
Comparison of the Smart Grid Simulation Tools RAPSim and GridLAB-D

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Abstract

Increasing energy demand, ecological risks, the demand for energy generation from alternative renewable sources, the integration of energy storage, and the need for increasing energy efficiency via management systems are key motivations for transforming the conventional grid to a smart grid. During this transformation, many major challenges must be overcome in order to integrate the variety of renewable resources such as wind turbines and solar photovoltaic with the power grid. In addition, integration between information and communication technologies has resulted in new challenges such as the need for providing dynamic pricing in real time, security issues, and non-intrusive load monitoring via smart metering.

One of the most important tools for the development of the smart grid is simulation. Therefore, analyzing, designing, modeling, and simulating the smart grid will improve decision making about the grid's development. For instance, simulation results can be used to determine the optimal time for connecting chargers for electric vehicles to the grid, avoiding periods of peak load. Thus, simulation can be used to anticipate problems that could arise before the smart grid is implemented.

The increasing relevance of the smart grid for society in terms of energy provision will be discussed throughout this thesis. The components that need to be simulated are highlighted and current technologies for simulating the smart grid are presented, including two free, open-source software tools for research communities, named GridLAB-D and RAPSIm. These two software tools will be compared by implementing two scenarios for power flow and the integration of renewable sources and their respective results and performance will be evaluated.

Kurzfassung

Die steigende Nachfrage im Bereich Energie, ökologischer Risiken und grüner Energie, die Notwendigkeit für alternative Erzeugung von Energie und Energiespeicherung und Steigerung der Effizienz durch Energiemanagementsysteme, führten zu einer großen Bestrebung eine Umformung eines traditionellen Stromnetzes in ein intelligentes Stromnetz voranzutreiben. Diese Umformung bringt große Herausforderungen in Bezug auf die Vielfalt der erneuerbaren Ressourcen wie Windturbinen und Photovoltaik und deren Integration mit dem Stromnetz hervor. Darüber hinaus bedingt die Integration zwischen Informations- und Kommunikationstechnologie neue Herausforderungen im Bereich der dynamischen Preisgestaltung in Echtzeit, Sicherheitsfragen und der Datenanalyse von intelligenten Stromzählern.

Eines der wichtigsten Werkzeuge auf dem Weg der Entwicklung eines intelligenten Stromnetzes ist die Simulation. Durch die Analyse, die Konzeption, die Modellierung und schließlich die Simulation sind wir in der Lage, Informationen zu erhalten, um genauere Entscheidungen zu treffen. Simulationsergebnisse können beispielsweise die perfekte Zeit erschließen, in der man Elektrofahrzeuge an ein Ladegerät am Stromnetz anschließt um Höchstlastzeiten zu vermeiden. Somit kann Simulation verwendet werden, um Probleme vor der Umsetzung einer Maßnahme zu ermitteln.

Die folgende Arbeit zeigt auf, wie das Intelligente Stromnetz in unserer Gesellschaft immer mehr an Bedeutung gewinnt und ein immer wesentliches Element im Energiebereich wird. Dazu werden die Komponenten identifiziert, die entlang des Stromnetzes simuliert werden müssen und sprechen den Stand der Technik an, um das intelligente Stromnetzwerk zu simulieren. Die Arbeit weist auf zwei kostenlose Open-Software-Tools für die Forschung am intelligenten Stromnetz, GridLAB-D and RAPSIm, hin. Diese beiden Software-Tools werden in zwei Szenarien zur Energieflussberechnung und der Integration von erneuerbaren Energiequellen verglichen. Anschließend wird der Unterschied in Ergebnis und Performanz bewertet.

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List of Acronyms

ICT Information and Communications Technology

OpenDSS Open Distribution System Simulator

APREM Parametric Analysis of Power Grids with Matlab

RAPSim Renewable Alternative Powersystems Simulation

PV Photovoltaic

WAN Wide Area Network

AMI Advanced Metering Infrastructure

NAN Neighborhood Area Network

FAN Field Area Network

IAN Industrial Area Network

BAN Building Area Network

HAN Home Area Network

PVPS Photovoltaic Water Pumping Systems

GUI Graphical User Interface

Volt-VAR Volt-Voltage Ampere Reduction

GLM GridLAB-D Model

TCL Tool Command Language

ANN Artificial Neural Network

SMES Superconducting Magnetic Energy Storage

CAES Compressed Air Energy Storage

NAS Sodium(Na) and Sulfur(S)

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Chapter 1

Introduction

Prior to the development of smart grids, the conventional model of a grid was a unidirectional grid from the sources e.g., power plants to the load or destination such as factories and houses. This incurred high power losses, especially along transition lines. The conventional grid did not support the integration of renewable energy and there was limited consumer participation with the grid's functionalities. To create a functional smart grid, it is necessary to predict the behavior of the energy grid when certain parameters are changed. Simulation is fundamental to fulfill this requirement. A power grid simulator must simulate one-way communication between the utility and the consumers to study a wide range of planning and operational situations such as power generation and transmission expansion planning.

The introduction of smart grids has allowed the development of concepts such as distributed renewable sources and two-way communication between utilities and consumers by integrating Information and Communications Technology Information and Communications Technology (ICT) with the conventional grid. Consequently, simulators must accommodate these new concepts; there are effectively two directions of power generation sources, the first being the main utility grid, which could be many power plants located in different places, the second being consumer-owned renewable energy sources such as wind turbines and solar panels which direct energy back to the grid, i.e., the end-user of the power grid can produce energy. For example, many houses have solar panels installed, while still being grid-connected, so homeowners can sell excess energy to the grid in periods of peak production (usually daytime) and buy energy during periods of little or no production (usually night) [47].

Aside from the example above, further development of smart grid technologies e.g., battery technologies could allow owners to store excess energy during the daytime and use the energy at night, if they do not wish to sell it.

The benefits of a consumer controlling renewable energy sources must be considered. What is the impact of adding renewable energy sources and how should they be integrated with the main utility grid? The main considerations in this instance

relate to economy, efficiency, and reliability.

Simulating the traditional power grid usually relates to power only, without simulating other fields such as communication systems or other distributed power sources. Power grid simulation for smart grids, on the other hand, must consider the following [47]:

- Operational models such as load flow calculation, minimizing the power losses, the cost of power losses, and power flow optimization.
- Expansion models to accommodate any new technologies that could be integrated with the grid; for instance, the variety of renewable energy sources such as solar panels and wind turbines, and their integration with communication and information technologies for economic studies and energy management.
- Contingency analysis in order to assess the risk when load is changing, alongside disasters and security issues.
- Power market models as well as specific models for critical assessment in specific circumstances from various disturbances. The capability and accuracy of a simulator to predict the demand at a specific time in future should be evaluated.

All the aforementioned issues, especially the integration of the renewable energy sources and energy storage should be addressed by any smart grid simulator. This will be discussed further in Chapter 2.

1.1 Related Work

There are many simulations and pieces of research pertaining to the traditional power grid that greatly enhanced power transition and optimized the power flow along the grid. Many studies have been conducted in the field which relate to this thesis, especially studies on power flow optimization to improve grid reliability [15].

The IEEE has published models which have already been implemented for simulation purposes. A number of studies have used those models for simulating the smart grid using different simulators. In [2], a study was presented which analyzed the impact of various electric vehicles penetration rates for 1000 houses. The study was also implemented using GridLAB-D and IEEE 13 Node Test Feeder [14]. Moreover in [32], IEEE 34 Node was used to study the impact of distributed generation using DigSILENT PowerFactory.

Regarding the comparison of simulators in smart grid field, [27] is most closely related to this thesis. In [27], three free pieces of smart grid simulation software were presented and described, namely GridLAB-D, Open Distribution System Simulator

(OpenDSS) and Parametric Analysis of Power Grids with Matlab (APREM). Two case studies were explored and the respective performances of each piece of software were compared.

1.2 Motivation and Goals

The smart grid presents an immense challenge for many disciplines such as information technology, energy management, power engineering, and energy economics. Simulation is an important research method and remains an emerging research area.

Many of the studies being undertaken in this field will help avoid costly failures and evaluate communication technology. Studies are also being undertaken to study user acceptance and the power market. In light of this, this thesis has the following goals to bolster existing research:

- To classify the challenges in simulating the smart grid, to address the problems, and to present the state of art in the field.
- To present two free software tools and describe their basic characteristics and features. This could be useful to decide which simulator is more appropriate for a given case study.
- To describe and implement two case studies which include a power flow problem and integration of renewable energy sources with the grid. Comparisons are made between GridLAB-D and Renewable Alternative Powersystems Simulation (RAPSim).

1.3 Structure of the Thesis

Chapter 2 provides an overview of the smart grid and its main characteristics, as well as an overview of simulating and modeling the smart grid. The chapter examines the most up-to-date technology, and explores challenges related to smart grid simulation, such as deciding which areas and components must be simulated, and the various simulators available to the research community. In addition to examining difficulties around simulating both communication networks and power grids in smart grid applications, this thesis will discuss the applicability of smart grid simulations as prediction tools for demand response.

Chapter 3 presents two case studies (scenarios) which are to be implemented in this thesis. The scenarios focus on power flow and the impact of integrating renewable energy sources into the grid. Alternative scenarios such as integrating a communication network with a power grid are not included.

Chapter 4 introduces the first simulator (RAPSim) and discusses its strengths and weaknesses. Following this, the chapter describes the implementation of the scenarios in Chapter 3 using RAPSim and visualizes the results for each case study.

Chapter 5 introduces the second simulator (GridLAB-D) and lays out its strengths and weaknesses. Further details for its capability are discussed, in particular the US Department of Energy's support for GridLAB-D and its apparent potential as a smart grid simulator. The scenarios outlined in Chapter 3 are then implemented using GridLAB-D, their implementation is described, and the results of each case study are visualized.

Chapter 6 presents a discussion of the results from Chapter 4 and 5 to compare both simulators (GridLAB-D and RAPSim). The thesis is then concluded and opportunities for future research are highlighted.

Chapter 2

Modeling and Simulating the Smart Grid

2.1 An Overview of the Smart Grid

2.1.1 Introduction

The operation of the traditional power grid can be broadly characterized as being:

- Dependent on a high capacity fossil-fuel generation which causes high carbon emissions.
- In production of a large amount of power in comparably distant places requiring long transmission lines to deliver power for customers.
- Limited in its real-time control of power flow in specific areas e.g., houses.
- Unreliable should sudden faults or disasters occur [21].

To address some of these limitations, the smart grid has been developed to make power systems more environmentally friendly by using renewable energy sources. The smart grid aims to resolve some of the economic issues by enabling consumers to supply energy and to increase the grid's reliability even during disasters or sudden faults also [21].

Figure 2.1 illustrates the basic system for an ideal house in the smart grid, where the house has its own energy production. The components in Figure 2.1 (appliances, power storage, an electric vehicle, Photovoltaic (PV) arrays, inverters, smart meters, and communication networks) are able to exchange information related to power flow, power production, and power consumption. Consequently, simulating the information exchange among appliances would be of great importance for a simulator in order to achieve a high performance and quality of electrical service.

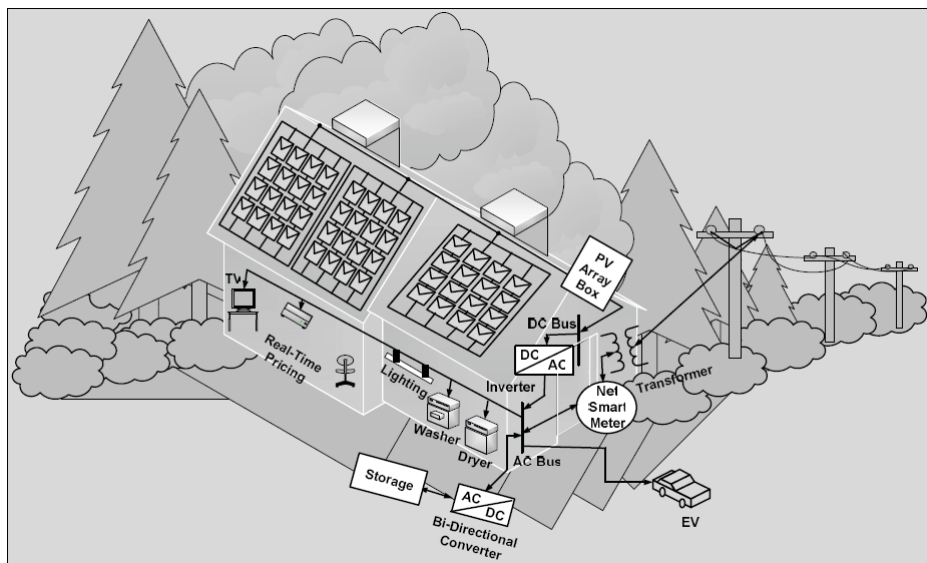


Figure 2.1: Ideal house in the smart grid [22]

2.1.2 Definitions for the Smart Grid

Over the past ten years, interest in the smart grid has increased, as well as the drive for its creation. A great deal of research has been performed in order to study the interactions between many technologies such as distributed energy sources and communication with the electric grid to transform it into the smart grid.

In this context, the word "smart" relates to the grid's embedded computation (it has its own capability to make local data processing), communication (such as protocols to exchange information), and sensing (observing the power flow in real time). The term "smart grid" has been defined in many ways, and several of these definitions are given in the following paragraphs:

The European Technology Platform states that: "*A Smart Grid is an electricity network that can intelligently integrate the actions of all users connected to it—generators, consumers and those that do both—in order to efficiently deliver sustainable, economic and secure electricity supplies.*" [12, p.6]

According to the US Department of Energy: "*A smart grid uses digital technology to improve reliability, security, and efficiency (both economic and energy) of the electric system from large generation, through the delivery systems to electricity consumers and a growing number of distributed-generation and storage resources.*" [12, p.6]

Other literature uses an advanced definition and defines a "smart grid" as follows: "*A smart grid uses sensing, embedded processing and digital communications to enable the electricity grid to be observable (able to be measured and visualised), controllable (able to be manipulated and optimised), automated (able to adapt and self-*

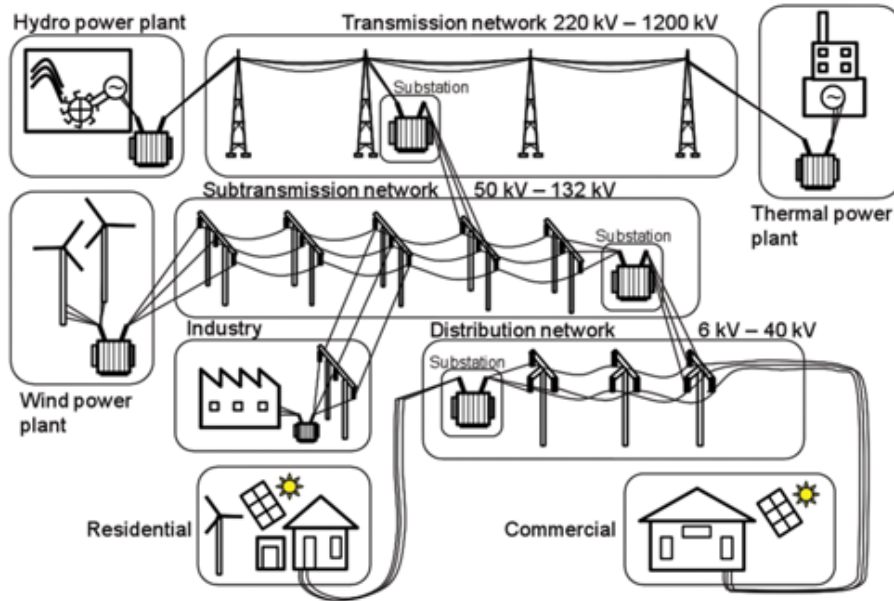


Figure 2.2: Basic elements of electric grid [31]

heal), fully integrated (fully interoperable with existing systems and with the capacity to incorporate a diverse set of energy sources). "[12, p.7]

There are many national and regional initiatives that aim to support research and investment in smart grids such as those of China, Japan, the UK, USA, and the EU. For instance, the Smart Grids Technology Platform of the European Union outlines its vision and strategy for Europe's electricity networks as follows: "*It is vital that Europe's electricity networks are able to integrate all low carbon generation technologies as well as to encourage the demand side to play an active part in the supply chain. This must be done by upgrading and evolving the networks efficiently and economically.*" [12, p.4]

2.1.3 Main Characteristics of the Smart Grid

Power Generation, Transmission, and Distribution

As well as the conventional power grid, the smart grid has the following basic components: the generation power, the transmission grid, and the distribution grid.

Figure 2.2 shows the main components of the smart grid. Power generation is based on transforming other forms of energy such as wind, sun, coal, gas, and nuclear into electrical energy. The smart grid is supported by distributed energy generation which utilizes distributed power resource systems. Renewable energy sources can be local generators in the microgrid and can continue providing power to customers when there is no connection with a utility grid [17].

New concepts of the smart grid in energy transmission networks, smart control centers, and smart substations can be seen in the transmission grid. Conceptually, the new energy transmission grids are built by enhancing the existing electric transmission infrastructure. However, new technologies and methods that have recently appeared (sensors, new electric materials, communications, sensing, computing, and signal processing) help to improve power quality, utilization, system reliability, and security [45].

As in any distributed system, the assigned generators will cooperate with a smart distributed network. In a smart grid, there are many distributed systems: advanced metering, communications, distributed generation, and distributed storage. By integrating these systems, the smart grid will be able to offer highly reliable, quality electrical power, robust communication against cyber attacks, and operate with multi-directional power flow [7].

Smart Metering

An electricity meter's main task is to measure the quantity of electricity that is consumed by the end user by recording the power over time or over a short interval (e.g., half an hour) [12]. However, increasing demand for power and advancements ICT have allowed smart meters to be developed which offer two-way communication and provide a real time display of the consumed energy. This allows consumers to see pricing information in real time.

Smart meters can be used to optimize energy-efficiency within houses. To achieve this, electrical data must be collected for the particular house, either by monitoring occupancy directly, which is intrusive and can give rise to privacy concerns, or by using a smart meter to collect such data in a non-intrusive manner to study the interaction between customer occupancy and loads [9].

Energy Storage

Energy storage is an essential functionality of the smart grid which can be distributed to make the grid smarter and achieve greater efficiency [38]. Furthermore, using energy storage at the grid can be useful in many aspects such as increasing the reliability, power quality, avoiding sudden faults, and enabling peak shaving [42]. Also, one of the most important applications for stored energy is supplying electric vehicles.

Figure 2.3 shows a comparison between different energy storage techniques according to the time and energy. However, there are different promising technologies for energy storage [42, 12]: batteries, flow batteries, fuel cells and hydrogen electrolyzers, flywheels, superconducting magnetic energy storage systems, supercapacitors, and compressed air energy storage.

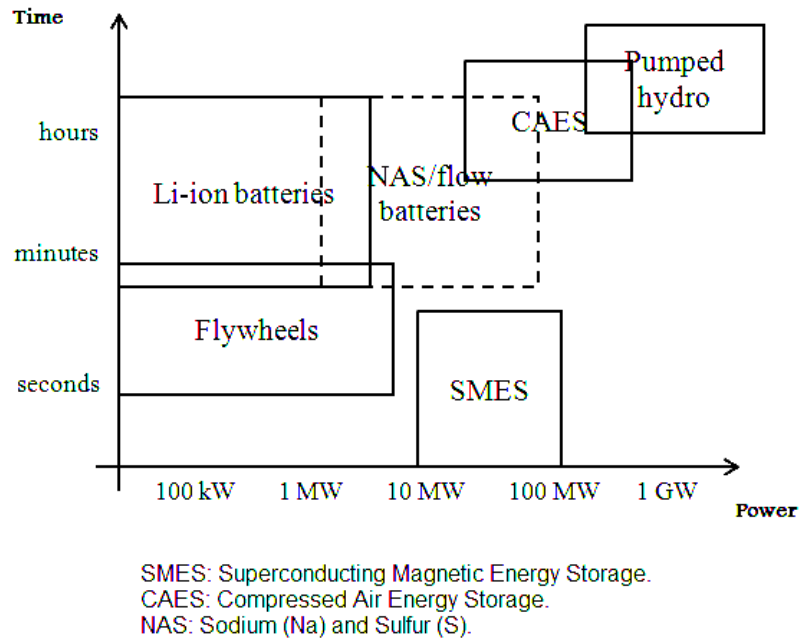


Figure 2.3: Comparison of discharge duration versus rated power for some grid energy storage technologies [42]

Information and Communication Technology

The integration between the power grid and communication networks is the fundamental way in which the conventional power grid will be transformed into a smart grid. The basic requirements for this integration are measurement, monitoring, and control of the overall grid. Therefore, information exchange along the smart grid has become essential for the smart grid's development. Naturally, new challenges have arisen in the domain of the smart grid by considering a communication perspective such as:

- Fragmented architecture and lack of adequate bandwidth for two-way communication.
- Lack of information exchange between smart grid components.
- Finding ways of handling the massive amount of data from smart meters.
- Exchanging and storing information, and shielding information from cyber-attacks [46].
- Providing a real-time connection between the provider and the consumer to provide grid-wide coordinated monitoring and control capabilities [29].

- Making the smart grid scalable to guarantee integration with many renewable energy sources, smart meters, and sensors along the grid [18].
- Quality of service for the connection between power supplier and customers [19].

There are three types of networks in the overall grid with different applicabilities which are [26]:

1. Wide Area Network (WAN): in the highest-voltage network, WAN is used over long distances to exchange information between the main station (power plant) and other substations (distribution centers). The WAN provides the highest communication bandwidth.
2. For low-voltage networks, different communication bandwidths are used: Field Area Network (FAN), Neighborhood Area Network (NAN) and Advanced Metering Infrastructure (AMI). These networks are connected to the main network WAN. They are also connected with distribution power networks for houses, buildings, or factories as end-users.
3. After that, communication bands will be used with appliances inside houses or other end-users to establish a connection between the appliances and the smart meter using Home Area Network (HAN), Building Area Network (BAN) and Industrial Area Network (IAN).

Figure 2.4 illustrates the general architecture for the interactions between communication networks and smart grid applications in generation, transmission, distribution, and customer domains [24]. Figure 2.4 displays the variety of smart grid applications such as meter reading and demand response, which are established between power distribution centers and end-users.

Regarding the technologies described above, many communication techniques and protocols have been developed for this purpose such as Wireless Mesh, ZigBee, Power Line Communication, Cellular Network Communication, and Digital Subscriber Lines, which are not the focus of this thesis. For more details, [19] presents those techniques and individually describes their advantages and disadvantages.

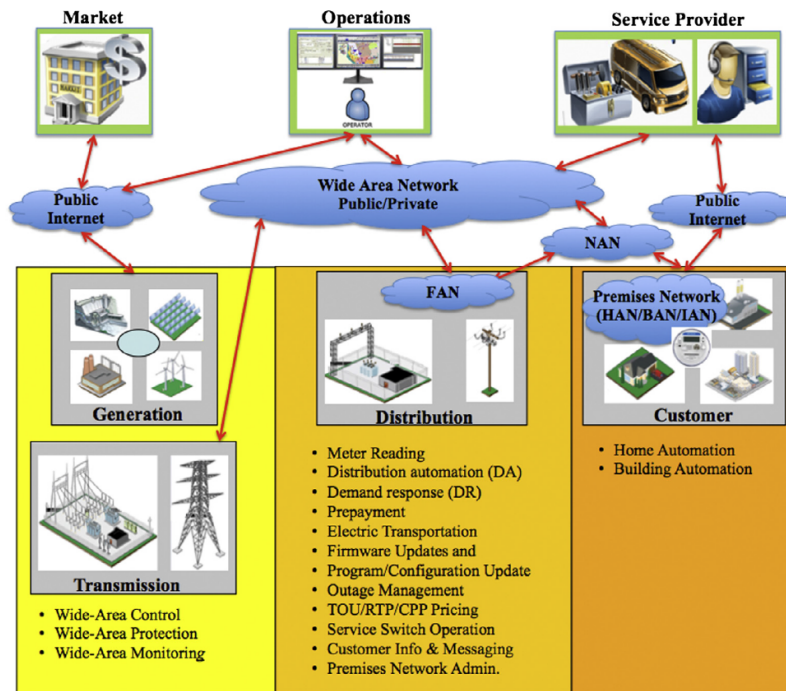


Figure 2.4: General architecture for the interactions between communication networks [24]

2.1.4 Smart Microgrid

The concept of the microgrid has developed with the following basic characteristics [22]:

- It is a small-scale network with its own power supply from a variety of renewable energy sources such as photovoltaic, wind turbines, and fuel cells, and it has different sizes ranging from one household to an entire village.
- A small microgrid can produce power of 5-10 MW, and does not incur large transmission losses due to its short-distance transmission lines [1].
- A microgrid increases reliability during sudden disasters because it can operate independently by using renewable energy sources. The microgrid has different modes of operation: networked to the utility grid, isolated from the utility grid, and connected to other microgrids [43].

Figure 2.5 illustrates the general architecture of a microgrid. It can be seen that a microgrid can be connected to the local power grid or it can remain isolated from the local grid using an energy management or micro-grid energy management system. Storage techniques (e.g., flywheels) are vital for saving excess power or, in other cases, excess energy can be bought from/sold to the utility grid.

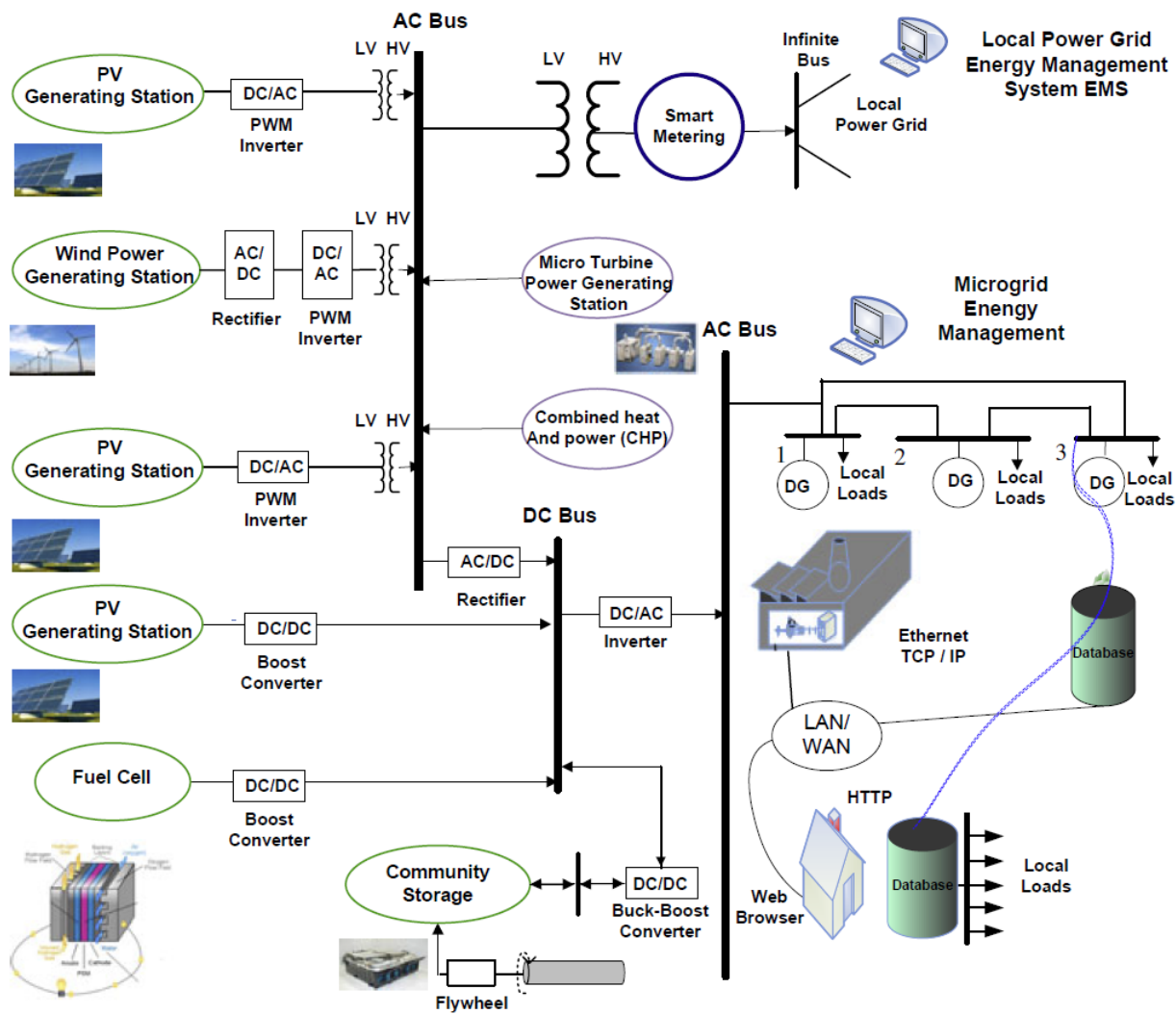


Figure 2.5: General architecture of the microgrid [22]

2.2 An Overview of Modeling and Simulating the Smart Grid

2.2.1 Introduction

Smart grid simulation is an essential prerequisite for computerized evaluation and analysis before establishing a real-world smart grid. This can be used to optimize the overall performance of the grid, specifically, by integrating renewable energy sources. For example, one important application of solar energy is in Photovoltaic Water Pumping Systems (PVPS), which are required in rural areas. Many economic benefits can be garnered by developing a model which optimizes the size and performance of the solar panels by considering two basic factors: metrological data and the average hourly water flow rate at the intended site [30].

Before the smart grid, power grid simulations were mostly concerned with estimating power losses and end user load for a given power flow. The transition toward the smart grid has increased the level of complexity of the energy system, because of the integration of distributed and renewable energy sources, smart meters, smart appliances, electric vehicles, etc. into the electric grid [35]. Therefore, new tasks are required of the simulator such as the optimization of distributed energy resource management when the smart grid is in operation [36], demand response in deregulated electricity markets [3], smart meters [11], energy storage in electric vehicles using smart grid [44], predicting consumer demand [25], and integrating power and communication networks [26].

2.2.2 Modeling and Simulating the Smart Grid

A simulator will yield better or worse results depending on the model that the simulation is based upon. After modeling the smart grid, a decision was made on the area that should be simulated. In the smart grid, there are a lot of methods and techniques that need to be modeled well such as ICT, distributed energy resources, energy storage, and smart meters. In addition, there are advanced simulators that model and simulate appliances inside the house like refrigerators and washing machines. GridLAB-D is capable of modeling most household appliances as shown in Chapter 5.

In [35], an interesting model was presented (multiple flow networks) which is illustrated in Figure 2.6. The main characteristics of the model are that:

- It is an agent-based model where the agents (Consumers - Producers - Grid Operator) are the decision-making entities and control several nodes and are the main interconnections between the different flow networks.
- It extends a power flow model with smart grid concepts in order to cover the flow of data in ICT network and the flow of payment through the financial

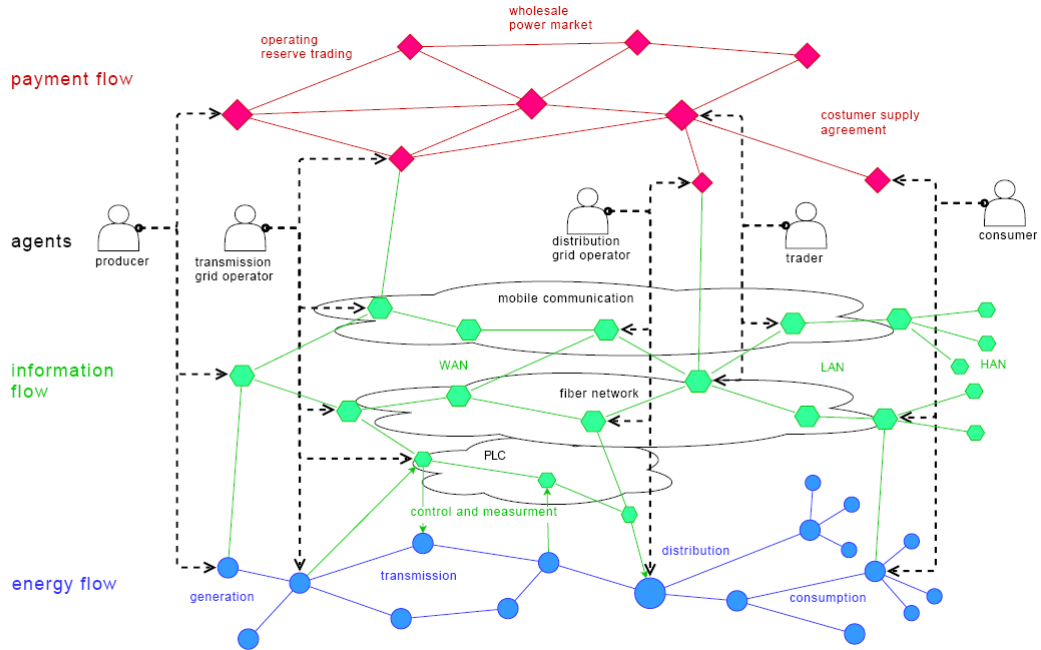


Figure 2.6: Multiple flow networks [35]

transaction network.

- It is flexible and it can be scaled to any type of sub-model such as gas distribution.

This model demonstrates the many problems simulators must address in present research, which are also listed below:

- Power flow simulation and optimization with respect to many distributed energy sources.
- Combined simulation of power and communication systems.
- Consumption prediction and demand response.

In the following sections, current technologies for addressing such challenges are discussed. These challenges are grouped into three categories: power flow, co-simulation, and demand prediction.

2.2.3 Power Flow Simulation

Modeling and simulating power flow provides a steady-state solution for a power grid with respect to both grid topology and load levels. The power flow simulation is given the voltages and phase angles, then as result, the power injections at all buses and power flows through transmission lines, cables, and transformers [12].

Therefore, simulation of the power flow can be the basic tool for analysis, operation, and planning of the smart grid as it was for transmission power systems before.

There are four basic quantities in a power system:

1. The magnitude of the voltage ($|V|$).
2. The voltage angle (θ).
3. The real power injection (P).
4. The Reactive power injections (Q).

Generally for study and analysis of the power flow, two of these quantities are specified, and the remaining two are obtained by forming a set of nonlinear algebraic equations, then, by choosing a suitable mathematical method such as the Gauss-Seidel method, the Newton-Raphson method, fast-decoupled load-flow (FDLF), or the forward-backward algorithm.

Recently, a variety of software packages have been produced for smart grid simulation, which are divided into two main categories [35]:

1. The first is commercial software which is mostly costly, highly specialized, and difficult to modify, which is thus less suitable for research and teaching.
2. The second is free software; there are several freely available simulators. In [35], ten free simulators such as GridLAB-D, AMES, InterPSS, OpenDSS, and MatPower were compared and a test case was made for four simulators (GridLAB-D, MatPower, PSAT, and InterPSS) using the same model IEEE 14-bus system to compare the results and the methods employed by the simulators. As previously mentioned, power flow calculations must be solved iteratively, therefore, most of the simulators use the Newton-Raphson method or the Gauss-Seidel method.

In [34], RAPSIm was introduced as a new simulator for microgrids. RAPSIm has a graphical user interface. In addition, RAPSIm offers many algorithms for simulation such as simple power distribution with no transmission losses. Figure 2.7 illustrates a simple test case (using RAPSIm) with a system of four buses and grid connection. Three houses act as the loads and the PV system acts as a variable source. The aim is to show the effect of altering the PV position on the voltage levels in the microgrid.

Figure 2.8 illustrates the simulation results over a one month period with hourly timesteps to configure bus voltages for different positions of the PV system, where the lower graph shows bus voltages for the scenario with the PV connected to the left-hand house and the upper graph for the scenario with the PV connected to the right-hand house. It was noted that *"voltages match exactly the fluctuation in the*

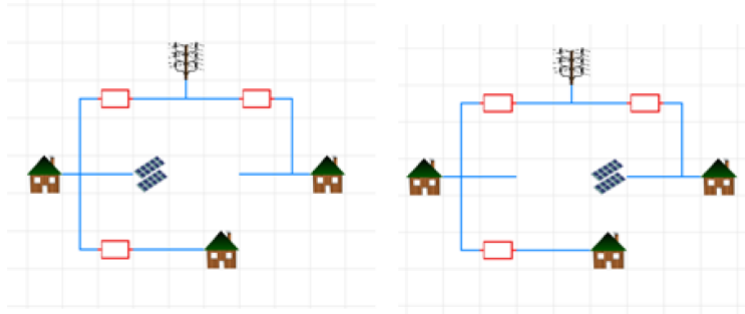


Figure 2.7: Sample test case for microgrid [34] PV is on the left side (bus number 2)
 - PV is on the right side (bus number 4)

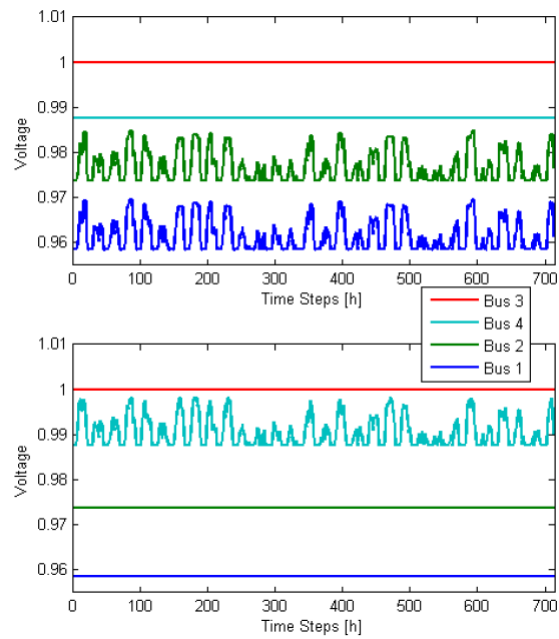


Figure 2.8: Bus voltages for different position of the PV[34]

PV production driven by the weather condition, or more specifically the sun radiation factor"[34, p.6].

In addition to RAPSIm, GridLAB-D is one of the most promising smart grid simulators. It has many functionalities and applications such as Volt-Voltage Ampere Reduction (Volt-VAR) Optimization, real-time pricing demonstration, and demand response for renewable integration [8]. However, GridLAB-D lacks a Graphical User Interface (GUI).

Chapters 4 and 5 will provide a more detailed discussion where RAPSIm and GridLAB-D are used to simulate two case studies (scenarios) related to power flow simulation.

2.2.4 Co-Simulation

With regard to the integration between the two diverse technologies of power and communication networks in smart grids, a large quantity of research is still ongoing to create unified co-simulation of the two technologies.

Co-simulation is a method of merging two or more different subsystems to create a unified modeling and simulation system [37]. Therefore, co-simulation will be a great challenge to overcome in the smart grid domain. Since there is no freely available software which combines both power flow and ICT in smart grids, several attempts have been made to realize that goal.

In the context of smart grids, co-simulation would consist of a specialized communication network simulator such as NS-2 or OMNET++ and a specialized power simulator such as GridLAB-D or OpenDSS also. Synchronizing both simulators is challenging because each simulator has its own simulation time. However, co-simulation is very useful due to increasing interest in smart grids from governments and researchers because building a new combined simulation environment from scratch is potentially time-consuming and expensive [26].

For instance, [37] presented a co-simulation scheme and a basic prototype based on open source material. NS-2 was used for communication network simulation and GridLAB-D for power grid simulation, where both simulators are licensed under open source and are widely recommended by researchers.

Figure 2.9 illustrates the high level architecture of co-simulation for both networks, where (a) models a power network (a wind turbine for four houses), and (b) models a communication system (a local area network with a server connected to four nodes). There is no mapping between power and communication networks. The start point for the prototype is provided by NS-2 as an entry point for the co-simulation, where there is a new agent (AgentGL), derived from the NS-2 agent class. The basic idea is to make a newly formed process and wait for its return. That forked process will execute a GridLAB-D Model (GLM) file using Tool Command Language (TCL) script.

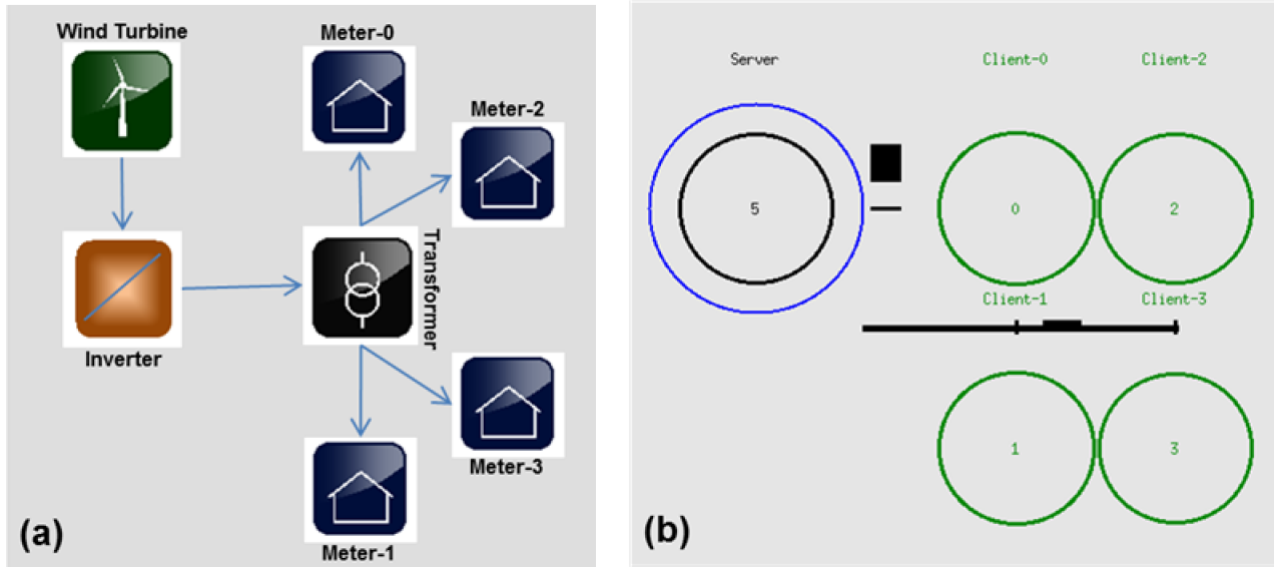


Figure 2.9: High level architecture of co-simulation[37]

In [10], an interesting approach was suggested using the Framework for PowerSystem and Communication Networks (FNCS), a promising approach in the co-simulation domain with a dedicated messaging system and time synchronization. However, the proposed solution still lacks logical mapping among the elements between power and communication networks.

Furthermore, there is an alternative approach to co-simulation named integrated simulation where a power grid and a communication network are simulated in one environment to overcome many challenges such as time management and shared data between power and communication networks. However, combining two simulators requires more hurdles to be overcome, such as:

- Improving simulator performance in real-time for both power and network simulators [4].
- Uniform design: deployment and integration of distributed energy resources, smart technologies, appliances, and advanced storage devices in both communication and power networks [20].

2.2.5 Prediction Methods for Consumption

The smart grid can be considered as a complex system for many reasons such as:

- The strong drive for change in the way electrical energy is produced, especially the drive for renewable energy sources.

- The question of how renewable sources should be integrated with the grid.
- The huge amount of data generated by smart meters.

The challenges that have appeared with smart meters such as continuously reconfiguring and connecting with appliances and sensors, as well as aggregating large amount of data which need to be analyzed in a sophisticated manner [28].

Applying artificial intelligence techniques such as Artificial Neural Network (ANN) and data mining would play a major role in modeling and simulating promising research in areas such as demand response, consumption prediction, and customer pattern [16].

In [16], four prediction methods were presented:

1. Auto Regressive Integrated Moving Average: predicts future electricity consumption values based on a linear combination of previous measurements [5].
2. New York ISO: the consumption baseline is calculated from the previous five days with the highest average kWh value [23].
3. South California Edison ISO: the consumption baseline is calculated by averaging ten days [16].
4. California ISO: the consumption baseline is the hourly average of three days with the highest average consumption value among a pool of ten selected previous days [16].

In [16], a neural network-based approach was proposed to select the best method for consumption prediction depending on a continuous flow of real-time data and huge historical data sets. The approach achieved over 84% accuracy in selecting the best electricity consumption prediction method for each customer.

Figure 2.10 illustrates the fast and accurate demand response model which uses both real-time and historical consumption to predict future consumption.

2.3 Summary

Smart grid simulation is challenging, and is still a central focus of current research. During the transition from the traditional power grid to a smart grid, many challenges have become apparent for simulating and modeling smart grid components such as distributed energy sources, ICT, and smart meters. This thesis presents an overview for the smart grid, modeling of smart grids, and simulation of smart grids and classifies it into three categories: power flow, co-simulation, and demand response.

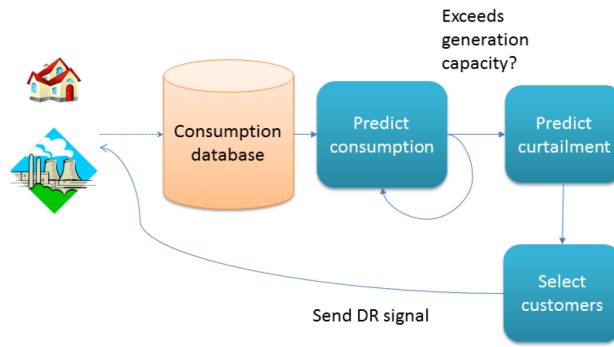


Figure 2.10: Demand response architecture [16]

Currently, co-simulation is faced with many challenges to integration of the two different domains between power and network systems and many attempts are still ongoing to try to overcome those challenges. Applying AI techniques appears very promising for the smart grid domain to create models for the future and to predict consumption accurately.

Chapter 3

Case Studies

In order to compare the performance of GridLAB-D and RAPSIm, two scenarios will be presented in this chapter and implemented in Chapters 4 and 5, respectively. The scenarios focus on evaluating the power flow in each case study and the effect of adding renewable energy sources (especially solar panels and wind turbines which are distributed generators that produce fluctuating power over time). Therefore, the simulator must be able to calculate load flow per unit time. In both cases, the calculation interval is one hour and the whole period is one month. The following paragraphs will describe the case studies in more detail.

3.1 Case Study One: Renewable Energy Generation

The basic aims of the first case study are power distribution among the power generators, assessing the impact of adding renewable energy sources, calculating the amount of available power production, and calculating the amount of consumption, considering production changes due to weather information (such as wind speed and cloud coverage). This case does not consider power losses along distribution lines.

Three different kinds of power generation are considered: substation, wind turbine, and solar panel. For the load, three houses are added with constant demand. In addition, two of these houses have solar panels and the third house has no distributed power sources.

The main parameters for this case are as follows:

1. A substation with nominal voltage 230 V.
2. A wind turbine producing power 1500 W.
3. Two solar panels with peak power production 500 W.

4. Three houses with constant demand (500, 500, 700 W). One of the houses has the same value as its solar panel value, the other house has a value greater than its solar panel value, and the third house does not have solar panels.

This will demonstrate how the power production would be distributed among the different generators, especially during the night when there is no power being produced by the solar panels.

Figure 3.1 illustrates the first case study and shows the loads and decentralized power generation.

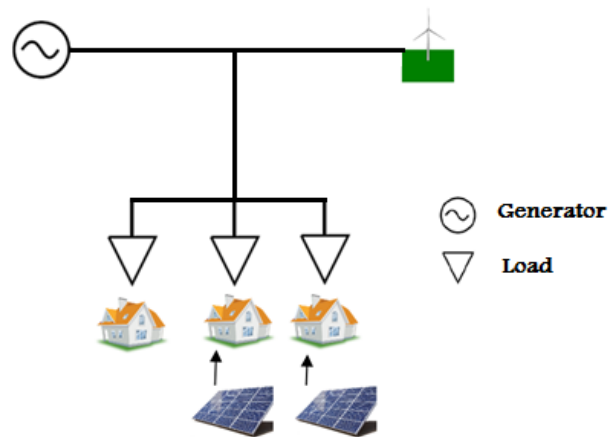


Figure 3.1: The first case

3.2 Case Study Two: Power Distribution in a Street

In the second case study, a scenario will be implemented consisting of two streets, each of which comprises four households, which are linked together and connected to a power provider. The main aim of this case study is to study voltage changes. Solar panels will also be added to assess their impact on the scenario results.

As will be discussed in Chapter 5, there are more functionalities in GridLAB-D than in RAPSim to study voltage and optimize power flow.

The main parameters for this case study are as follows:

1. The nominal voltage at the feeder is 230 V for both simulators.
2. Distribution lines with distance of 150 m for each street. The distance is 30 m between each house.
3. Generally, the electrical resistance of a conductor depends on the conductor length, the material of the conductor, the temperature of the material, and the cross-sectional area of the conductor. The resistance can be calculated using the following equation (3.1):

$$R = \rho l / A \quad (3.1)$$

Where:

- R = the resistance of the conductor (Ω).
- ρ = the resistivity of the conductor material (Ωm).
- l = the length of the conductor (m).
- A = the cross-sectional area of the conductor (m^2).

The case study used copper as a conductor with a resistivity of $1.724 \times 10^{-8} \Omega\text{m}$ at temperature of 20 C° . The cross-sectional area for the case study is 150 mm^2 , i.e., the typical feed cable properties at the street [13]. This gives a resistance value of 0.019Ω for $l = 150 \text{ m}$. More details are shown in Figure 3.2.

4. Eight households with the following demands: 4000 W for each house in the first street, 5000 W for the first three houses in the second street and 6000 W for the fourth house.

Initially, the second case will be simulated with the above conditions. The solar panels will then be added with nominal voltage of 230 V and peak power production of 5000 W. The simulation will then be repeated and the impact of adding the panels will be studied.

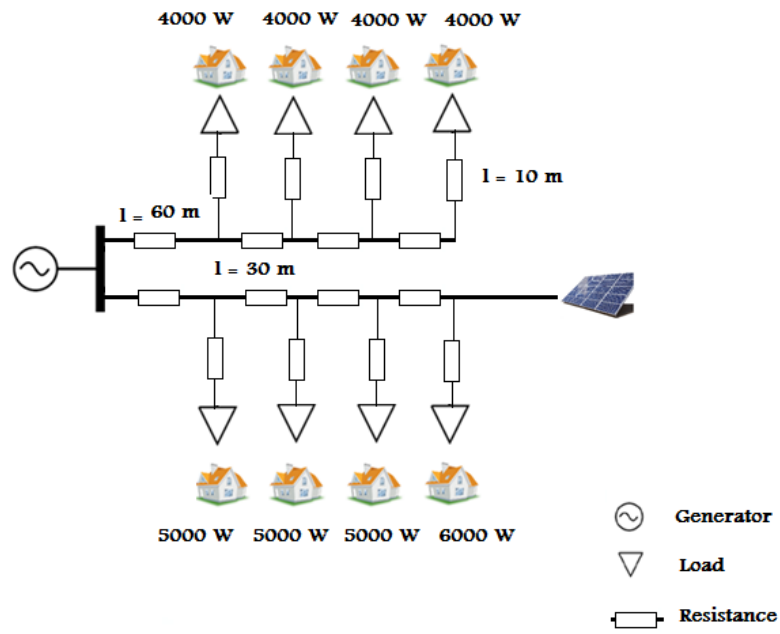


Figure 3.2: The second case

Figure 3.2 illustrates the second case study and shows the power provider and loads.

Chapter 4

Simulating the Case Studies Using RAPSIm

4.1 Introduction to the Software

RAPSIm has been developed at the Institute of Networked and Embedded Systems of the Alpen-Adria-Universität Klagenfurt [34]. It is a free and open source microgrid simulation framework with a graphical user interface, illustrated in Figure 4.1. In addition, it is specialized to achieve a better understanding of power flow behavior in smart microgrids with renewable energy sources. For this thesis, RAPSIm V0.95 has been used.

However, the main aim for designing RAPSIm is *"for use in science and classroom with a simple to use graphical interface. It is an easily extendable framework that supports users in implementation of their own models, for grid objects, and algorithms for grid control"* [34, p.1].

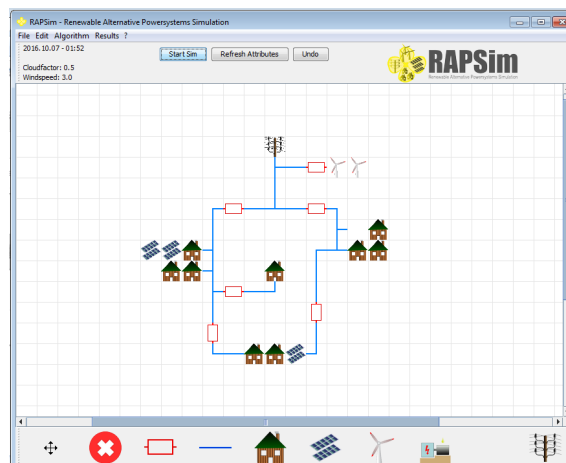


Figure 4.1: The main interface for RAPSIm

Figure 4.1 illustrates the main window of RAPSIm, showing the lattice-like simulation field where objects can be placed and connected to each other as needed.

In addition, Figure 4.2 illustrates the property window for solar panels that is placed in the lattice, allowing the parameters for each object to be displayed and edited.

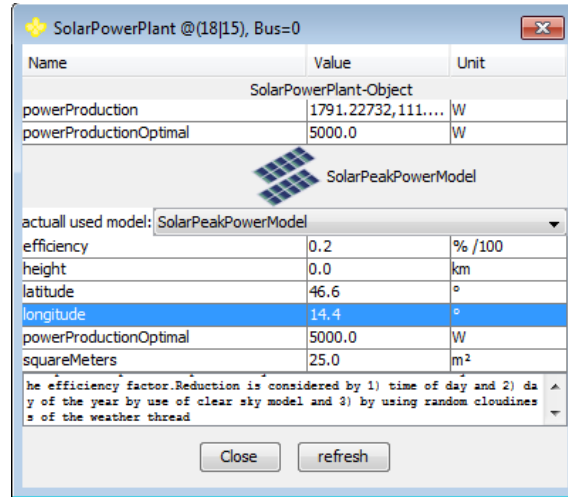


Figure 4.2: Property window for solar panels object in RAPSIm

The following paragraphs outline the main characteristics of RAPSIm:

- It is designed to simulate microgrids but it can also simulate and analyze power flow along the smart grid in both modes (connected to the main grid and isolated with solar panels, wind turbines, other renewable energy sources, or other power generation such as fuel motors). Therefore, RAPSIm is helpful to optimize power flow and improve distributed generation units in the grid.
- As mentioned, RAPSIm has a graphical user interface to create scenarios and during the implementation scenarios can be saved or loaded in the XML format. Furthermore, time simulation thread allows up to one-minute resolution. Simulation results are saved by generating an output file in the CSV format.
- RAPSIm comes with many algorithms such as Simple Power Distribution and ACPowerFlow and a description of each can be read from the user interface. For instance, Simple Power Distribution calculates only active power along the grid and does not consider any losses or reactive power.
- Since RAPSIm is free and open source, it has huge potential for developing new models and algorithms, as well as modifying existing ones. For instance, [33] presented an implementation for a new customized wind turbine model with three short code snippets. The new turbine is available in RAPSIm version 095 and will be used to simulate the two case studies.

4.2 Simulating the First Case

For the first case study, the following objects were needed: three houses with constant demand, a substation, two solar panels, and a wind turbine. These were placed in the lattice in RAPSIm as shown in Figure 4.3:

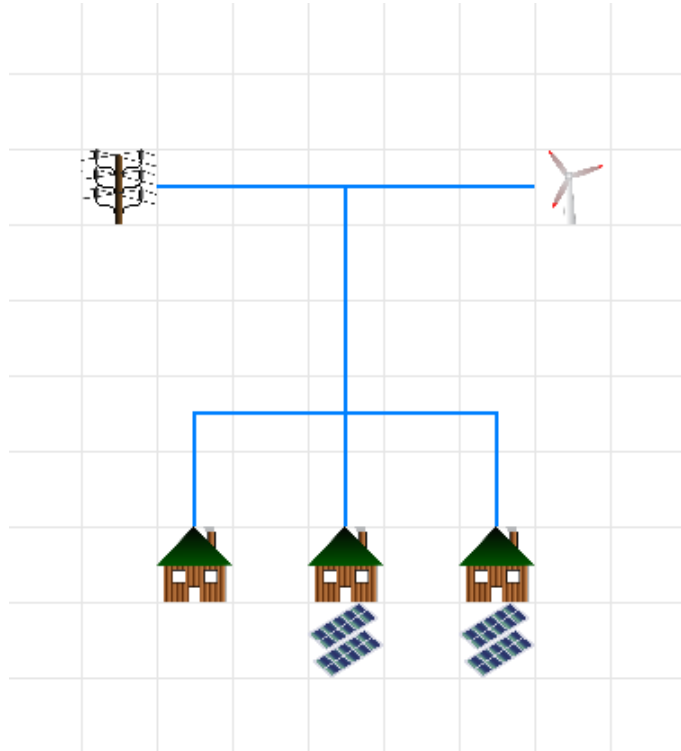


Figure 4.3: The first case modeled in RAPSIm

RAPSIm will automatically analyze the grid as a one-line equivalent circuit. After that, an algorithm must be chosen to be applied as illustrated in Figure 4.4. The simple power distribution algorithm was chosen for the first case study.

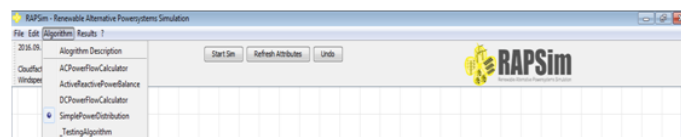


Figure 4.4: Choosing SimplePowerDistribution algorithm in RAPSIm

The property window then needed to be opened for each object, i.e., the three houses, solar panels, and the wind turbine, to determine their demands and optimal power production, as discussed in Chapter 3.

After choosing the algorithm and specifying the parameters, the simulation can be run, either specifying the output as a CSV file or saving the scenario as an XML

file. Figure 4.5 illustrates a solar panel object with its attributes saved as an XML file.

```
<SOLAR_POWER_PLANT>
  <X>12</X>
  <Y>8</Y>
  <currentCurrent>0.0</currentCurrent>
  <currentPowerLoss>0.0</currentPowerLoss>
  <currentPowerTransport>0.0</currentPowerTransport>
  <currentVoltage>1.0</currentVoltage>
  <maxPowerTransport>0.0</maxPowerTransport>
  <nominalVoltage>1.0</nominalVoltage>
  <powerConsumption>0.0</powerConsumption>
  <powerDemand>0.0</powerDemand>
  <powerLineCharge>0.0</powerLineCharge>
  <powerProduction>216.78016</powerProduction>
  <powerProductionOptimal>500.0</powerProductionOptimal>
  <resistance>0.0</resistance>
  <transportPowerDecrement>0.0</transportPowerDecrement>
  <voltageAngle>0.0</voltageAngle>
  <model name="SolarPeakPowerModel">
    <efficiency>0.2</efficiency>
    <height>0.0</height>
    <latitude>46.6</latitude>
    <longitude>14.4</longitude>
    <powerProduction>216.7801568748515</powerProduction>
    <powerProductionOptimal>500.0</powerProductionOptimal>
    <squareMeters>2.5</squareMeters>
  </model>
</SOLAR_POWER_PLANT>
```

Figure 4.5: XML description for solar panels

Finally, after running the simulation for one month with a resolution time of one hour (as shown in Figure 4.6), RAPSIm will generate cloud factor and wind speed values for each timestep, to evaluate the power production for the renewable energy sources in the lattice. During the simulation, power distribution and consumption will be calculated 720 times.

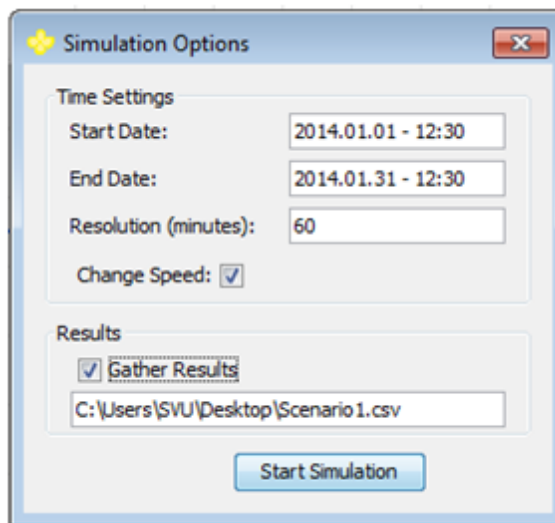


Figure 4.6: Simulation running in RAPSIm

4.2.1 Simulation Results

Since the weather information in RAPSIm was generated by a stochastic model, Figure 4.7 illustrates cloud factor and wind speed values with respect to the timesteps (from 1 to 720 hours).

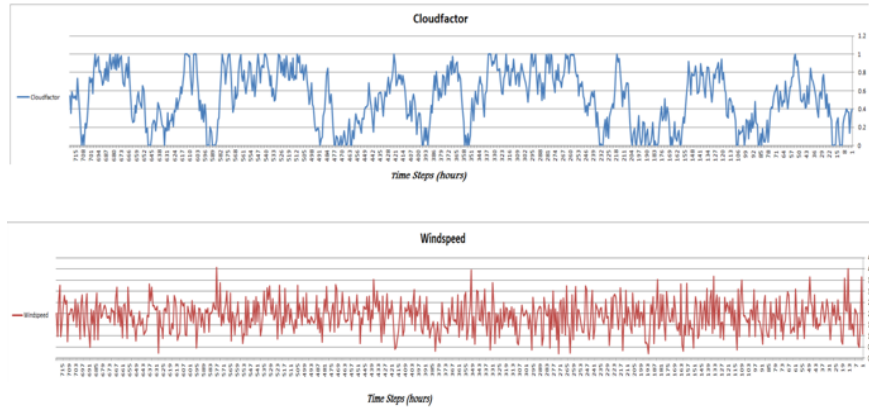


Figure 4.7: Cloud factor and wind speed

Figure 4.8 shows power production for all generators during a two-day simulation. During the night there is no solar energy generation, but wind turbines still produce power, therefore, the power grid or substation should feed the houses if the wind turbines do not supply sufficient power.

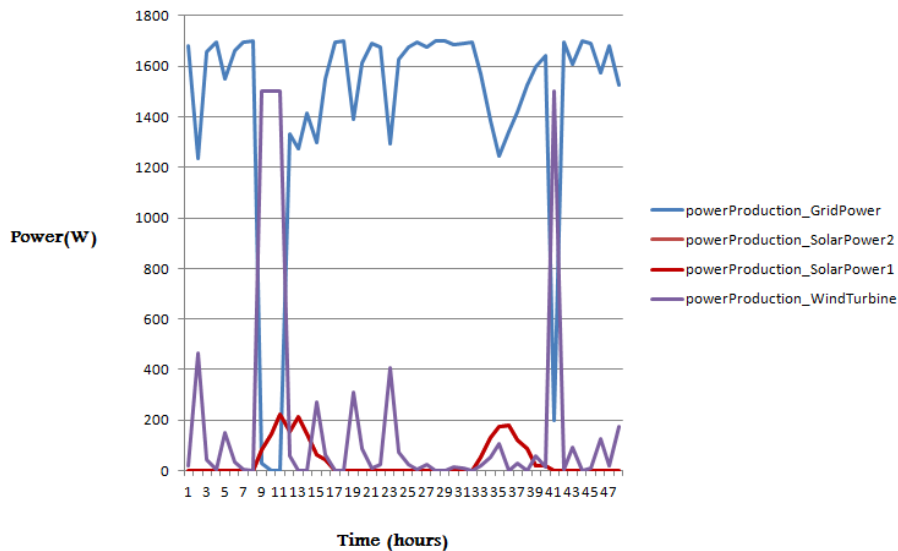


Figure 4.8: Power production

4.3 Simulating the Second Case

To simulate the second case study, eight objects (houses with constant demand without solar panels) are placed in a lattice in RAPSIm as shown in Figure 4.9:

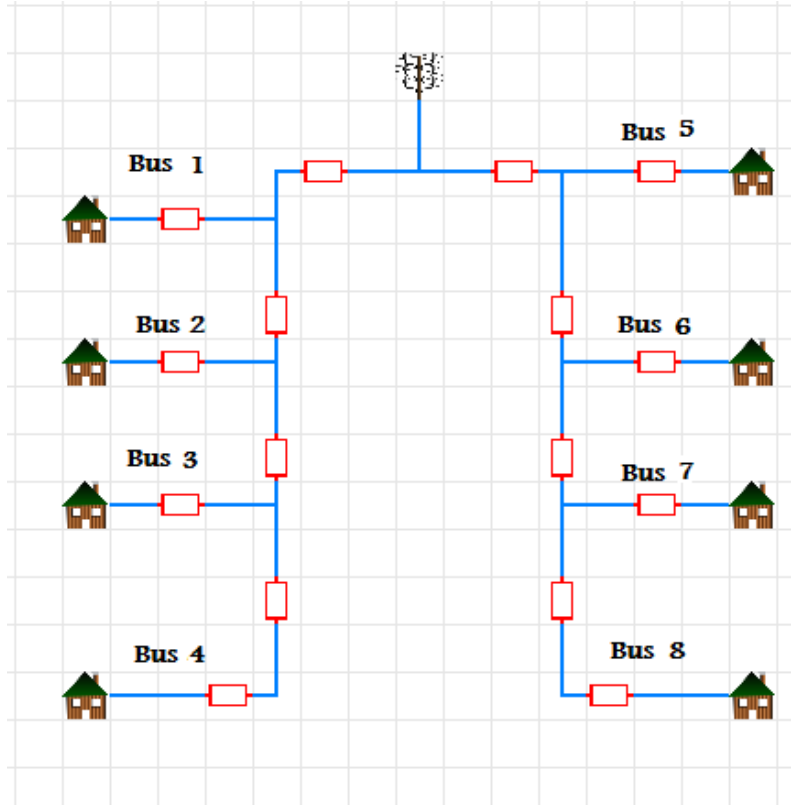


Figure 4.9: The second case modeled in RAPSIm

The ACPowerFlowCalculator algorithm was chosen for this case study (Figure 4.10), and the parameters for each object were then specified. The simulation was run for one month with a time resolution of one hour, giving 720 calculations in total.

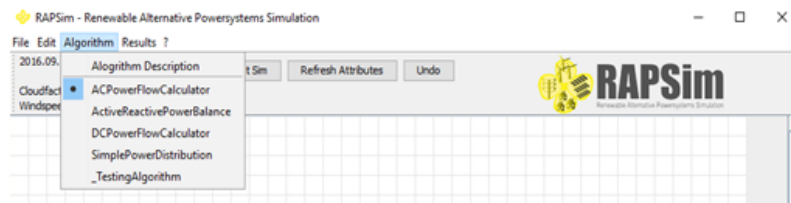


Figure 4.10: Choosing AcPowerFlowCalculator algorithm in RAPSIm

4.3.1 Simulation results without solar panels

Figure 4.11 illustrates the bus voltages for a one-month simulation. Voltage changes for each street are shown in Figure 4.12:

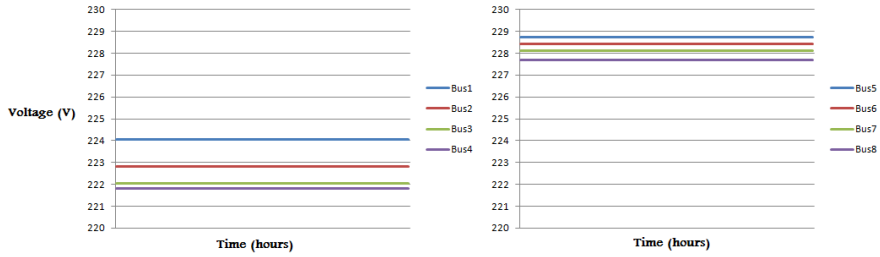


Figure 4.11: Bus voltages without solar Panels

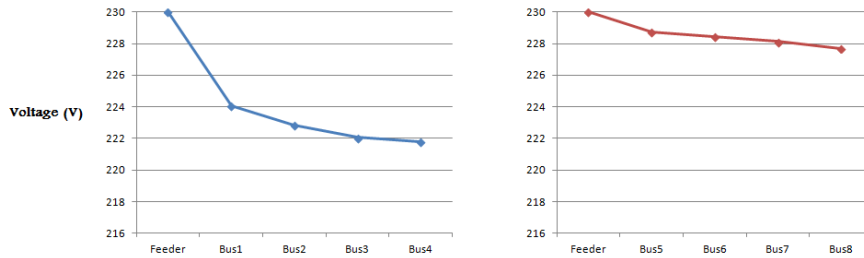


Figure 4.12: Voltage changes

4.3.2 Simulation Results including Solar Panels

After adding solar panels as shown in Figure 4.13, the simulation was repeated to determine the impact of adding solar panels on bus voltages.

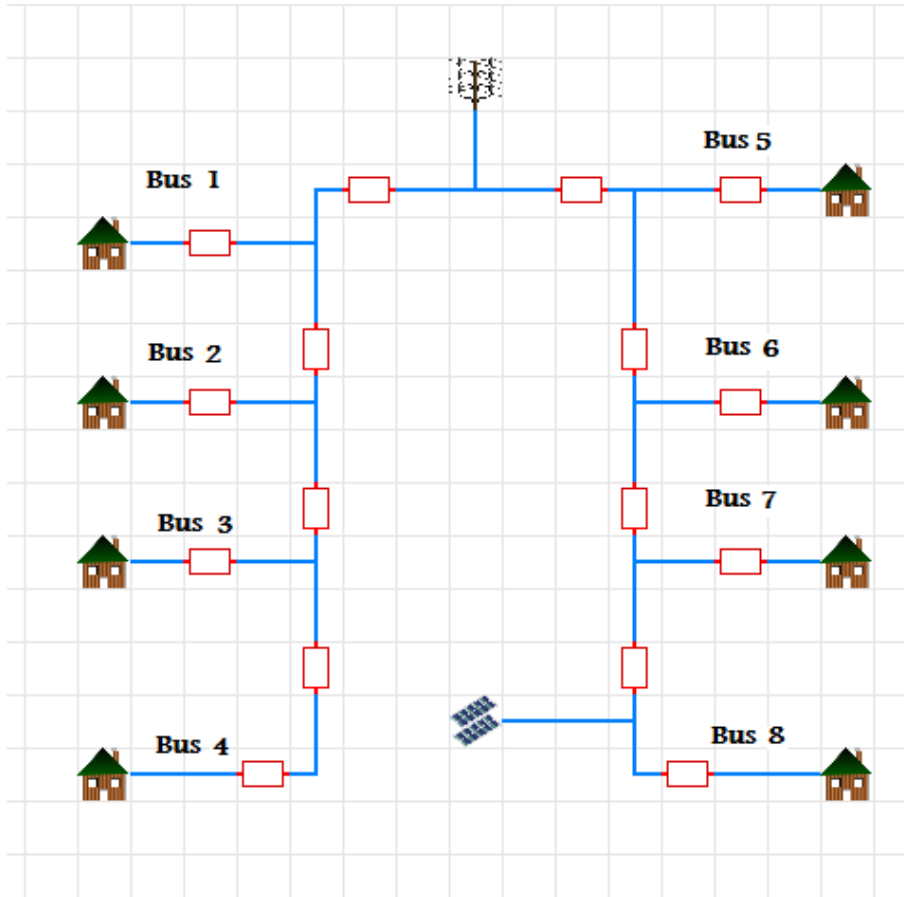


Figure 4.13: The second case after adding solar panels

Figure 4.14 illustrates bus voltages for the buses (Street 1: bus1, bus2, bus3, bus4) after adding solar panels, and shows that adding solar panels has no impact on the bus voltages. Figure 4.15 shows the impact on the other buses, and shows that the highest impact is on bus8.

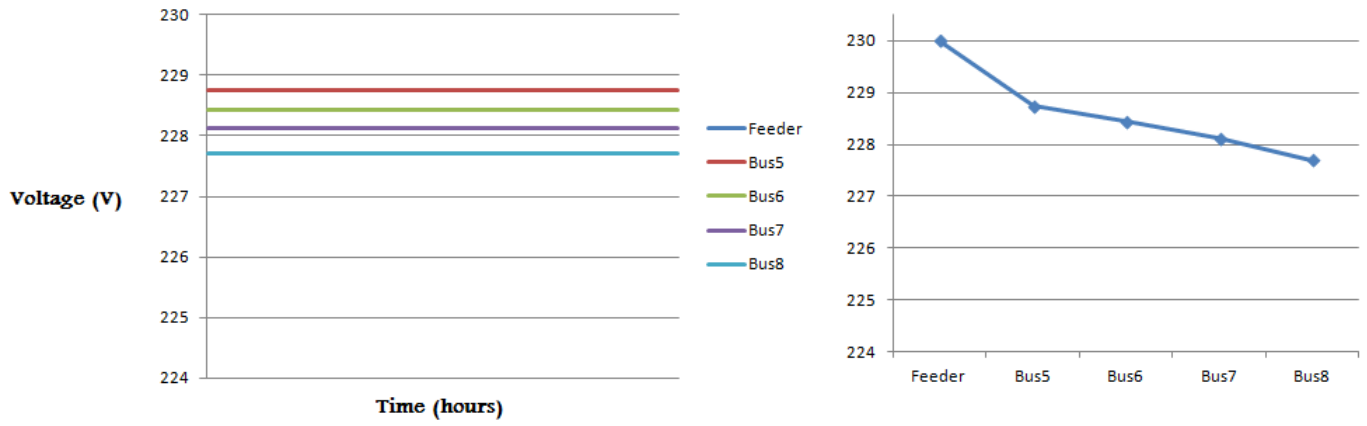


Figure 4.14: The impact of adding solar panels

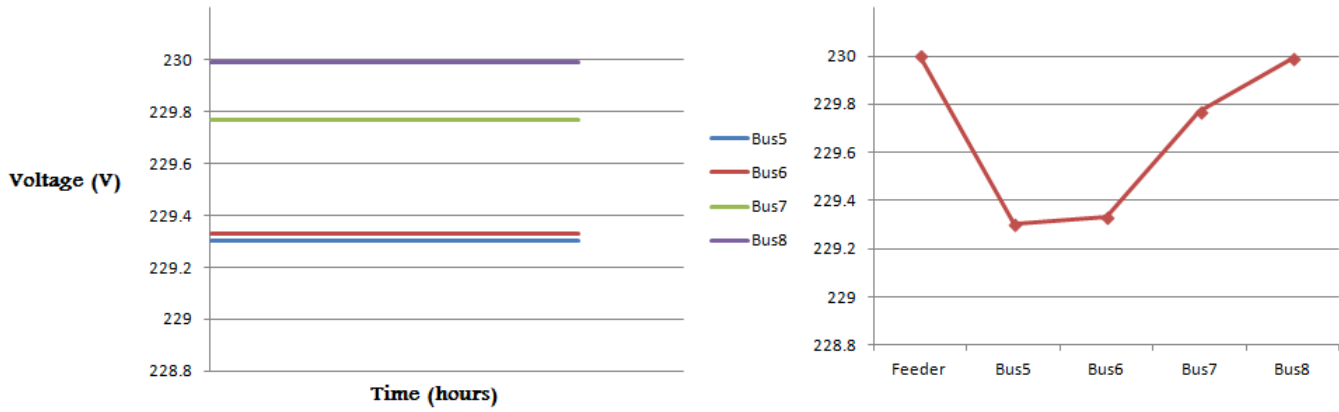


Figure 4.15: The impact of adding solar panels

Chapter 5

Simulating the Case Studies Using GridLAB-D

5.1 Introduction to the Software

GridLAB-D is an open source power system modeling and simulation environment developed by the United States Department of Energy specifically to integrate detailed power systems and end-use models [39]. Furthermore, GridLAB-D can simulate distributed power networks and analyze the impact of integrating renewable energy sources.

GridLAB-D is an agent-based simulator and capable of independently modeling the changes of devices or agents along the grid. It also models and simulates the interaction between different agents [8].

However, to simulate a mode in GridLAB-D, a GLM GridLAB-D model file must be written to be used as an input in GridLAB-D. In addition, there is no graphical user interface but rather a console (Figure 5.1), which makes working with GridLAB-D more difficult than other simulators which have a graphical user interface such as RAPSIm.

Recently, GridLAB-D has been widely used by researchers and therefore the simulator has been successfully used in many important applications which relate to the various challenges to be overcome, such as in [8]:

- **Volt-VAR Optimization:** to reduce energy consumption and avoid peak demand by lowering the voltage system, which can be achieved by using sensors and communication equipment, which increase the complexity of the system [41].
- **Real-Time pricing demonstration:** to reduce energy costs for both directions (customer and power provider). In [40], GridLAB-D was used in just such an application.

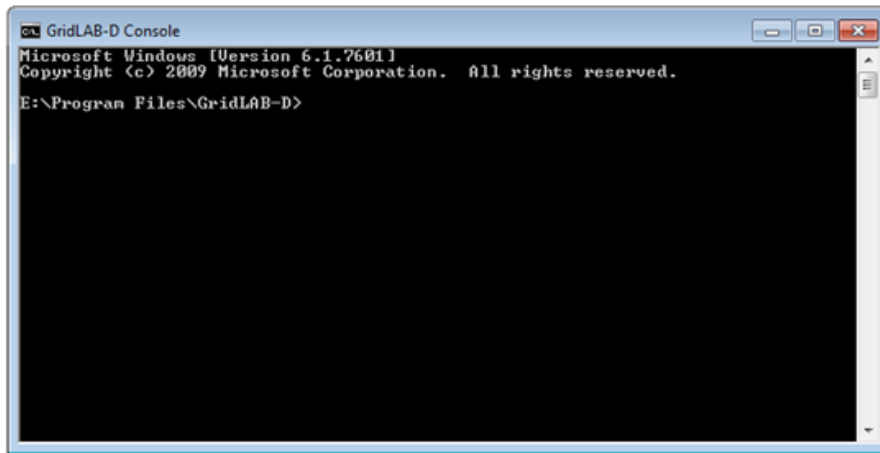


Figure 5.1: GridLAB-D Console

- Demand response for renewable integration: to improve energy efficiency, increase reliability, and modify load flow. An example of this using GridLAB-D can be seen in [6]

The main characteristics of GridLAB-D version 3.2 are outlined in the following paragraphs:

- GridLAB-D consists of modules which are six packages of classes. Depending on these packages, the related modules must be imported for the scenario that is being simulated. The various modules available in GridLAB-D version 3.2 are described below:
 1. Climate: objects can be imported to read data from specific file types such as CSV and tmy2.
 2. Residential: to declare objects such as houses and many household appliances such as washing machines and refrigerators. Values for attributes can be specified or left as default values.
 3. Power flow: based on a three-phase unbalanced distribution solver and has objects such as nodes, links, meters, and capacitors.
 4. Generators: to import objects related to renewable energy sources: battery, diesel, solar panel, and wind turbine.
 5. Tape: to input and output objects to read/write data from/to several possible sources of tape data such as Excel and MATLAB.
 6. Markets: for double-sided and single-sided auctions and appliance controllers.
- GridLAB-D offers a resolution for the time-series simulation variable of seconds through decades.

- GridLAB-D works with third-party data management and analysis tools.

5.2 Simulating the First Case

In GridLAB-D, models are implemented via text files with a .glm extension. Therefore, the steps for writing the code for the first case study are as follows:

First, the required modules must be imported or loaded:

- **Power Flow:** to add specific objects (e.g., a triplex meter) to form the interfaces between the power flow and the other objects in the grid.
- **Tape:** to save the results as a CSV file.
- **Generators:** to add the two solar panels and the wind turbine.
- **Residential:** to add eight houses and their parameters.
- **Climate:** to add a specific file for metrological data.

```
module powerflow;
module tape;
module generators;
module residential;
module climate;
```

Then, the time parameter must be set to a duration of one month, starting from the first month of the year. Next, climate data can be added using the "WA-Yakima.tmy2" file downloaded from (SourceForge) website ¹. At this stage, the same generated file for climate information that was used in RAPSim could not be used because of the difference in the factors of climate data between GridLAB-D and RAPSim.

```
clock {
  timezone PST+8PDT;
  starttime '2001-01-01 00:00:00';
  stoptime '2001-01-31 00:00:00';
}

object climate {
  tmyfile "WA-Yakima.tmy2";
}
```

¹<https://sourceforge.net/p/GridLAB-D/code/HEAD/tree/>

The next step is adding the electrical elements which are the load and the generators (solar panels-substation). However, since the first case study was simulated in RAPSIm using the simple power destination algorithm without considering power losses, the objects were placed in GridLAB-D without any specification for transmission lines or conductors. For the load, we used a triplex-load object instead of a house object because we need to set a constant value for the demand, which is not available in GridLAB-D for a house object, more details about that are discussed in the second case study. Furthermore, some objects cannot be placed directly in GridLAB-D in the same way as in RAPSIm, for instance, to add solar panels, an object (an inverter) must be added. The remainder of the .glm file is presented as follows:

```
// to connect wind turbine to power flow
object meter {
    name meter1;
    phases ABC;
    nominal_voltage 230;
}
object windturb_dg {
    parent meter1;
    phases AS;
    name windTurbine;
    Gen_status ONLINE;
    blade_diameter 1;
    wind_speed 0.5;
    Rated_VA 1500;
    power_factor 1.0;
    Gen_type SYNCHRONOUS;
    Gen_mode CONSTANTP;
    Turbine_Model 0; // GENERIC_SYNCH_SMALL
}

// to connect house1 with its solar panels to power flow
object triplex_meter {
    name triHouse1;
    phases AS;
    nominal_voltage 230;
    object triplex_load {
    name house1_load;
        phases AS;
        base_power_1 500;
        power_pf_1 1.00;
        power_fraction_1 1.00;
    }
}
```

```

};
};
object inverter {
    name inv_PV;
generator_mode CONSTANT_PF;
use_multipoint_efficiency TRUE;
maximum_dc_voltage 230;
maximum_dc_power 500;
minimum_dc_power 500;
rated_power 0.5;
group_rated_power 500;
    phases AS;
    generator_status ONLINE;
    inverter_type PWM;
power_factor 1.0;
    object solar {
        name solar1;
        generator_mode 5;
        generator_status ONLINE;
        panel_type SINGLE_CRYSTAL_SILICON;
        efficiency 0.2;
        area 20;
    };
};
}

// to connect house2 without solar panel to powe flow
object triplex_meter {
name triHouse2;
phases AS;
nominal_voltage 230;
object triplex_load {
    name house1_load;
phases AS;
    base_power_1 500;
    power_pf_1 1.00;
power_fraction_1 1.00;
};
};
}

// to connect house3 with its solar panel to powe flow
object triplex_meter {

```

```

name triHouse3;
phases AS;
nominal_voltage 230;
object triplex_load {
    name house1_load;
    phases AS;
    base_power_1 700;
power_pf_1 1.00;
power_fraction_1 1.00;
};
};
    object inverter {
        name PV2;
generator_mode CONSTANT_PF;
use_multipoint_efficiency TRUE;
maximum_dc_voltage 230;
maximum_dc_power 700;
minimum_dc_power 700;
rated_power 0.07;
group_rated_power 700;
    phases AS;
generator_status ONLINE;
inverter_type PWM;
power_factor 1.0;
    object solar {
        name solar3;
generator_mode 5;
generator_status ONLINE;
panel_type SINGLE_CRYSTAL_SILICON;
efficiency 0.2;
area 20;
    };
};
}

```


Finally, an output file must be specified which can be done by adding a (record) or (multi-record) object:

```
object multi_recorder {
property measured_real_energy,Solhouse3:VA_Out,house3:total_load;
file "House3withSolar.csv";
interval 3600; // every one hour
limit 720; // for one-month
};
```

This command is then executed in the GridLAB-D console:

```
<HOST>gridlabd FileName.glm
```

5.2.1 Simulation Results

Figure 5.2 illustrates measurements of the power for two solar panels. Solar1 and solar2 have the same measurements. The peak load in two days are noticeable where the results are shown for a two-day simulation.

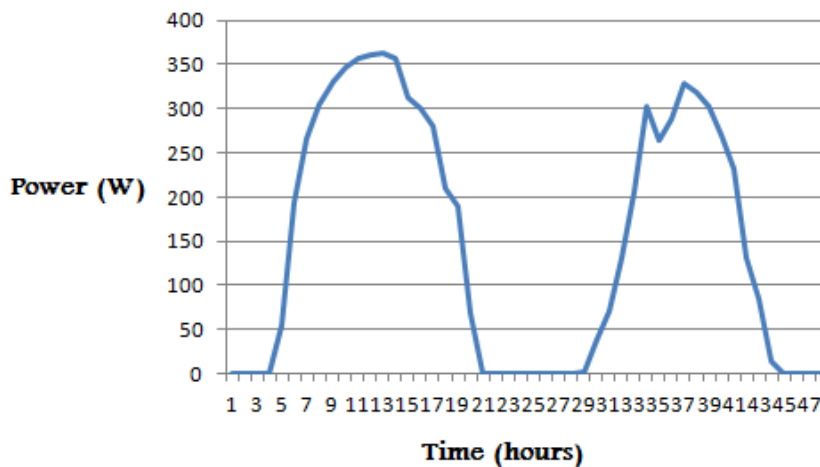


Figure 5.2: Power from solar panels

Figure 5.3 shows the power at the wind-turbine object. Because different weather information was used for each simulator, different results can be observed. As an example, the RAPSIm results do not display the zero value for production, unlike the GridLAB-D results.

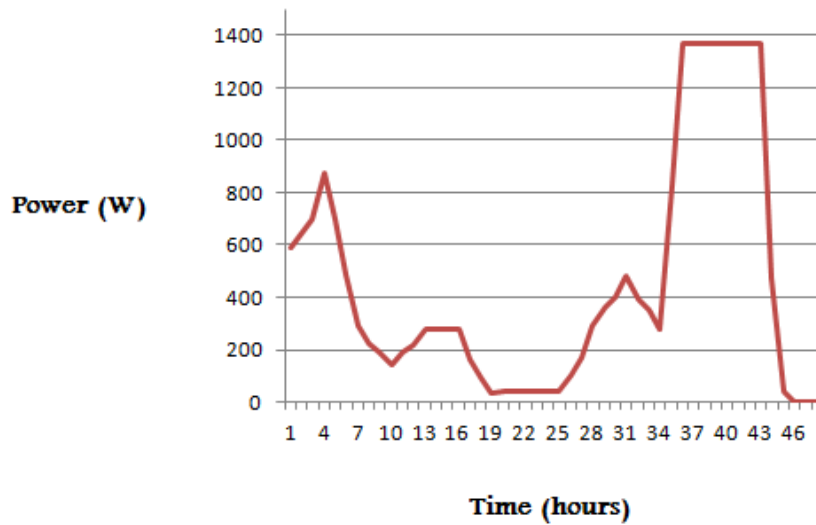


Figure 5.3: Power from wind turbine

5.3 Simulating The Second Case

The second case study was implemented similarly to the first, with a few notable differences:

In the second case study, the resistance was specified for the transmission lines (made of copper).

```
object line_configuration {
    name line_config_1;
    z11 0.203;
}
object node {
    name node1;
    phases AS;
    nominal_voltage 230;
};
object overhead_line {
    name line1;
    phases AS;
    from node1;
    to tri1;
    length 196.85;
```

```
configuration line_config_1;  
}
```

```
object triplex_node {  
name tri1;  
phases AS;  
nominal_voltage 230;  
};
```

```
object triplex_meter {  
name Tri_Meter1;  
phases AS;  
nominal_voltage 230;  
object house {  
name house1;  
object ZIPload {  
    name house1_load;  
    base_power 0.5;  
power_pf 1;  
};  
};  
}
```

```
object triplex_meter {  
name Tri_Meter2;  
phases AS;  
nominal_voltage 230;  
object house {  
name house2;  
object ZIPload {  
    name house2_load;  
    base_power 0.5;  
power_pf 1;  
};  
};  
}
```

As in the case when RAPSim was used, solar panels were then added to one of the two lines to determine the impact on voltages.

5.3.1 Simulation Results without Solar Panels

There are eight triplex meters which interface with the power flow and all of them are working in two-phase mode. However, it would be useful to see how GridLAB-D simulates voltage changes for each triplex meter. Figure 5.4 shows voltage changes over two days for all triplex meters for one phase:

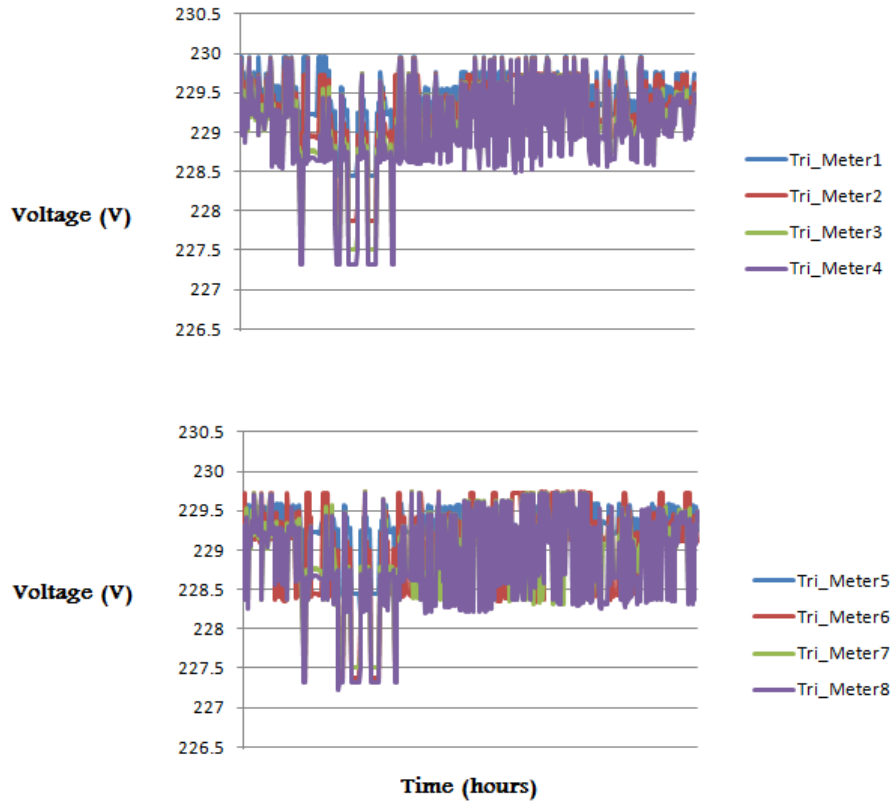


Figure 5.4: Voltage changes in triplex-meter1 and triplex-meter2

5.3.2 Simulation Results including Solar Panels

Solar panels were added to the triplex-node, which is connected to four houses using their triplex-meters. Figure 5.5 shows similar results as Figure 5.4 but shows the impact of adding solar panels. It can be seen that there is an effect on triplex-meter5, triplex-meter6, triplex-meter7, and triplex-meter8:

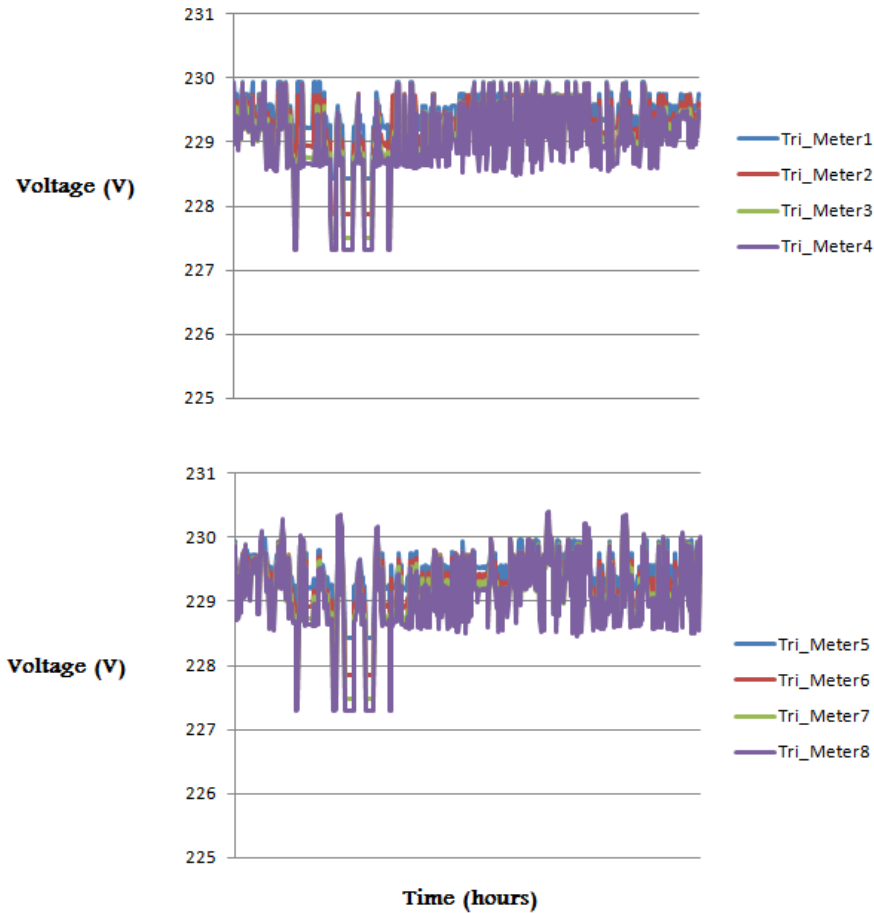


Figure 5.5: The impact of adding solar panels

The properties of a house object in GridLAB-D have no parameter to specify a constant load as we can in RAPSIm. The demand for a house in GridLAB-D model is thus fluctuating over time and therefore we can see voltage changes in Figure 5.4 and Figure 5.5.

However, the house object in GridLAB-D is basically set up to replicate a physical house, with variable loads and behavior, but in case we want to use a constant load on the system, we can either use a triplex-load object connected to the powerflow, or use a zipload object and specify a constant power load.

In the following, an example of using triplex-load as a load instead of house object is presented:

```
object triplex_meter {
name Tri_Meter5;
phases AS;
nominal_voltage 230;
object triplex_load {
name house5_load;
phases AS;
    base_power_1 5000; // constant demand with 5000 W
power_pf_1 1;
};
}
object triplex_meter {
name Tri_Meter6;
phases AS;
nominal_voltage 230;
object triplex_load {
    name house6_load;
phases AS;
    base_power_1 5000; // constant demand with 5000 W
power_pf_1 1;
};
}
object triplex_meter {
name Tri_Meter7;
phases AS;
nominal_voltage 230;
object triplex_load {
    name house7_load;
phases AS;
    base_power_1 5000; // constant demand with 5000 W
power_pf_1 1.00;
};
}
object triplex_meter {
name Tri_Meter8;
phases AS;
nominal_voltage 230;
object triplex_load {
name house8_load;
phases AS;
    base_power_1 6000; // constant demand with 6000 W
```

```

power_pf_1 1.00;
power_fraction_1 1.00;
};
}

```

Figure 5.6 illustrates voltages for tri-meter5, tri-meter6, tri-meter7, and tri-meter8. However, adding solar panels with its inverter can only be attached to a triplex-meter or meter object and any other objects like triplex-load, solar panels works in "stand-alone" mode, where it doesn't actually interface with the powerflow model.

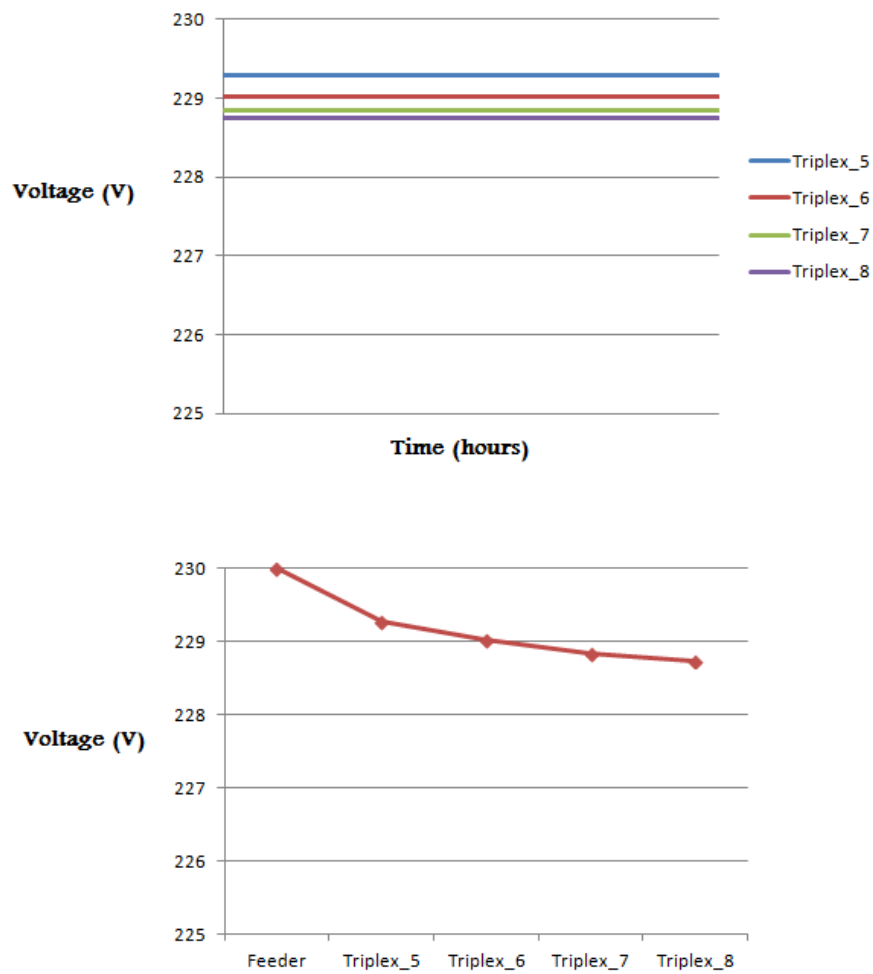


Figure 5.6: Constant demand using GridLAB-D

Chapter 6

Conclusion and Discussion

6.1 Discussion

Numerous studies have been conducted to simulate smart grid scenarios using GridLAB-D. GridLAB-D has been used more widely than RAPSim. RAPSim is designed for microgrid simulation, whereas GridLAB-D is more oriented towards the whole smart grid. The approach used throughout this thesis involved designing two scenarios and first simulating them using RAPSim then using GridLAB-D.

Both simulators are open source and appear promising for smart grid simulation. Both RAPSim and GridLAB-D are still in development, but currently GridLAB-D is more reliable and is recommended for simulating power flow and demand response scenarios. In addition, GridLAB-D has a large number of objects compared with RAPSim, e.g., RAPSim has no battery object, which is a basic microgrid component.

RAPSim provides lattice visualization with a user-friendly interface to place eight types of objects: solar panels, wind turbines, houses, power lines, connectors, fuel generators, power plants, and grid connections. The properties for these objects are extensible which holds great promise for developers. GridLAB-D offers many specific objects for modeling power flow such as capacitors, regulators, inverters and meters. However, GridLAB-D has no GUI which makes implementing scenarios more difficult and requires greater expertise from users.

For the first case study, both simulators were used to simulate power distributed generation as a simple calculation with a time resolution of one hour. Using different weather data gave different results, for example, there was no zero value-production for wind turbines using RAPSim but this appeared in GridLAB-D.

For the second case study, both simulators simulated the impact of voltage of adding a solar panel in the scenario. The configuration for the second case study in GridLAB-D was more complex than in RAPSim. However, RAPSim has a longer computation time than GridLAB-D for a one month simulation with a resolution time of one hour.

6.2 Conclusion

This thesis presented two recently developed smart grid simulators. The simulators have a number of similarities, including being free and open source, as well as offering power simulation and the ability to simulate distributed and renewable energy sources. GridLAB-D is more suited to studies that include modeling and simulating residential loads and power flow optimization. RAPSim is suited to the classroom environment and teaching the main concepts for the smart grid and simulating the microgrid.

Throughout this thesis, the importance of the smart grid was highlighted, as well as the components that must be simulated along the grid. Current technologies for simulating the smart grid were presented, as well as the many challenges which have emerged, such as the need for modeling and integrating distributed energy sources, ICT, and smart meters. An overview for smart grid modeling and simulation was presented, and the various challenges were grouped into three main categories: power flow, co-simulation, and demand response.

Finally, the conclusions of this thesis were based on two case studies (also referred to in this thesis as scenarios), both of which were simulated with RAPSim and GridLAB-D. Although still under development, GridLAB-D was seen to be a satisfactory simulator, especially for residential and power flow modeling. The GridLAB-D website shows many models and new features that will be released with the next version when the implementation is concluded. RAPSim is more suited to beginners, e.g., for high school teaching. It may also be of interest to follow the ongoing development of both simulators as and when subsequent versions are released.

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