proposed agent-based modeling approach is functional for modeling frequency control in the smart grid and could be expanded to include additional aspects of smart grid operation.

In addition, the simulation study did not indicate that modern communication architectures would be a bottleneck for the implementation of virtual power plants that organize demand response, as even with realistic worst-case communication links, the grid frequency could be kept stable with acceptable transients. The sensitivity of the control was studied by running a large amount of repeated simulations with varying parameters, but no cases of instability were observed. These results further indicate that demand response, especially if organized in a decentralized manner, could be a viable alternative, in terms of the communication involved, for providing primary control capabilities to the smart grid. Additional research could be carried out by expanding the agent model to include the effects on the local voltage of the grid, regarding line losses and possible inverter-to-inverter oscillations Lehnhoff et al. (2013) in a grid with more complex topology.

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