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A simulator for the control network of smart grid architectures

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ABSTRACT:

We present an extensible simulation framework that has been developed to facilitate research on smart data exchange in power grids. Smart grids integrate traditional power grid technologies and information and communication technologies to generate, transport, distribute and consume energy in a more efficient manner. The framework not only incorporates the main power grid characteristics, but also explicitly models the communication network and control entities. Thus we enable the study of realistic implementation approaches to coordination mechanisms for smart grid applications. These coordination mechanisms are required for example to balance demand and supply, especially considering energy originating from renewable energy sources. We illustrate the design of the simulator with a use case in which the integration of electric vehicles in the distribution grid is managed.

INTRODUCTION

The power grid is evolving into a smart power grid, where power systems and information and communication technology meet in order to generate, transport, distribute and consume energy in a more efficient manner. Distributed generation and storage, smart meters and electric vehicles are examples of influencing technologies, but this evolution is not only motivated by technological aspects but also by regulatory aspects such as the liberalization of the energy market. Smart grids will also support new and innovative business models and services.

Distributed generation, especially based on renewable energy sources, is a driving force behind the evolution towards smart grids. Transport losses can be reduced by placing generators in the distribution network or at the customers' premises. We become less dependent on the limited fossil energy sources due to the utilisation of renewable energy sources, which have the added advantage of lowering green house gas emissions. Although distributed generators offer many benefits, there are still some problems associated with them [1]. The distribution grid is not designed to support distributed generation. Connecting distributed generators to the distribution grid leads to changes in the fault-currents, possibly requiring changes in existing protection systems. Power flow in the distribution grid used to be one-directional, but due to the integration of distributed generation, power flows are bi-directional. Distributed generation based on renewable energy sources offers additional difficulties in generation planning due to their unpredictability and variability. Electricity supply and demand have to be balanced, but this is complicated by the unpredictability and variability of renewable energy. We can see that management of these distributed energy resources is required to assure optimal and reliable operation of the power grid

The rising electrification of transportation is apparent when considering the (hybrid) electric vehicles which are already available on the market. The following years, even more electric vehicles will find their way to the market, for example in the form of Plug-In (Hybrid) Electric Vehicles (PHEV) which is the successor of Hybrid Electric Vehicles (HEV). They will result in additional demand on the power grid because they are charged with electricity from the power grid, which is stored in the vehicle's batteries and afterwards used as an energy source for the operation of the vehicle. This additional demand could have a negative impact on parts of the power grid when not managed correctly. For example voltage or frequency variations could occur [2].

Security, privacy, reliability and robustness are important aspects concerning power grid operations. The deployment of smart grid technologies can give benefits in these areas [3]. Fault detection and restoration can be automated, leading to faster response time and less risk of human operator errors. The smart grid will give access to enormous amounts of data, including personal information related to energy consumption such as owned appliances, time of use of certain appliances, etc. This gives rise to questions concerning privacy and security, which are therefore also active topics in smart grid research. Other topics related to smart grids include impact assessments, business models, legal and regulatory issues, power electronics, user research, etc.

The focus of this paper and our research in general is targeted at the application of information and communication technologies in smart grids. In this paper we discuss a simulation framework for smart grid applications that is used to develop and evaluate control strategies and networks, ICT architectures, etc. The use of a simulator has many advantages such as ease of use and flexibility.

The rest of this paper is organized as follows. First we discuss the simulation framework, especially the requirements, design and operation. Second we discuss a use case illustrating the workings of the simulation framework. Third we conclude this paper with a summary and conclusion.

SIMULATOR

Requirements

An extensible simulation framework is being developed to facilitate research on smart data exchange in power grids. The first requirement is to provide a framework supporting the development of control strategies and their corresponding software architectures targeted on energy management. Different approaches are supported for the development of these software algorithms and architectures: multi-agent systems, client-server systems, etc. The second requirement is to enable users to analyze the communication requirements and the impact of communication technologies on the control strategies. The third requirement is to simulate the impact of the control strategies on the power grid and to support the integration of electrical devices with the simulation framework. We require the ability to model the power grid at different scales: transmission, distribution, residential, etc. The fourth requirement is modularity and flexibility. Power grid and communication network topologies have to be easily adaptable and different control strategies have to be evaluated. These requirements support evaluating the interdependencies between the different facets of smart grids.

Design

The simulation framework is based on an open source discrete event simulator, OMNeT++ [4]. Many components and features from the OMNeT++ simulator can be reused; hence we can focus on developing proper models, algorithms and architectures targeted at smart grid applications. It has a modular design and many features are provided such as data logging, visualization, statistics, random data generation, etc. These components are integrated with the Eclipse IDE which enhances usability.

The simulation framework allows simulating the management and control strategies, the communication network and the power grid. In order to do this, the smart grid simulator defines a layered architecture. The layered architecture supports decomposing the system and groups similar responsibilities. Low-level features are reused and abstracted from the user. Layers can also be changed without influencing the other layers which enhances the modifiability of the system. We identify three main layers: application, ICT and support layers. The support layer is composed of two components: the network and electrical components. This layered architecture is illustrated in Fig. 1.

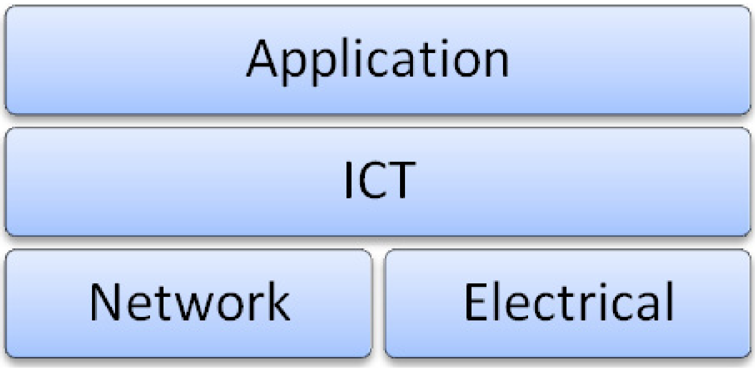

Figure 1, Simulation Framework Layers

High level applications and services are implemented in the application layer. Examples of such services are real time energy monitoring, demand side management or billing. These applications use the functions provided by the ICT layer, which provides generic functionality that can be used by any service. This includes communication features that work independent of the underlying physical medium (e.g. ZigBee), discovery of devices or energy management services, etc. The support layer, composed of the network and electrical components, also provides support functions for the layers above. Communication between services is made possible by the network layer that provides communication modules for multiple physical media and makes simulation of communication using a variety of technologies possible. An essential requirement is the possibility to model and interact with the simulated power grid and (virtual) electrical devices, which is enabled by the electrical layer. Virtual devices only exist as models in the simulator and have no physical counterparts linked to the simulator. Physical electrical appliances can be connected to the simulator if a driver is provided in the electrical Layer. The electrical layer not only also allows to model individual appliances, but also the whole power grid. It provides functionality to determine the topology and status of the power grid, enabling users to calculate for example power flows.

Operation

This section discusses how the simulation framework is used. The advantage of the simulation framework is that the power grid as well as the communication network and coordination services can be simulated simultaneously, supporting e.g. the assessment of the interdependencies between them.

We provide models for common components such as transformers, transmission lines, generators and loads, enabling the user to model the basic components of the power grid. These models can be adapted and extended, or new models can be added to the simulator. Similar models based on existing OMNeT++ frameworks (e.g. INET) are provided to model the communication network.

The simulator has a modular design in which different components communicate using messages. Due to this modular and message based approach, different use cases can be easily implemented by combining the necessary modules, requiring none or minimal changes to existing components. In order to do so, the topology of the control network, which consists of the communication network and control entities, and the power grid can be modified, allowing the user to analyse and compare different network architectures. The configuration of the simulator is done with configuration files. The power grid and communication network topology can be easily changed using these configuration files. Control algorithms are implemented in energy management services and the user can define which specific energy management services have to be used during a simulation. Changing a service implementation is accomplished by changing a parameter in the configuration file.

Simulation data can be logged, visualized and analysed using tools provided by OMNeT++, but the data can also be exported to other applications such as Matlab or Octave. The simulations can be executed in a graphical user interface, but this is not necessary. The graphical user interface gives a visual overview of the simulated power grid and communication network topology and the messages being exchanged between the modules. Simulation parameters and variables can also be watched, giving insight in the workings of a certain simulation. These properties make the graphical user interface especially suited for demonstration and debugging purposes. Overall, the simulator is flexible in its usage and can be easily extended and adapted to new use cases as a result of the aforementioned properties.

USE CASE

The use case illustrated in this section is concerned with the integration of Plug-In Hybrid Electric Vehicles in the distribution grid and is based on earlier work [5]. We illustrate how the charging process of these vehicles can be managed and how this is supported by the simulation framework. Managing the charging of the vehicles consists of determining the time at which charging is allowed and the charging rate.

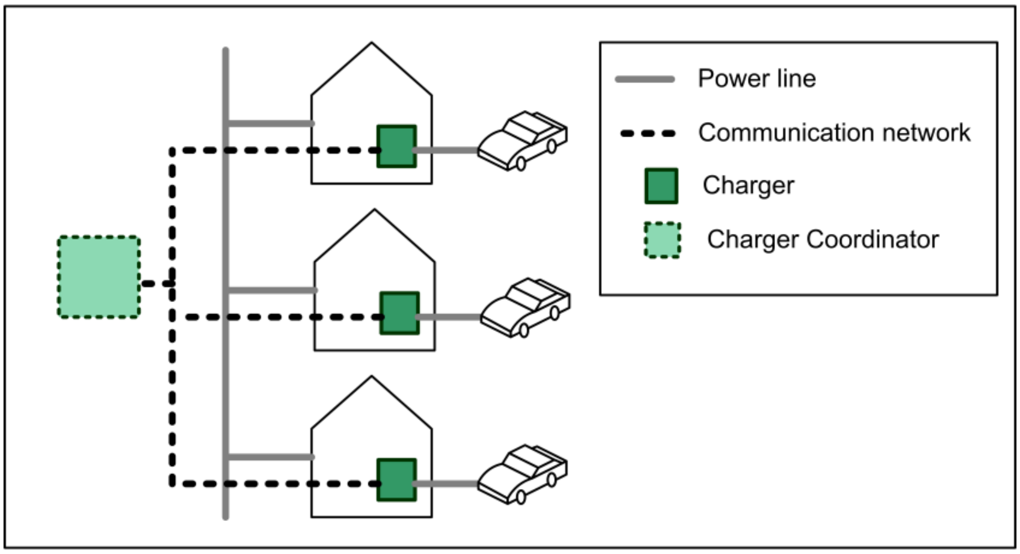

Figure 2, Use Case: Integration of Electric Vehicles

Consider the smart charging scenario illustrated in Figure 2. The charging process of multiple vehicles is coordinated by a central coordinator. The goal of this coordinator is to reduce the overall peak load, but other optimization goals are also a possibility. In order to do so, the coordinator determines for each vehicle a charging schedule that includes the times of charging and the rate at which charging happens. This decision is based on the charging schedules of other vehicles, their impact on the power grid load and existing loads which can not be controlled. Each house has a smart charger that communicates with the coordinator, hence a communication network is required.

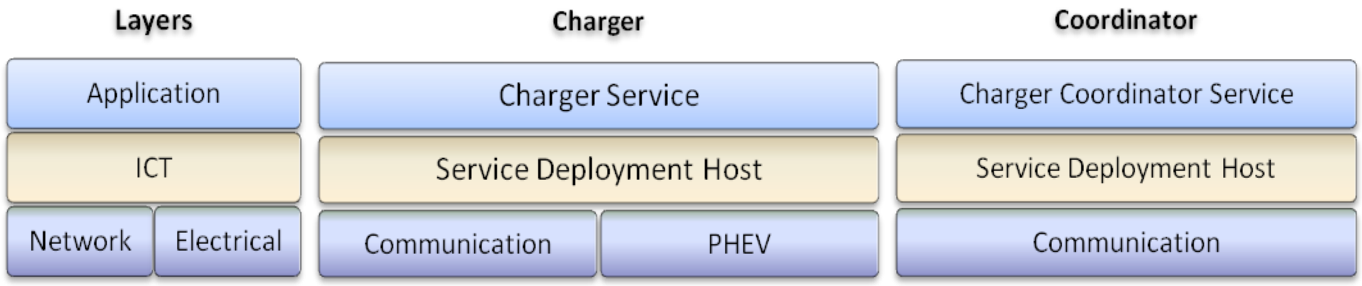

Figure 3, Architecture: Electric Vehicles Use Case

Figure 3 illustrates the architecture with the high level components and the layers to which they belong. We can see the three layers discussed earlier. The Charger Service manages the charging process at the consumer side based on information provided by the coordinator. The Charger Coordinator Service coordinates the operation of multiple Charger Services. The Charger component could reside in a smart charger pole or in the vehicle itself. The Coordinator component could reside in the utilities network. These services are both part of the Application layer as they contain the intelligence of the system. The Service Deployment Host is part of the ICT layer and gives access to the available communication channels and devices, in this case a Plug-In (Hybrid) Electric Vehicle, while hiding low-level issues from the user. The Coordinator is not linked to a specific device, but is solely responsible for the coordination of the different Charger services, so no components from the electrical layer are present. The Charger and the Coordinator both need a communication network to interact with each other.

Simulation Results

We simulated a residential area of 150 homes with a PHEV adoption rate of 10% and 60% over a period of 24 hours to determine the impact of the smart charger discussed in the previous section. Each PHEV has a battery capacity of 16 kWh and a maximum charging rate of 4.6kW. The charging schedule for each PHEV is determined upon arrival at home. The results from these experiments are shown in Figure 4 and Figure 5. Each figure shows the total load in three scenarios. During the first scenario there are no PHEVs present. During the second and third scenario PHEVs are present. There is no control or coordination in the second scenario, PHEVs start charging at a fixed rate upon arrival at home. The charging is controlled and coordinated during the third scenario. Charging PHEV raises power consumption with 6% and 40% respectively. A 60% PHEV penetration may lead to almost 2 times the peak load compared to the scenario without PHEVs. Hower by controlling and coordinating the charing of the PHEVs, this peak load can be reduced by 42% and the load pattern is more constant. This is achieved by shifting demand in time and controlling the rate of charging.

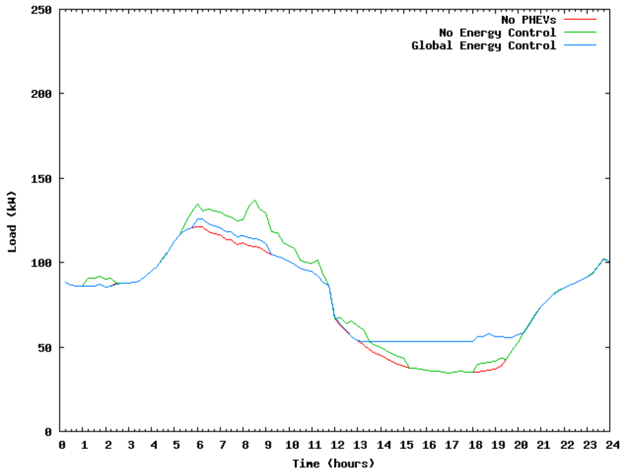

Figure 4, 10% PHEV adoption rate

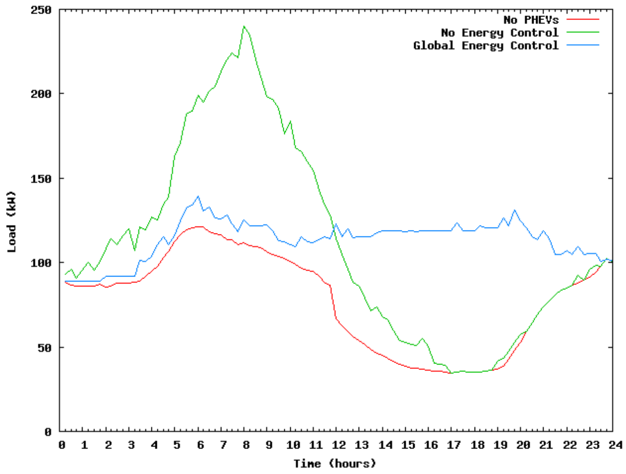

Figure 5, 60% PHEV adoption rate

CONCLUSIONS

In this paper we presented a simulation framework facilitating smart grid research. The discussion includes the requirements, design and operation of the simulator. It has been successfully used to develop and evaluate energy management strategies that are targeted at reducing peak load and levelling demand resulting from charging PHEVs. We will continue the development of the framework, which includes adding new models to the simulator and enhancing existing ones.

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