Software-Defined MicroGrid Testbed for Energy Management

SOFTWARE-DEFINED MICROGRID TESTBED FOR ENERGY MANAGEMENT

BY

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To my Parents,

my Gurus,

Family and Friends

Abstract

The advent of small-scale, distributed generators of energy has resulted in the problem of integrating them in the conventional electric power system, which is characterized by large-scale, centralized energy generators. *MicroGrids* have emerged as a promising solution to the integration problem and have duly received increasing research attention. Microgrids are semi-autonomous collections of controllable microsources and loads, which present themselves to the utility grid as single, controlled entities. In order to achieve the semi-autonomous and controlled nature of microgrids, especially, overcoming the challenge of balancing demand and power generation, an intelligent energy management scheme is required.

Developing an energy management scheme is an interesting and challenging task, which provides the potential to exploit ideas from a plethora of fields like Artificial Intelligence and Machine Learning, Constrained Optimization, etc. However, testing energy management strategies on a microgrid would pose a multitude of problems, the most important of them being the unreliability and inconvenience of testing an energy management strategy, which is not optimal, on a functional microgrid. Errors in a test strategy might cause power outages and damage installed devices. Hence it is necessary to test energy management strategies on simulated microgrids.

This thesis presents a *Software Testbed of MicroGrids*, specifically designed to suit the purposes of development of energy management strategies. The testbed consists of two components: *Simulation Framework* and *Analysis Tool*. The modular simulation framework enables simulation of a microgrid with microsources and loads, whose configurations can be specified by the user. The analysis tool enables visual analysis of data generated using simulations, which would enable the improvement of not only the management strategy and prediction techniques, but also the computer models used in the simulation framework. A demonstration of the software testbed's simulation and analysis capabilities is presented and possible directions for future research are suggested.

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Abbreviations and Notations

List of Abbreviations

AC	Alternating Current
CDS	Cognitive Dynamic Systems
CHP	Combined Heat and Power
CWEC	Canadian Weather year for Energy Calculations
DC	Direct Current
DER	Distributed Energy Resources
DG	Distributed Generation
EM	Energy Manager
FIT	Feed-in Tariff
IDAPS	Intelligent Distributed Autonomous Power Systems
IEA	International Energy Agency
IESO	Independent Electricity System Operator

MC	Microsource Controller
NG	Natural Gas
OECD	Organisation for Economic Co-operation and Development
PCC	Point of Common Coupling
PV	Photo-Voltaic
SD	Separation Device
SQRA	Security, power Quality, Reliability and Availability
STC	Standard Test Conditions
UPS	Uninterruptible Power Supply

List of Notations

$\alpha(day)$	Daily load scalar representing fluctuations in the load profile due to changes in weather, production loads, etc.
$\beta(day, time)$	Disturbance term representing load dips and peaks due to turning on and off of large machinery
$AverageLoad(time)$	The monthly average load at a given time, obtained from historic data
G_{ING}	Incident irradiation
G_{STC}	Irradiation at Standard Test Conditions
k	Temperature coefficient of power for a PV module

$Load(day,\ time)$	Load demand on a given day and time
$Load\ Demand_{\mu-grid_{pred}}(n)$	Predicted load demand for a given simulation day and time in the same year as the one used for simulating load demand in the load module
$Load\ Demand_{province}(n-1)$	Provincial load demand for the corresponding date and time in the year preceding the one used for simulating load demand in the load module
$Load\ Demand_{province}(n-2)$	Provincial load demand for the corresponding date and time in the year two years prior to the one used for simulating load demand in the load module
P_{PV}	Output power of the PV module at incident irradiation G_{ING}
P_{STC}	Output power of the PV module at Standard Test Conditions
T_c	PV cell temperature
T_r	Reference temperature for PV computer model calculation
$Data_i$	The sequence of interpolated hourly fuel consumption data for a given percentage load point i for the natural gas generator
BR	Circuit Breaker

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Chapter 1

Introduction and Problem Statement

The way traditional electric power systems, throughout the world, are designed and operated has not undergone drastic changes for almost a century. These power systems are vertically integrated: power is generated centrally, at facilities capable of generating thousands of megawatts of power; transmitted over long distances through high-voltage transmission lines, usually involving transmission losses; and distributed to consumers using local distribution networks, which operate at lower voltages, by drawing power from various points along the transmission lines. A schematic illustration of such systems is shown in Figure 1.1. However, the present need to address climate-change and to reduce environmental impact, economic considerations, emphasis on efficiency and reliability, deregulation and the availability of new power-generation technologies have all factored in the advent of *Distributed Energy Resources.*

The term 'Distributed Energy Resources'(DER) denotes both power sources and

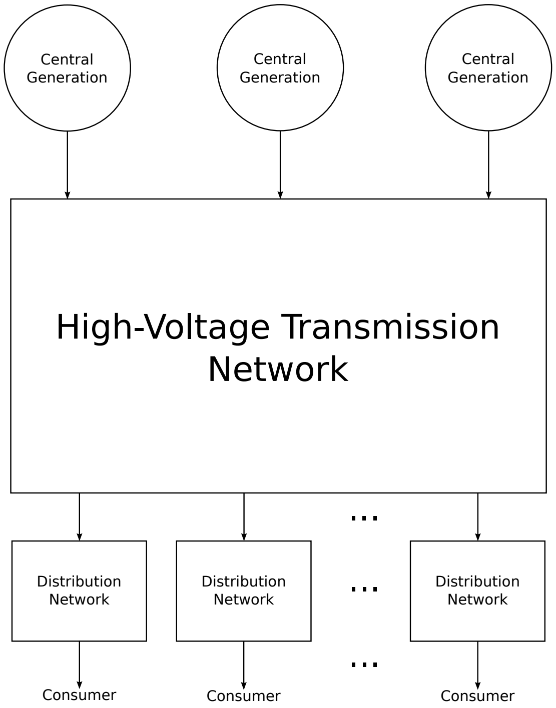

Figure 1.1: Schematic of conventional, vertically integrated power systems

controllable loads, characterized by their locations being situated closer to where power is consumed, usually to the distribution networks and their scale being much smaller in terms of wattage. Some in the industry and certain regulatory authorities impose stricter definitions of what can be called distributed energy resources, in most cases, based on the voltage and power levels at which they operate. For instance, Borbely and Kreider (2001) define distributed generation as those technologies whose outputs are below 10MW and are located close to the load they serve. This definition effectively rules out the possibility of wind and hydro-electric power generators to be termed distributed generators, since these technologies do not always operate close to the loads they serve. Electric power systems which make use of DERs are termed *Distributed Energy Systems*(DES). El-Khattam and Salama (2004), Ackermann *et al.* (2001), Pepermans *et al.* (2005) and OECD and IEA (2002) present detailed surveys of DER technologies, classify them in groups and provide necessary definitions of related terminology.

1.1 Factors Contributing to the Emergence of DERs

Pepermans *et al.* (2005), OECD and IEA (2002) and Jenkins *et al.* (2009) discuss factors which drive the trend towards DERs and issues which might hinder their progress. In this section, some of the factors which aid their emergence in the energy sector will be discussed.

1.1.1 Deregulation of Energy Markets

Liberalization of energy markets by Governments in developed economies has given rise to fierce competition among energy suppliers. In such a scenario, energy suppliers need to find ways to adapt to changing market conditions in an economically profitable manner. For instance, suppliers might need to find flexible ways to manage peak use demand or to expand existing infrastructure to accommodate new users, while at the same time providing ancillary services to maintain grid stability. Many Distributed Generation(DG) technologies provide such flexibility to suppliers.

In cases where DG technology is used to expand network, it will result in large savings on transmission and distribution costs which the supplier might need to bear if power was generated centrally. In addition to that, transmission losses will be reduced by virtue of the generator being closer to demand. Suppliers can plan and choose their DG technology so as to source fuel locally. For example, a distributed generator which runs on land-fill gas could be built near land fill sites. Moreover, one may use a distributed source to produce both heat and electricity. Such sources are called Combined Heat and Power(CHP) sources. CHPs can result in high energy efficiencies of around 75%, according to Tselepis *et al.* (2003). Thus, benefits, such as those described above, will result in energy suppliers preferring DERs over conventional energy resources.

1.1.2 Green Energy Policies and Environmental Concerns

With growing world-wide apprehension regarding the issue of climate change, accelerated by human influence, Governments across the globe are becoming increasingly active in effecting the reduction of greenhouse gas emissions and promotion of sustainable and renewable energy technologies. For instance, according to Jenkins *et al.* (2009), the European Union has set itself the target of producing 20% of its total energy needs with renewable energy sources by the year 2020. The US state of California has set a similar target of achieving 33% of its total energy produced by renewable energy sources by 2020. Many scientists suggest that there needs to be an 80% reduction in green house gases by the year 2050, if we hope to maintain the raise in temperatures to within 2° C above current averages.

Electric power generation sector provides an easier and more immediate opportunity to achieve greenhouse gas targets compared to transportation and other sectors. To achieve said targets, most Governments have formulated policies which encourage usage of zero to low carbon energy. Such policies facilitate implementation of devices such as *Feed-in Tariff* (FIT) and *Carbon Taxing* programs. Feed-in Tariff programs reward contracted renewable energy producers with a higher-than-market-value price for each kilowatt-hour(kWh) of electricity they produce, in order to encourage investment in renewable energy technologies. Carbon Taxes are taxes levied on the amount of hydrocarbons burnt by energy producers, based on the carbon content of the fuel. An example of such a program to encourage the use of distributed and renewable energy resources is Ontario's *microFIT* program, a feed-in tariff program which rewards use of most of the small-scale renewable technologies available in the market.

1.1.3 Reliability

Problems related to reliability in an electric power system are those of outages. Once DGs begin to be used widely by energy suppliers, emphasis on cost effectiveness might see reliability being assigned lower priorities. However, provision of reliable power supply is crucial to industries and many customers. According to OECD and IEA (2002), distributed generation technologies such as fuel cells and diesel generators, backed up by storage and support devices such as flywheels and UPSs(Uninterruptible Power Supplies) will play a valuable role in addressing these issues.

1.2 Technological Challenges

The emergence and popularity of DERs will pose challenges on many fronts: policies, regulations, technological and economic. This section is dedicated to the discussion of technological challenges with introduction and integration of DERs with current infrastructure. Jenkins *et al.* (2009) gives a very good review on this topic.

With instantaneous balancing of power demand and supply being a necessity in power systems, any power generated by DGs must be compensated by an equivalent reduction in power generated by central power stations. There will be challenges arising with integration of distributed generation due to the fact that conventional distribution networks were designed to facilitate flow of power from higher to lower voltage circuits. In addition to that, as the proportion of power supplied by DG technologies increases, DGs have to take on the responsibilities for providing ancillary services which were traditionally provided by central generators. These ancillary services would include the capability to respond to frequency drops to maintain grid stability, reactive voltage and power control etc. In a conventional power system these services were provided, *passively*, without the need for a system operator. However integrating DERs in distribution network and providing ancillary services would require *active control*: decisions and actions by system operator(either manual or computerized).

1.2.1 Solutions

In order to overcome the challenges discussed above, solutions need to be devised. Wang and Nehrir (2004) and Söderman and Pettersson (2006) propose solutions for optimal placement of DG sources in a distribution network to maximize efficiency; the latter also proposes optimal operating strategies for such sources. However, these solutions do not consider integration of DERs while providing active control for power management and ancillary services.

A good solution to the challenge of integrating distributed energy resources into current distribution networks must involve the use of mixed technologies for power sources, in order to facilitate the ability to respond to network disturbances. Controllability and flexibility can be introduced through the use of *smart* technologies like Smart Grids. *Smart Grids* are future electric power networks which make use of information and communication technologies to provide flexible, secure, clean and efficient power to consumers. A report by Standing Committee on Natural Resources (2009), presented in the Canadian House of Commons is in tune with these ideas and proposes integrated energy systems, incorporating resource management, efficient, diverse and flexible power sources. It also recommends economic stimuli for such systems in the form of rebates and tax incentives among others. One of the solutions, which incorporates many of the ideas mentioned above, is a concept called the *MicroGrid*; it proposes a controllable, flexible and secure integration of local power generation and loads. MicroGrids will be described in the next section.

1.3 MicroGrid

According to the *Consortium for Electric Reliability Technology Solutions*(CERTS) definition of a MircoGrid, presented in Lasseter *et al.* (2002):

> The MicroGrid is an aggregation of loads and microsources operating as a single system providing both power and heat. The majority of the microsources must be power electronic based to provide the required flexibility to insure operation as a single aggregated system. This control flexibility allows the MicroGrid to present itself to the bulk power system as a single controlled unit which meets local needs for reliability and security.

In addition, microgrids have the capability to isolate themselves from the utility power grid in case of faults in the grid, in order to protect the microsources and loads within the microgrid. This mode of operation is called the *islanded mode*, in which the microgrid operates independently until stability is restored in the utility grid, at which point the microgrid re-establishes links with the utility grid.

Microgrids contain an *Energy Manager* within them, which is responsible for maintaining balance between energy demand and supply within the microgrid by the use of an *energy management strategy*, while making sure certain criteria such as minimizing operating cost, fuel comsumptions, emissions etc. are met. Microgrids are expounded upon in Chapter 2.

1.4 Problem Statement

McMaster University's campus has several microsources and a local university grid. The microsources available are six natural gas powered reciprocating engines located in the Hamilton Health Sciences: McMaster Hospital and photo-voltaic modules installed on building rooftops. This provides an opportunity to build a microgrid on campus using existing facilities, with an intelligent and efficient energy management strategy.

When one wishes to develop an energy management strategy, it is cumbersome and expensive to test them on actual microgrids. Moreover, it is not desirable to test a management strategy on a campus microgrid which would serve several critical loads like a hospital, electron microscopes, particle accelerators etc. because of the power disruptions it might create. In order to address this problem, it is proposed that a *software testbed of a microgrid*, capable of employing computer models of microsources and loads which mimic the behaviour of their physical counterparts, be developed. In effect, the problem addressed in this thesis is:

> The development of a software testbed of a microgrid, which comprises a simulation framework and an analysis tool, in order to facilitate the development of energy management strategies for microgrids.

1.5 Organization of the Thesis

Subsequent chapters will explain the microgrid and the testbed in greater detail. Chapter 2 expounds on microgrid structure and operation. It also presents the design of the microgrid structure to be used in the microgrid testbed. The architecture of the simulation framework and the different software modules which make up the framework are described in Chapter 3. Chapter 4 contains the description of the analysis tool, its structure and demonstrations of the capabilities of the simulation framework and analysis tool. The author's conclusions are presented in Chapter 5 along with a discussion on possible future research directions.

Chapter 2

MicroGrids

A microgrid, as described in the previous chapter, is a collection of distributed power generators and loads acting together. To the utility grid, it presents itself as a single, self-controlled system and behaves in a manner such that, the microgrid, at the very least, follows grid rules and causes no more harm than is acceptable from existing customers. In addition, it may also provide power back to the grid and offer ancillary services locally.

This chapter describes the structure of a typical microgrid, information essential for energy manager design, the proposed microgrid design to be simulated to facilitate energy manager design. References are provided, wherever necessary, if one is interested to read further on a topic. Lasseter *et al.* (2002), Jiayi *et al.* (2008), Driesen and Katiraei (2008), Lasseter and Paigi (2004) and Lasseter (2002) provide good introductions to the microgrid concept, decribe its architecture, components and operation well, offer good insights into benefits and features of microgrid systems and review and survey some of the microgrid projects which have been implemented. Before one studies the structure of microgrids, it is important to understand the features which any design of a microgrid must facilitate. These features are described below.

Control and Flexibility The use of distributed generation in microgrids will necessitate the use of means to control and regulate voltage and power flow in the microgrid. In addition, it is desired that a *dynamically adaptable* design be adopted in the microgrid design, i.e., the design must incorporate plug and play simplicity to provide for addition and/or removal of new microsources without requiring any change in other microsources in the microgrid and without greatly affecting the dynamics of the microgrid. This can be achieved by the use of fast, power electronics based inverters to interface microsources to the microgrid.

Effective Energy Management A microgrid requires an intelligent system to supervise and manage energy demand and generation within the microgrid. The energy management system must make decisions such as whether to opt for purchase of energy as against local generation, based on economic considerations, fuel prices and fuel availability etc. In essence, an intelligent energy management strategy is required to supervise the microgrid and to facilitate semi-autonomous operation. Moreover, a dynamically adaptable microgrid requires advanced supervision to ensure smooth transition of the microgrids to new environments created by the addition and/or removal of microsources.

Protection and Heterogeneous Quality of Service In the event of occurrence of a fault in the microgrid or in the utility grid to which the microgrid is connected, the microgrid or part of the grid needs to be isolated, so that faults affect the least number of sources and consumers in the microgrid. This can be effected by implementing a series of circuit breakers and relays, strategically placed throughout the microgrid and controlled by a protection coordinator.

In cases when the whole microgrid is isolated, called islanding, dispatch of some non-critical load might have to be cancelled or postponed, depending on instantaneous power generation capacity, future power requirements and fuel availability in the microgrid. This scenario is a typical example of the concept of *heterogeneous quality of service*, which is essential in microgrids. The term quality of service in an electric power system is used to signify Security, power Quality, Reliability and Availability(SQRA) of power. Conventional power systems attempt to provide uniform(homogeneous) quality of service to all consumers, spread across large geographical areas. Marnay (2007) discusses the economic advantages of using heterogeneous quality of service in the future as energy demand increases. The work also proposes microgrids as a potential solution for implementing heterogeneous quality of service locally.

2.1 MicroGrid Architecture: Distributed Energy Resources

Figure 2.1 shows the schematic of a typical microgrid, shown here with 4 microsources. The *Point of Common Coupling*(PCC) defines the point of separation between the utility grid and the microgrid and is followed by a step-down transformer(not shown in figure). In the rest of this section, the distributed energy resources in microgrids are discussed, while the next section deals with the controls in a microgrid.

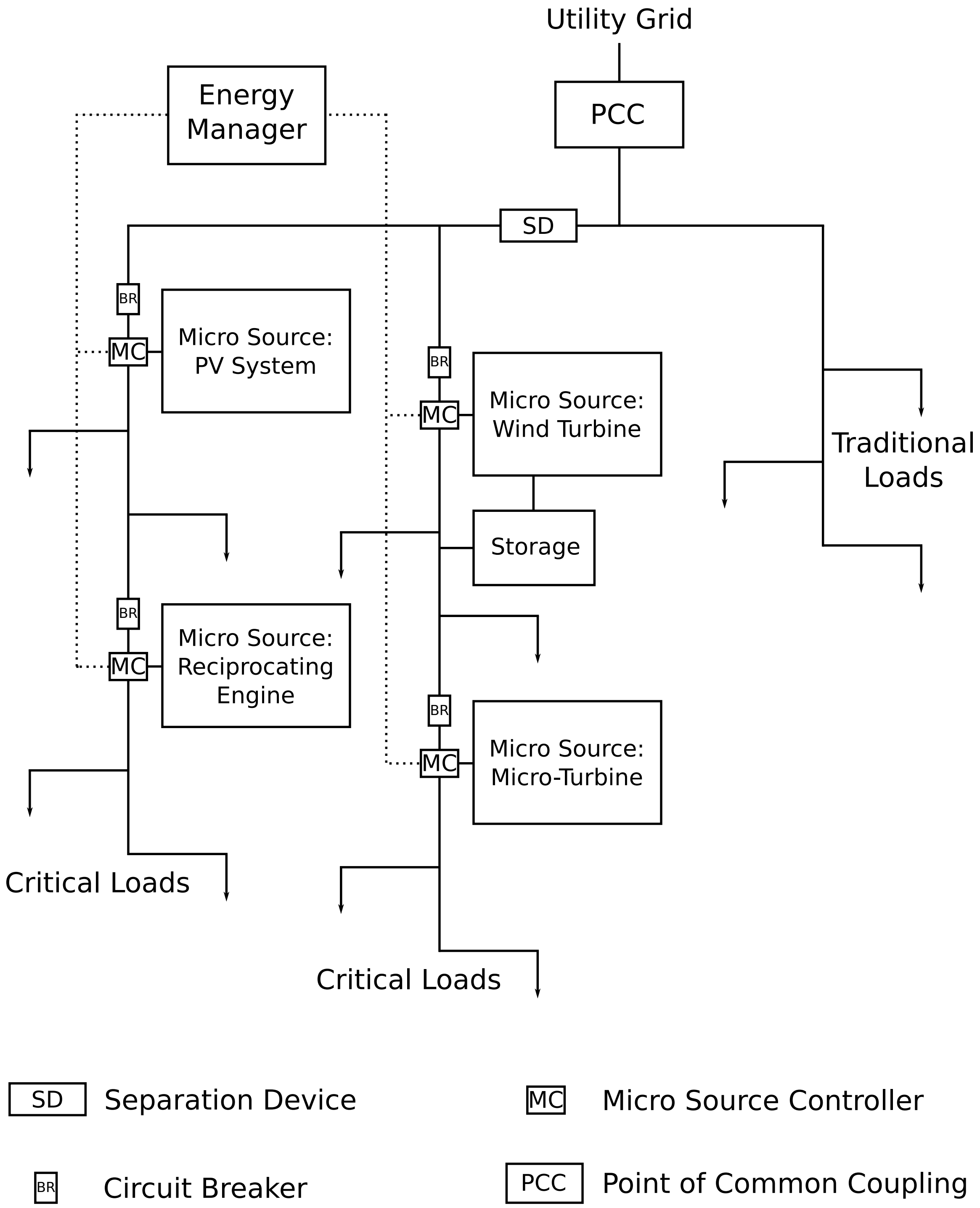

Figure 2.1: Schematic of a typical MicroGrid

2.1.1 Microsources and Storage Devices

Microsources, which generate power locally within microgrids, can be of different types based on the technology they use. Their primary fuel might be renewable or hydrocarbon based. Most distributed generators need power electronics based inverters to interface with microgrid feeders. The different kinds of microsources which were considered for the microgrid structure for the testbed are discussed in Appendix A.

Storage devices are required in microgrids mainly as back-ups and to help the grid when load points change more rapidly than microsources can handle. Storage devices may also be used to capture excess energy produced by temperamental microsources such as photo-voltaic and wind based generators, as well as being used as a means to store energy for later use, when it is cheaper in the market. They could take the form of electrical storage such as batteries and mechanical storage such as flywheels among others. Wood (2008) gives a good account of several microsource and storage technologies.

2.1.2 Loads

As previously discussed, microgrids are a means to provide heterogeneous quality of service locally. This means that certain loads would have to be treated preferentially over others. This might be done to reschedule dispatch of a particular load to a different time when energy prices are at their peaks, or in islanded mode when certain loads might have to be shed due to limited available generation capacity. Thus, as explained by Firestone and Marnay (2005), loads in microgrids can be classified as *critical*, *curtailable*, and *reschedulable* loads.

Critical Loads

These are loads which must be serviced at all times. These are usually vital equipments such as web or data servers, hospital apparatus, etc. These loads ought to be treated, by the microgrid, in preference to any other load in the microgrid and shall not be shed when there is a shortage of power or when it is economically unviable to meet the demands of all the loads.

Curtailable Loads

These are a certain kind of loads which can be flexible with their demands, i.e., their demands can be lowered to satisfy certain conditions like monetary savings and reduction of emissions. For instance, devices which are used for space heating and cooling such as boilers and chillers, can be set to operate at lower operating points. Load curtailment depends on several factors such as the choice between the acceptable level to which demands can be lowered and amount of money saved, time, cost and frequency of curtailments, etc.

Reschedulable Loads

Some load demands are flexible in that, they do not need to be serviced at a fixed point in time. Dispatch of such loads can be moved forward or backward in time. This gives the energy management strategy the ability to plan the dispatch of loads beforehand, in the most suitable schedule. For example, chillers may be run earlier than morning rush hour in corporate buildings, so that electricity consumption during day time, when energy prices are high, is reduced.

2.2 MicroGrid Architecture: Controls

The characteristic features of microgrids, which were explained earlier in the chapter, cannot be achieved without controlling microgrid operations at various levels. There are three distinct types of controls in microgrids. They are discussed below.

2.2.1 Microsource Control

Microsource controllers(MC), depicted in Figure 2.1, are fast acting, power electronics-based controllers used for local control, mainly voltage and power regulation, in a microgrid. Each microsource has a dedicated microsource controller. Microsource controllers are required to respond to any locally measured voltage or power changes in a short time in the order of milliseconds and, in most microgrid designs, do not rely on fast communications with other MCs.

Their main functions include regulation of power and voltage when loads points in the microgrid change. The energy manager dispatches set point values at which the microsource should operate to the corresponding MC and the MCs make sure stable voltage and power values are maintained. They also play an important role in islanding and reconnection of the microgrid, by ensuring that load demand is shared by all microsources in the microgrid and that resynchronization with the utility grid is achieved when the microgrid reconnencts to the utility grid. These capabilities are achieved through control techniques such as *voltage regulation through droop* and *frequency droop for power regulation*, etc., as described by Lasseter *et al.* (2002) and Lasseter (2002). A lot of research efforts have focused on proposing design solutions to achieve such control capabilities in microgrids. Some of them are mentioned below.

Zoka *et al.* (2004) study interaction problems in an islanded microgrid by using simulations, while Katiraei *et al.* (2005) use simulations to show how power electronics interfaced microsources can maintain stability and voltage quality by means of fast control. Kariniotakis *et al.* (2005) present a simulation platform with dynamic modelling and analysis capabilities for various microsources. This would be suitable for testing microsource control techniques. Pogaku *et al.* (2007) present sensitivity analysis of autonomous operation of inverter based microgrids, in order to develop state-space models of inverters for small signal modelling. Katiraei and Iravani (2006) propose 3 real and reactive power management systems for reactive power control based on voltage droop characteristics, voltage regulation and load reactive power management. Application of small signal analysis to study stability of droop control microgrids is presented by Barklund *et al.* (2008). Ito *et al.* (2004) discuss control without communications in DC microgrids to suppress circulating currents, whereas Li *et al.* (2004) propose a unified controller to perform the functions of MCs. Prodanović and Green (2006) present distributed control of coordinated inverters to maintain high power quality and to achieve suppression of circulating currents in a power park microgrid.

2.2.2 MicroGrid Protection

In order to enable islanding in microgrids and isolation of parts of it to protect microsources and loads from faults, fast switches, circuit breakers or digital relays need to be placed strategically throughout the microgrid. This setup is depicted in Figure 2.1. The *separation device*(SD) helps island the microgrid and *circuit breakers*(BR) enable isolation of sections of the microgrid. It may be noticed that traditional loads which lack integrated controllers and breakers are connected to a separate feeder and are allowed to ride through the grid faults. These protection devices must also aid reconnection of microgrids or sections of it when faults are cleared and normal operations resume. In many cases, these relays are coordinated by a protection coordinator.

Nikkhajoei and Lasseter (2007) give a good introduction to issues related to microgrid protection. Fault currents within the microgrid during operation in islanded mode are not at a magnitude which would be detected by traditional protection devices. Moreover, philosophies used to design protection for traditional power systems would not work for microgrids, because of new challenges such as bi-directional power flow and looped feeders. Sortomme *et al.* (2010) propose a protection scheme using digital relays with a communication overlay. The system is tested by simulating High Impedence Fault models.

In order to facilitate plug and play capabilities in the microgrid, protection needs to be embedded in microsource interfaces. In addition, even though microsource controllers regulate voltage and power in the feeder lines, microsources need to be protected from voltage sags affecting them. Vilathgamuwa *et al.* (2006) propose two algorithms to protect microsources from voltage sags and and large line currents, by controlling inverters in microgrids.

2.2.3 Energy Manager

The semi-autonomous nature of a microgrid is facilitated by the supervisory control capabilities of the *energy manager*(EM). Functions of the energy manager are multifarious and includes many tasks such as dispatch of set point values to microsources, decisions on fuel purchase, energy purchase, managing load demand requests, etc.

The response time of EM actions is in the order of minutes to hours. The nature of the tasks of the energy manager necessitates a communication framework between the energy manager and all other entities in the microgrid, in order to exchange measurement data and control signals.

Typical objectives of an EM may include minimizing operating costs under conditions that electrical and heat loads in the microgrid are served, equipment performance and safety specifications are met, while fuel and energy purchase costs are kept to a minimum and fuel supply limitations are taken into account. While the energy management decisions could just be made by a system operator manning a physical control panel, a computer controlled, intelligent, optimal management strategy which makes use of weather and load data to make predictions and schedules dispatches is a more desirable proposition. The energy management strategy might be a real-time optimizer, expert control system or a hierarchical control algorithm, among others, depending upon the computational resources and the extent and number of controllable parameters available within the microgrid.

A detailed introduction and description of the energy manager can be found in Firestone and Marnay (2005) and Kueck *et al.* (2003) would serve as a good guide for developing an energy management strategy for microgrids. Several projects have focused on implementing EM strategies for microgrids of various specifications. An EM strategy with the aim of minimizing fuel consumption is presented by Hernandez-Aramburo *et al.* (2005). Oyarzabal *et al.* (2005) present a software agent based microgrid management system for generators and storage, tested on laboratory facilities. Communication between the central controller and local controls in this system is performed using internet protocols. A multi-agent system for control of microgrids is presented by Dimeas and Hatziargyriou (2005). This particular system employs control mechanisms at levels higher than the microgrid and local controls, in addition to them, to control a collection of microgrids. Chakraborty *et al.* (2007) present a hierarchical, distributed intelligence energy management system for a high-frequency AC bus(500Hz) microgrid. Neural networks are utilized for prediction of power output of renewable energy sources, by using weather data.

Several feasibility studies and study-trials of microgrids have been performed at institutions around the world. Georgakis *et al.* (2004) present one such effort, where a prototype microgrid using photovoltaic source, storage devices and loads was built to explore control concepts and operating policies. Another feasibility study presented by Degobert *et al.* (2006) performs dynamic simulations of a microgrid with microturbine and photovoltaic generator as sources. Intelligent Distributed Autonomous Power Systems(IDAPS) is a specialized microgrid concept presented by Rahman *et al.* (2007). While most of the microgrid designs assume that all microsources belong to the same utility, IDAPS assumes an environment where distributed energy resources are customer owned and proposes new demand side management strategies and proposes use of web protocols for communication between DERs and EMs to enhance portability and interoperability. Design, modelling and simulation of IDAPS is presented in the project report by Rahman and Pipattanasomporn (2010).

2.3 Factors to be Considered for Design of Energy Management Strategy

The primary aim of the research presented in this thesis is to develop a software testbed of a microgrid, simulating its operations, so as to test different energy management strategies for the microgrid's energy manager. Hence, it is important to incorporate, in the design of the test bed, the capability to simulate most, if not all, of the possible factors which would affect the energy management strategy's design and operation. These factors are described in this section.

For the sake of convenience, the microgrid energy management strategy, which signifies the function of the energy manager, shall be referred to as *management strategy*, and the entity which contains it, as the *management module* in the rest of this text.

There are numerous factors which need to be considered for the design of the management strategy, such as fuel prices, energy tariffs, performance of equipment, weather conditions etc. Some of these data might be readily available and some harder to get. A perfectly optimal management strategy would require all of the data. However, it is usually not possible to obtain values such as real-time load demand, or real-time energy costs. So, some of the data is predicted from historical values. Firestone and Marnay (2005) and Kueck *et al.* (2003) explain all of the factors in great detail. Some of them are described below.

Tariff Information Almost all management strategies aim to minimize total energy cost. In order to achieve that, current costs of electricity, gas and other fuels must be readily available. There are different kinds of electricity tariffs in the market;

some of them such as *demand charges* introduce uncertainties, with the result that it is not possible to know real-time cost of electricity consumed. Demand charges depend on highest the rate of electricity consumption over fixed time intervals during a billing period, and hence cannot be known until the billing period ends. Other kinds of electricity pricing include, *time-of-use charges*, *real-time pricing* and *interruptible tariffs*.

Equipment Performance Parameters All distributed energy resources have different performance characteristics at different operating levels. Transient characteristics of devices might also need to be taken into account, since drawing large currents during transience would result in high demand charges, which depend on average power consumption in brief time periods. Management strategies must also operate devices within regulatory limits on noise, gas and particulate emissions. Fuel and electricity storage limitations must also be considered.

Weather Data and Prediction Ambient weather conditions determine the quantity of power generated by renewable sources of energy. They also determine the effect of gas and particulate emissions, which some microsources release, on the local environment. In order for the management strategy to plan and schedule power generation, it needs to be aware of the weather conditions. Hence, real-time monitoring and short and long term forecasting of weather needs to be performed to aid the functioning of the management module. Real-time weather data can be obtained from local weather stations or through on-site sensors. Forecasts can be done with the aid of historical weather data.

Load Data and Prediction Microgrid loads might be electrical, heating or cooling loads. Electrical load demands must be met on a real-time basis. So, instantaneous load demand must be known to the management strategy. In order to make power available to be used ahead of time and to schedule load dispatch in advance, load predictions must be made based on historical load data, and forecast weather data, which affects load demand patterns. Heating and cooling loads need not be met real-time and can be handled a little more flexibly.

Heterogeneous Quality of Service Many microgrids are designed to provide heterogeneous quality of service to consumers. To enable curtailment and rescheduling of loads and to ensure critical loads are always serviced, the management strategy must identify the priority of loads and maintain an inventory of the loads and their types in the microgrid. Based on energy prices, the need to conserve energy and store it in batteries, and priorities of the loads in the microgrid, the management strategy must manage and schedule load dispatches.

2.4 Proposed MicroGrid Structure for MicroGrid Testbed

The diagram shown in Figure 2.2 represents the schematic of the proposed design for the microgrid to be used in the testbed for developing and testing management strategies. The design presented in this figure shows only those components and modules of the microgrid which are relevant to the design and analysis of the management strategy, which resides in the management module. It is assumed that the microsource

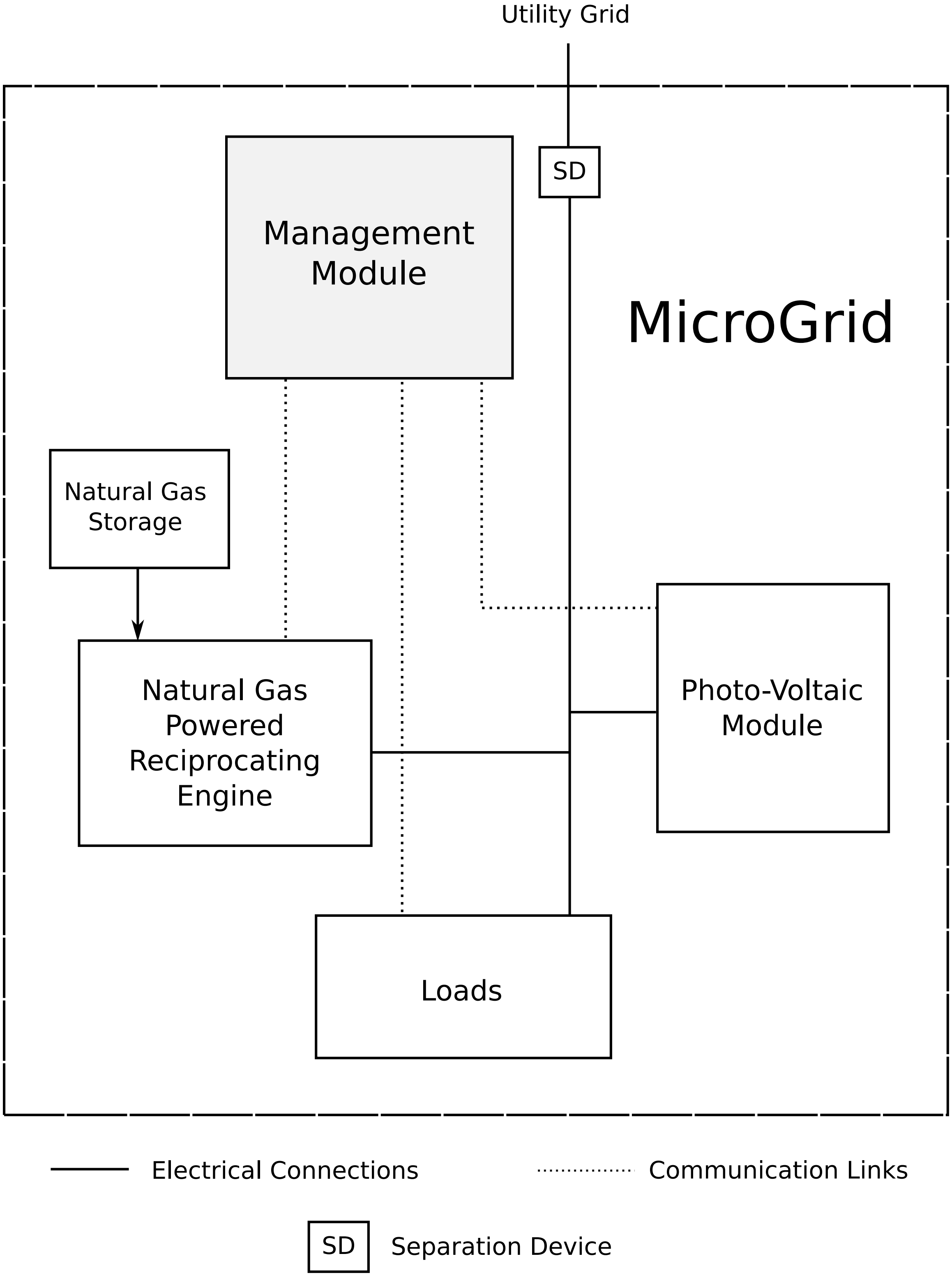

Figure 2.2: Schematic of the proposed structure for the Microgrid, to be used in the microgrid testbed - Only components relevant to the design of management strategies are shown.

controller and protection coordinator, described in previous sections, take care of the issues of maintaining power quality within the microgrid and enabling islanding and reconnection of the microgrid when faults occur and are, hence, not shown in the figure. The type of microsources and loads shown in Figure 2.2 can be replaced and/or augmented by any other kind of microsource or load and the testbed is flexible enough to accommodate that. Details on how this is achieved is discussed in the subsequent chapters.

The proposed structure of the microgrid was designed, keeping in mind a long-term view of implementing a microgrid with facilities available in McMaster University's campus. This is reflected in the choice of microsources for use in the testbed: a reciprocating engine, a reliable, controllable microsource which can support base-load needs and a more temperamental microsource in the form of photo-voltaic modules. Hamilton Health Sciences: McMaster Hospital has six natural gas powered reciprocating engines on campus; photo-voltaic arrays have been installed on the rooftops of several campus buildings. This situation affords the possibility of integrating these facilities in the form of a microgrid in the future and thus, provides an impetus to use them in the design of the microgrid structure to be simulated in the testbed. However, other microsources can also be used, as mentioned earlier. As seen in the diagram, curtailable and reschedulable loads are not shown. These loads, however, can be easily added to the testbed software, if needed.

2.5 Summary

In this chapter, the microgrid concept was introduced. It was explained that a microgrid must have certain essential characteristics. One of them is **control and**

flexibility, to facilitate easy addition and removal of microgrid components without greatly affecting the rest of the microgrid. The second is the capability for **effective energy management**, by the use of intelligent strategies to balance demand and supply of energy within the microgrid. The third essential characteristic is the provision of **protection and heterogeneous quality of service**, in order to manage situations arising due to faults on the grid lines.

A typical microgrid structure was shown and the components and control mechanisms which embody the characteristics of microgrids were described. **Microsources and storage devices** serve as local sources of energy for **loads** within the microgrid. Loads in a microgrid may be of different types: **critical loads**, which cannot be shed on any occasion, **curtailable loads**, whose demands can be lowered if required and **reschedulable loads**, whose dispatch times are not fixed.

Microgrids have three different types of control mechanisms embedded in them. **Microsource controllers**, which are power electronics based, help the regulation of voltage and power in microgrid feeder lines. **Microgrid protection** is achieved by a series of digital relays and breakers which facilitate isolation of faults and protection of devices installed in a microgrid. The **energy manager** enables microgrids to function semi-autonomously, by efficiently balancing energy demand and supply and by managing fuel and energy purchase and sale.

Factors which need to be considered for the design of **energy management strategies**, such as tariff information, power generation and load demand prediction using historical load and weather data, heterogeneous quality of service, etc. were described. The proposed microgrid structure, which is to be used in the microgrid testbed was presented. The structure was designed keeping in mind that the testbed is to be used for developing and testing energy management strategies.

Chapter 3

Simulation Framework and Computer Models

The microgrid testbed consists of two parts: The *Simulation Framework* and the *Analysis Tool*. The design and working of the simulation framework is explained in this chapter. The simulation framework is intended to aid the testing and comparison of different management strategies and computer models. It should enable easy change of simulation configurations, viz. models and strategies, and their comparative analysis. Hence, the simulation framework has been designed in a *modular* fashion. Modularity is achieved through the use of Object Oriented Programming principles in the framework's software implementation. The code for different computer models and management strategies are separate and are thus easy to replace.

Features

In essence, the two main features of this simulation framework, which enable it to effectively assist in the development of management strategies for microgrids are:

Adaptability The computer models, management strategy and even the way the simulation is run can be altered or completely replaced. This achieved through modularity, as discussed above.

Configurability Each module including its associated computer model, management strategy and associated variable is configurable by the user, using configuration files. This renders the framework flexible and facilitates fine-tuning of computer models and management strategies.

3.1 Simulation Framework Structure

The architecture of the simulation framework is illustrated in Figure 3.1. The various modules and the connections between modules are in evidence in the figure. There are two different kinds of connections between modules:

- The connections depicted by *thick, solid lines* are those linkages which enable the passage of module-specific simulation data between the main simulator routine and the modules which generate the data by virtue of executing *computer models* which reside in them. These connections are part of the simulation framework and do not correspond to anything in a physical microgrid.
- The connections depicted by *thin, dashed lines* are those which facilitate the exchange of control and status signals between the management module and the rest of the modules. These connections represent the communication network found in a physical microgrid.

It can also be seen that some of the modules and the simulation loop have configuration files and data files associated with them. Each of these will be explained

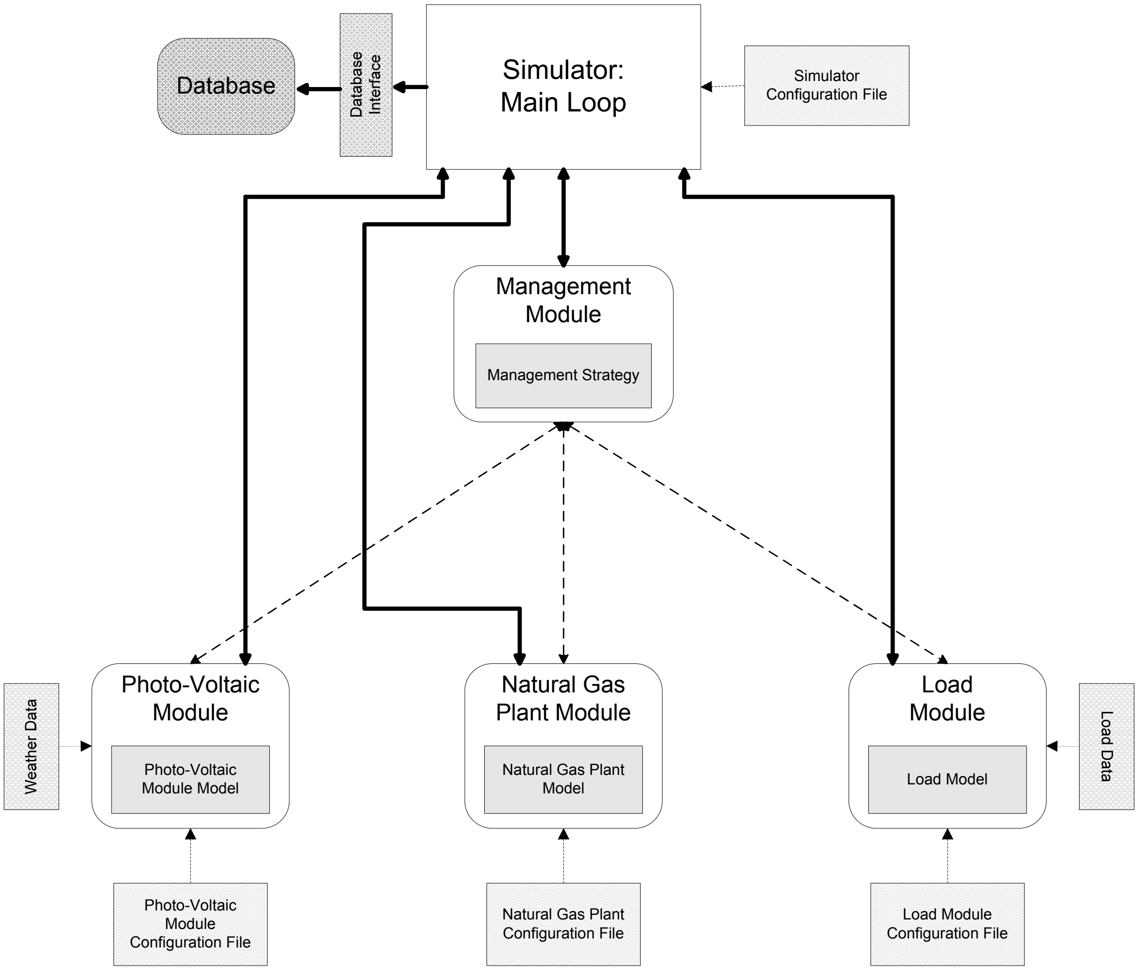

Figure 3.1: Simulation architecture

along with the corresponding module with which they are associated. The rest of the chapter is devoted to the explanation of those modules and routines which constitute the simulation framework and the computer models which currently define their behaviour. The modules will be discussed from the bottom up as they appear in Figure 3.1. It is to be noted that the computer models, introduced in the following sections, are easily replaceable by any other appropriate model if desired, without significant modifications to the rest of the simulation framework.

3.2 Natural Gas Powered Generator Module

This software module serves to imitate the working of a natural gas powered reciprocating engine. Figure 3.2 illustrates the internals of the module.

Attributes of the natural gas powered generator to be simulated, like the *maximum power capacity*, *maximum fuel storage capacity*, *volume of fuel available initially* can be specified in the *configuration file.* The module reads these values from the configuration file in the beginning of the simulation. The configuration file also specifies the data to be used in the computer model of the natural gas powered generator.

The module is in direct communication with the management module, from which it receives instructions regarding *set point* values at which to operate and sends information on *fuel consumption* and *fuel available.*

3.2.1 Computer Model

The function of the natural gas generator computer model is to simulate the working of a physical reciprocating engine. The model currently employed scales the interpolated

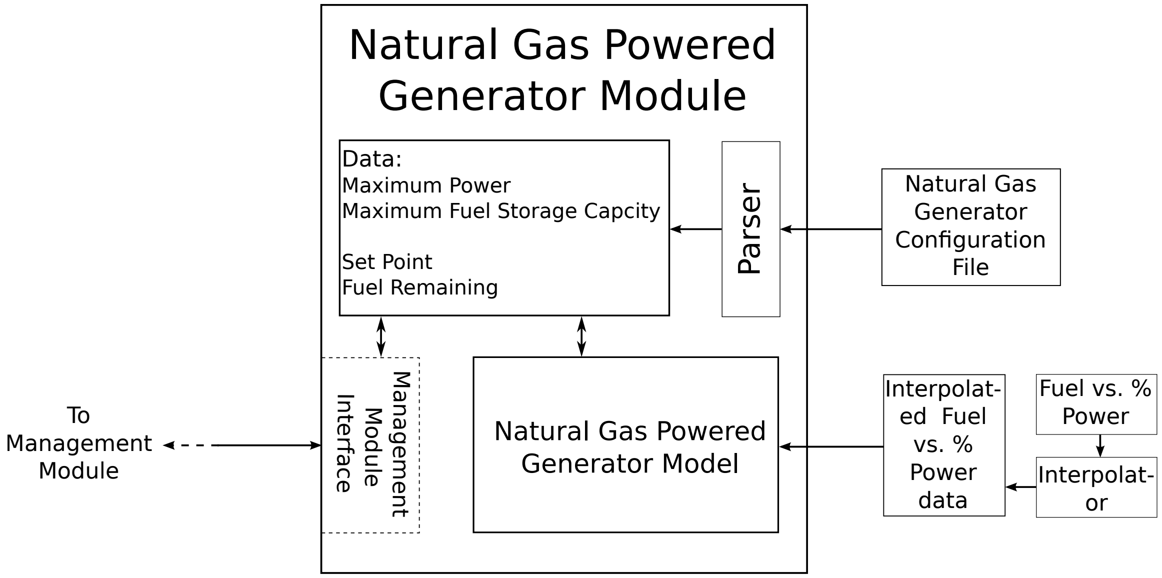

Figure 3.2: Diagrammatic representation of the natural gas powered generator software module

values of fuel consumed for a given percentage of a generator's power generation capacity used, relative to the value of *set point* at which the generator is instructed to operate by the management module and the maximum power capacity of the generator. The outputs of the model are fuel consumed during an hour's operation and the power output in megawatts during that period.

The current computer model is based on data from performance test reports of *Hamilton Health Sciences McMaster Hospital*'s natural gas powered reciprocating engine power generator. The plant comprises six *Cummins QSV91G* engines, each with a maximum power generation capacity of 1.75 MW. The data obtained from the performance reports was the values for hourly fuel consumption by the power generator for various load points at which it was operated. In order to be able to execute the model at a finer resolution of load point values, the data were interpolated using the *Piecewise Cubic Hermite Interpolating Polynomial* routine in Matlab.

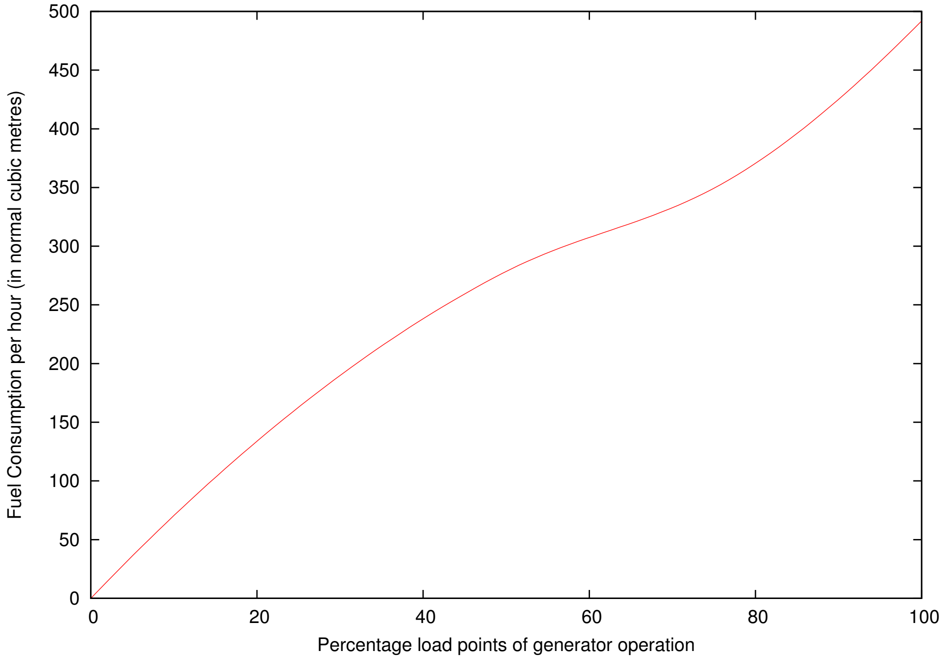

Figure 3.3: Plot of interpolated values of hourly fuel consumption versus operating points of natural gas powered generator

Figure 3.3 gives the plot of hourly fuel consumption of the power generator against the percentage load point at which the generator was operated.

Model Functioning

The working of the computer model of the natural gas powered generator can be explained through a series of steps as follows. These steps are also illustrated in a flowchart in Figure 3.4.

Step 1 The model receives the value of power output that it must achieve from the management module.

Step 2 It sets the output of the generator(s) to be at the value received from the management module.

Step 3 The amount of fuel that will be consumed for operating at the set point is calculated using the relations 3.1 and 3.2.

$$Percentage\ Set\ Point = \frac{Set\ Point}{Maximum\ Power\ Output} \times 100 \tag{3.1}$$

$$Fuel\ Consumed = Data_i,\ i = Percentage\ Set\ Point \tag{3.2}$$

where, $Data_i$ is the sequence of interpolated hourly fuel consumption data for a given percentage load point i

Step 4 Decrement the value of fuel available.

$$Fuel\ Available = Fuel\ Available - Fuel\ Consumed \tag{3.3}$$

Step 5 Send fuel consumption and power generation to Simulator Module.

3.3 Photo-Voltaic Module

This module is the software representation of a collection of physical photo-voltaic modules constituting a micro-source for a microgrid. The components of this software module are illustrated in figure 3.5.

Parameters such as *Maximum Power Output*,*Temperature Co-efficient of Power* are characteristic of the physical PV arrays which are being modelled. Constants such as *Reference Temperature* and *irradiation at STC* form reference points for electrical behaviour of the model. These values are read from the *configuration file.* Photo-Voltaic micro-sources are usually comprised of more than one PV module.

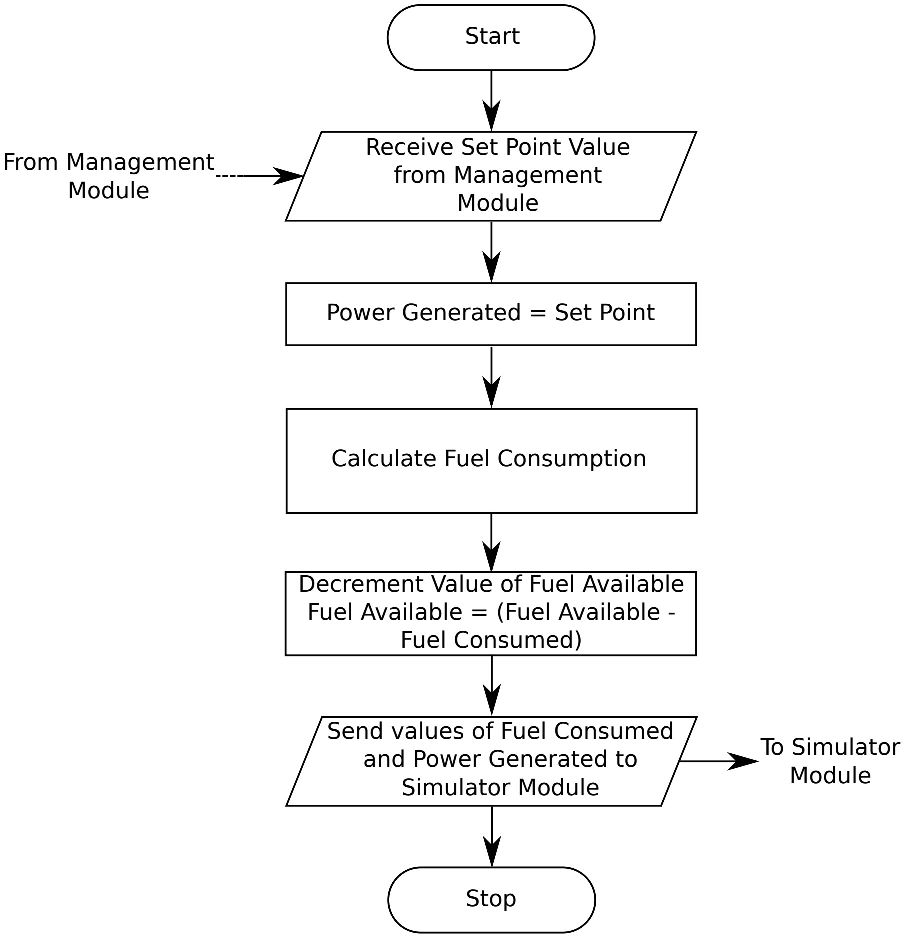

Figure 3.4: Flow-chart representing the execution of the natural gas generator model

Maximum power output may vary according to the number of similar PV modules being employed for the simulation; it is an integral multiple of the maximum power output of one PV module.

3.3.1 Computer Model

The computer model of the PV module tries to mimic the behaviour of its physical counterpart, with the aid of ambient weather data. An analytical model to calculate output voltage and current in PV cell is presented by Sze and Ng (2007). Krauter

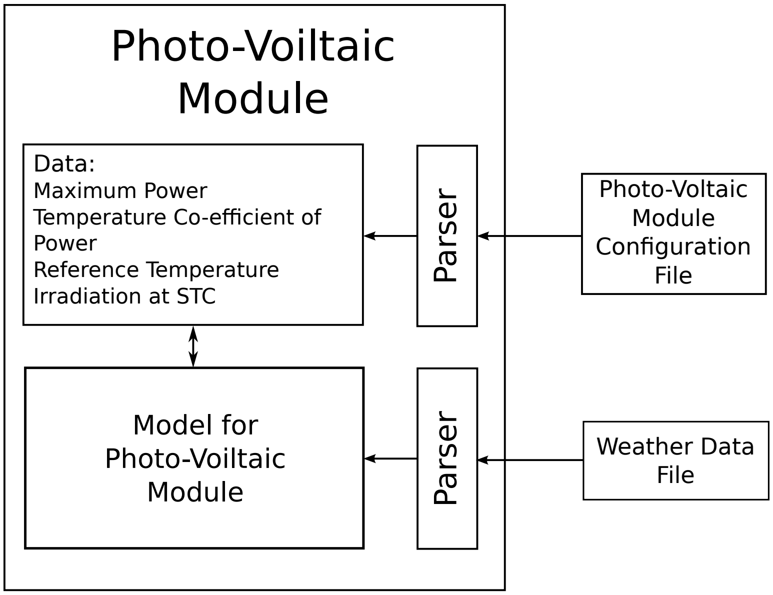

Figure 3.5: Diagrammatic representation of the software module for Photo-Voltaic power source

(2010) proposes to calculate energy yield from a PV module, by extensive modelling of the sun's position relative to the earth at a given time to ascertain incident irradiation and modelling heat flow in PV modules to arrive at the cell temperature. There exist computer models which can calculate the maximum possible PV power that could be generated in a given geographical location, based on its historical solar irradiation data. Superposing the effects of ambient weather on this model will make for a fairly accurate computer model. However, for the purposes of testing management strategies, modelling of PV modules at such high levels of detail is not necessary. In the current version of the simulator, the simple yet functional model used in Mohamed (2008), given by equation 3.4 is implemented to calculate power generated by the PV module. According to this model, the power generated by the PV module is proportional to the difference of ambient(T_c) and reference(T_r) temperatures, and to incident radiation(G_{ING}). Power generated at Standard Test Conditions(P_{STC}) and irradiation at Standard Test Conditions(G_{STC}) are constants and are characteristic of the type of PV Module used.

$$P_{PV} = P_{STC}\frac{G_{ING}}{G_{STC}}(1 + k(T_c - T_r)) \tag{3.4}$$

where

P_{PV} is the output power of the PV module at incident irradiation G_{ING}

P_{STC} is the output power of the PV module at Standard Test Conditions

G_{ING} is the incident irradiation

G_{STC} is the irradiation at Standard Test Conditions and is equal to 1000 W/m^2

k is the temperature coefficient of power

T_c is the cell temperature

T_r is the reference temperature

Model Functioning

The steps involved in the execution of the computer model for PV module are described below. An illustration of these steps is show in Figure 3.6.

Step 1 Parse weather data-file and read values of the parameters, radiation and temperature.

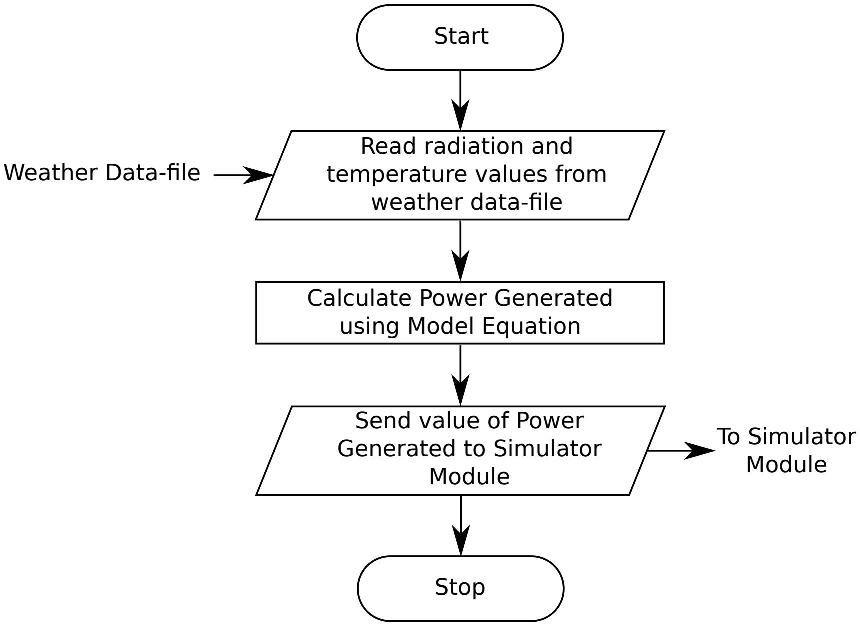

Figure 3.6: Flow-chart representing the execution of the computer model for PV module

Step 2 Calculate PV power generated using equation 3.4.

Step 3 Send value of power generated to simulator module.

The *weather data* used for the execution of this model in simulations were obtained from the *Government of Canada*'s *National Climate Data and Information Archive.* The particular data-sets made use of in the simulations are the *Canadian Weather year for Energy Calculation* data-sets. According to the archive description on the website, these data-sets are a collection made by joining twelve typical meteorological months from a database of around 30 years. The months are chosen by statistically comparing individual monthly means to long term monthly means for various parameters such as dry bulb temperature, global horizontal radiation etc. Data-sets are available for major Canadian cities.

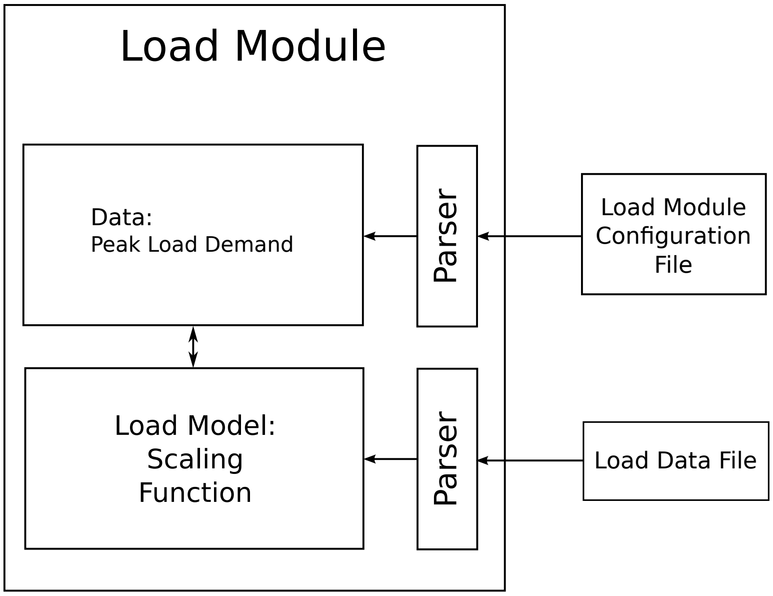

Figure 3.7: Diagrammatic representation of the Load Module

3.4 Load Module

This module serves to simulate the behaviour of all the loads in the microgrid taken together as a collective entity. Figure 3.7 shows components which make up the load module. Value of the parameter *Peak Load Demand*, which signifies the maximum possible load demand from within the microgrid, is obtained from the *configuration file*. The configuration file also provides the module with the location of the weather data-file and the maximum load demand value in the specific weather data-file. Behaviour of loads varies according to the location and kind of loads viz. residential, industrial, critical loads such as hospital equipment etc. Use of data from either of these kinds will have a great influence on the way the management strategy works.

3.4.1 Computer Model

As mentioned earlier, load behaviour is specific to the location and it is not easy to define a generic computer model for load behaviour. Yet some models have been proposed, like the one used by Firestone and Marnay (2005), which uses scalars to modify monthly average load at a given time to arrive at the load value at that time, according to the relationship shown in Equation 3.5. However, the current version of the simulator uses data for power demands for Province of Ontario and assumes that the microgrid load behaviour follows a similar pattern, albeit, at a much smaller scale. The net energy demand in Ontario arises from a very broad spectrum of load kinds and thus represented a mixed-load scenario at a large scale.

$$Load(day, time) = \alpha(day) \cdot AverageLoad(time) + \beta(day, time) \tag{3.5}$$

where,

$Load(day, time)$ is the load on a given day and time

$AverageLoad(time)$ is the monthly average load at a given time, obtained from historic data

$\alpha(day)$ is a daily load scalar representing fluctuations in the load profile due to changes in weather, production loads, etc.

$\beta(day, time)$ is a disturbance term representing load dips and peaks due to turning on and off of large machinery

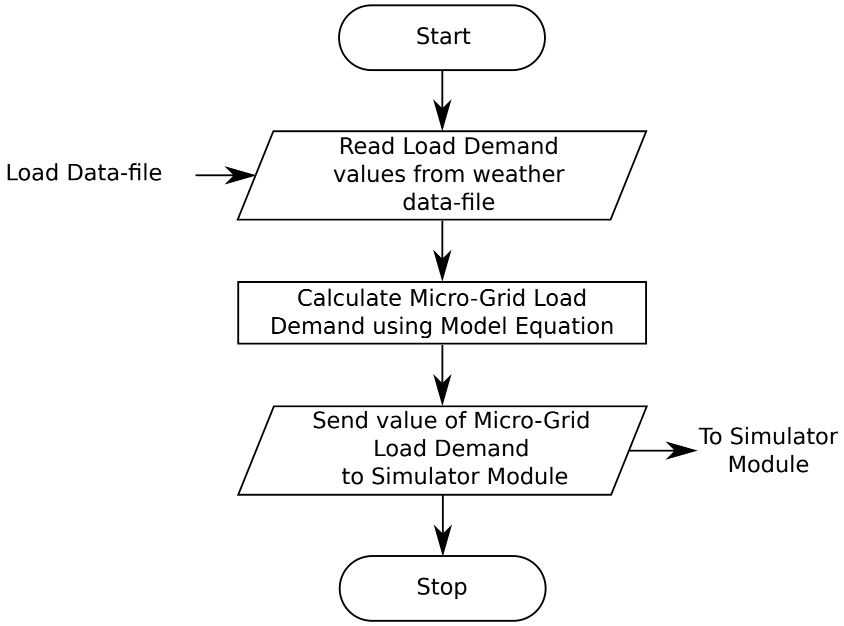

Figure 3.8: Flow-chart representing the execution of the Load model

Model Functioning

The way the model functions can are explained below and the steps involved are illustrated in a flow-chart in figure 3.8.

Step 1 Read province-wide power demand value from load data-file.

Step 2 Calculate load demand for microgrid using equation 3.6. It can be seen that the value read from the data-file is scaled by a ratio of peak demand values in the microgrid and the province.

$$Load\ Demand_{\mu-grid} = \frac{Peak\ Load\ Demand_{\mu-grid}}{Peak\ Load\ Demand_{province}} \cdot Load\ Demand_{province} \tag{3.6}$$

Step 3 Send value of microgrid load demand to simulator module.

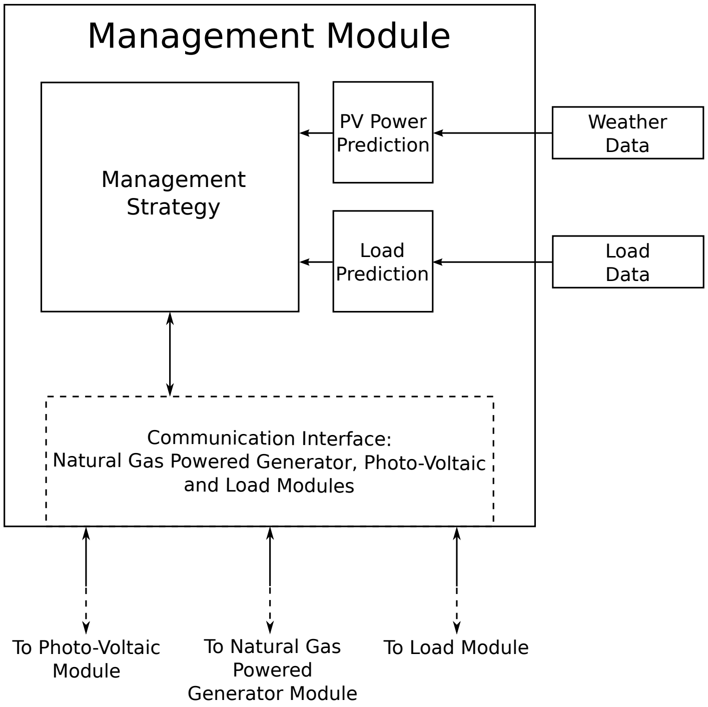

Figure 3.9: Diagrammatic representation of the management module

The data to run this model was obtained from *Independent Electricity System Operator*, which is responsible for day-to-day balancing of demand and supply of electricity in Ontario. Hourly data for power demand in Ontario from May 2002 are available for download from their website.

3.5 Management Module

The *management module* in the simulation framework is the software module which represents the the energy manager in a physical microgrid, depicted in Figure 2.1. It houses the management strategy for controlling microgrid components based on different criteria.

Figure 3.9 shows the internal architecture of the software module. The management strategy is the vital core of the module. The module is in communication with all the software modules which represent micro-sources and loads. This facilitates gathering of status information and dispatch of control and instructional information by the management module to other modules.

3.5.1 PV Power and Load Prediction

It can be seen in Figure 3.9 there are prediction components within the management module. These components serve to enhance the management strategy's functioning by providing it with predicted values of load and photo-voltaic power. Prediction can be accomplished by using historical data and neural networks or other learning machines. However, in the current version of the simulation framework, the prediction components have direct access to the weather and load data files discussed in previous sections, and utilize modified versions of equations 3.4 and 3.6 to arrive at the respective predicted values. In order to ensure that the management strategy works to satisfy load demand at all times, the value of PV power output is under-predicted and the value of load demand is over-predicted.

$$P_{STC}\frac{G_{ING}}{G_{STC}}(1+k(T_c-T_r)) \geq P_{PV_{pred}} \geq P_{STC}\frac{0.95\times G_{ING}}{G_{STC}}(1+k((0.95\times T_c)-T_r)) \tag{3.7}$$

where

$P_{PV_{pred}}$ is the predicted output power of the PV module at incident irradiation G_{ING}

P_{STC} is the output power of the PV module at Standard Test Conditions

G_{ING} is the incident irradiation

G_{STC} is the irradiation at Standard Test Conditions and is equal to 1000 W/m^2

k is the temperature coefficient of power

T_c is the cell temperature

T_r is the reference temperature

Here, G_{ING} and T_c are values obtained from the weather data-file. It can be seen that the relation 3.7 varies from equation 3.4 in that there is a reduction of upto 5% in the values read from the data-file.

$$\begin{aligned}\frac{Peak\ Demand_{\mu-grid}}{Peak\ Demand_{province}} \cdot Load\ Demand_{province} &\leq Load\ Demand_{\mu-grid_{pred}} \\ &\leq \frac{Peak\ Demand_{\mu-grid}}{Peak\ Demand_{province} \cdot 1.05 \times Load\ Demand_{province}}\end{aligned} \tag{3.8}$$

In this case, $Load\ Demand_{province}$ is the value read from the load data-file. It is observed that relation 3.8 uses a value which represents an increase of upto 5% in the value read from the data-file.

3.5.2 Management Strategy

The management strategy is the most important entity within the microgrid as it oversees, manages and controls the activities of components within the microgrid. In a typical microgrid, it would have to

- Decide the operating point of the reliable source of power within the microgrid.
- Manage purchase of fuel for any energy source within the microgrid.

- Predict attributes associated with components of the microgrid which are to a certain degree, uncertain. For example, components whose behaviour depends on weather conditions or market consumption dynamics.
- Manage resources within the microgrid so as to balance local demand and supply. Furthermore, purchase energy from utility power grid if local resources are insufficient.
- Make decisions on when to island off from the main grid.
- If economic or technical reasons(if in islanded mode) demand it, shed or reschedule dispatch-able load.

In the current version of the simulator, a simple sample management strategy has been implemented to showcase the flexibility and analysis capabilities of the simulation framework. Description of this management strategy is discussed below. It should be noted that, since faults, power surges etc. in the main grid are not simulated. Hence, in order to demonstrate simulation of islanded mode, it is assumed that faults in the main grid, which in turn trigger islanding, occur with an arbitrary probability of 0.01.

Sample Management Strategy

The following steps elucidate the operation of a sample management strategy, designed to demonstrate the capabilities of the simulation framework and analysis tool. The flow-chart of this strategy is shown in Figure 3.10.

Step 1 Obtain predicted values of photo-voltaic power and load demand, which are generated as described in sub-section 3.5.1.

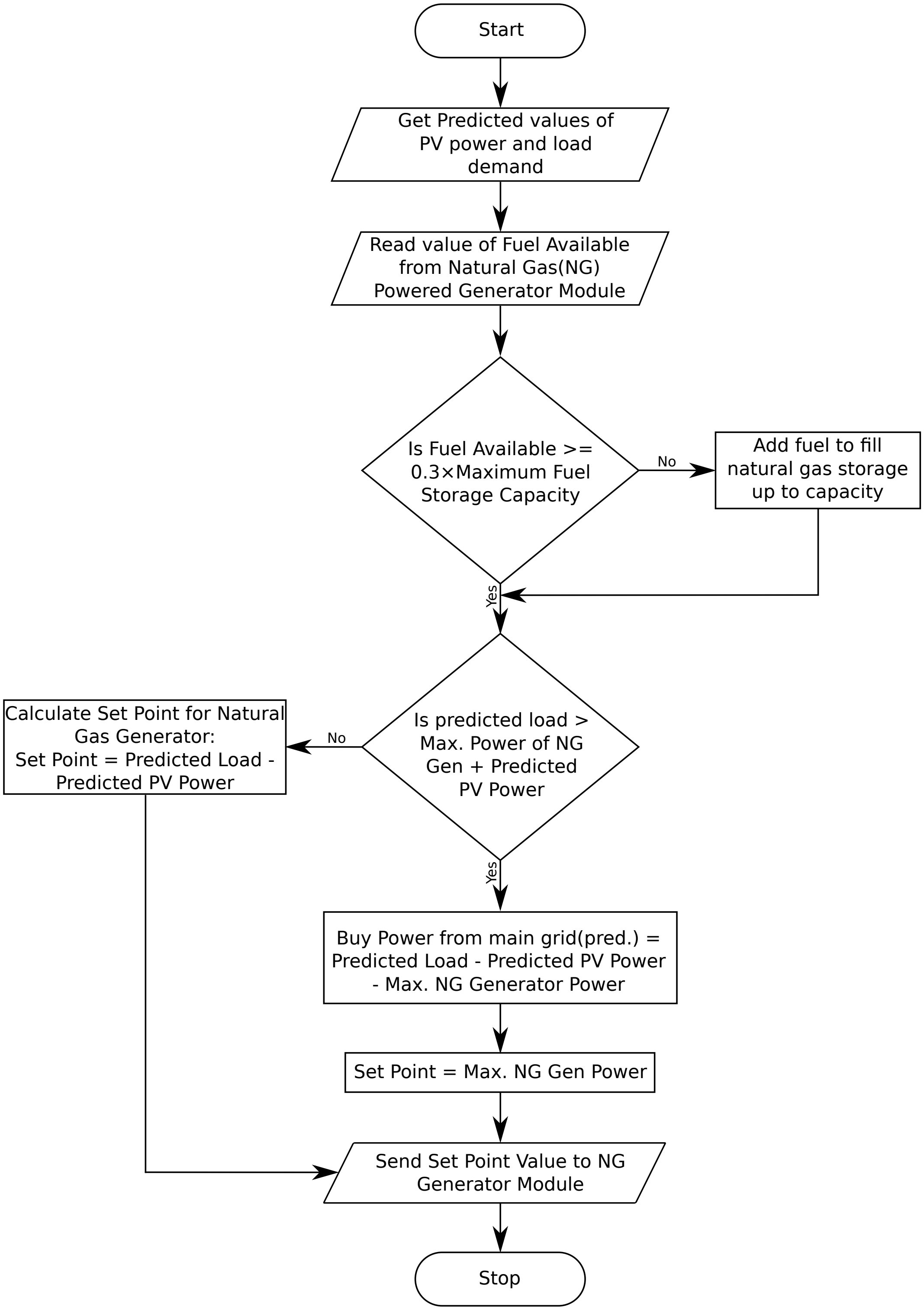

Figure 3.10: Flow-chart representing sample Management Strategy

Step 2 Read the value of fuel available for usage for the natural gas powered generator from the corresponding software module.

Step 3 If fuel available is less than 30% of the maximum fuel storage capacity, buy enough replenish storage to capacity. Otherwise, proceed to step 4.

Step 4 If predicted load demand is greater than the combination of predicted PV power and maximum power capacity of natural gas powered generator, buy power needed to satisfy load demands and proceed to step 6. Otherwise, proceed to step 5. Power to be bought is calculated using the equation 3.9.

$$Power\ Bought = Predicted\,Load - Predicted\,PV\ Power - NG\,Generator\ Power_{max} \tag{3.9}$$

Step 5 Calculate set point value of natural gas generator using the relation 3.10 and proceed to step 7.

$$Set\ Point_{NG\ Generator} = Predicted\ Load - Predicted\ PV\ Power \tag{3.10}$$

Step 6 Set operating point of natural gas generator to be equal to its maximum power generation capacity.

Step 7 Send set point value to natural gas powered generator module.

3.6 Simulator Module and Database

The *simulator module* is the most vital part of the simulation framework and contains the main routine which executes models and strategies contained in other modules of

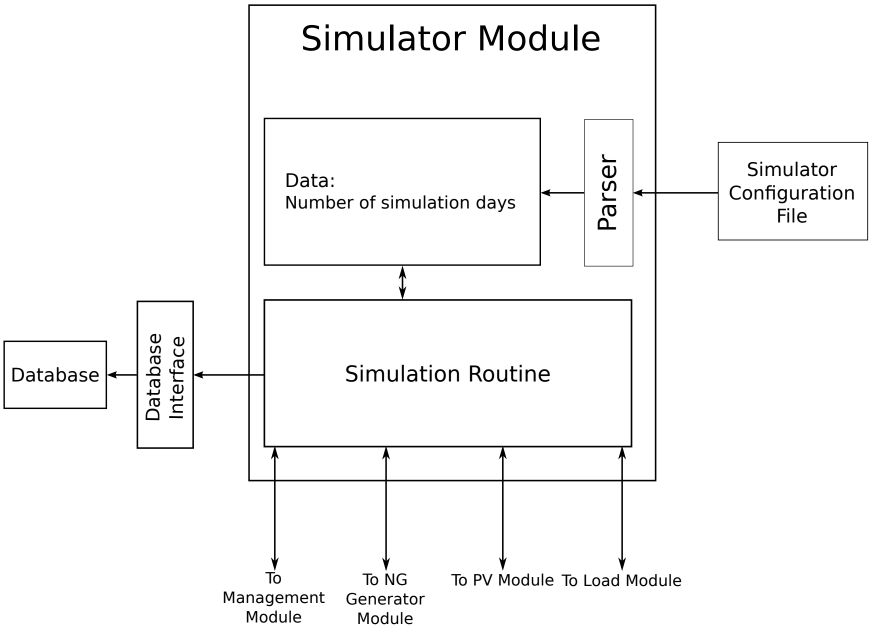

Figure 3.11: Diagrammatic representation of the simulator module and database interface

the framework, including the management module. A separate module was dedicated to the main routine so that it is easy to modify code to add or remove a module, which would represent the addition or removal of a new kind of micro-source or load to the microgrid, and to make necessary changes to the database.

The simulation framework uses MySQL databases for recording data generated during simulations.The *database interface* is a wrapper program which uses the MySQL++ libraries to facilitate database creation and management.

Figure 3.11 shows the internals of the simulator module and its connection to the database through the database interface. The *simulator configuration file* contains the names and location of the configuration files for the other software modules which constitute the simulation framework. It also contains the *number of simulation days*, a variable which can be specified by the user. It signifies the number of simulation days, each executed at an hourly time-step, for which the simulation is to be executed. The initial simulation time, specified by date, month and year are randomly selected and the simulation commences. The main routine of the simulator is connected to all the other modules in the framework as well as the database. It initializes the modules, executes them and stores simulation data in the database.

3.6.1 Data stored in Database

Execution of each time-step of the simulation entails generation of simulation data. These data need to be recorded so as to enable analysis of the functioning of the management strategy and computer models. Following are the fields recorded for every time-step in the current version of the simulation framework:

- Simulation Date and Time
- Natural Gas Generator Set Point
- Fuel Available in storage for Natural Gas Generator
- Fuel Bought
- Deficit Power: To be bought/Load to be shed
- Deficit Power: To be bought/Load to be shed(predicted)
- Power reserve available to be sold
- Power reserve available to be sold(predicted)
- Predicted Photo-Voltaic Power

- Predicted Load Demand
- Power Generated by Natural Gas Powered Generator
- Incident Solar Radiation(from weather data-file)
- Ambient Temperature(from weather data-file)
- Fuel Consumed by Natural Gas Powered Generator
- Power Output of Photo-Voltaic Module
- Load Demand
- Provincial Load Demand(from load data-file)
- Islanding(*Boolean* value: either *true* or *false*)

3.6.2 Simulation Routine

The flow-chart in Figure 3.12 illustrates the functioning of the main simulation routine in the current version of the simulation framework. The functioning is to be described below in a few steps. It is to be noted that a simulation time-step corresponds to 1 hour.

Step 1 Read value of the variable, number of simulation days and the names and locations of module configuration files from the simulation configuration file.

Step 2 Initialize other software modules in the framework by sending them the names and locations of their respective configuration files.

Step 3 Select a random date, month and hour at which to begin the simulation.

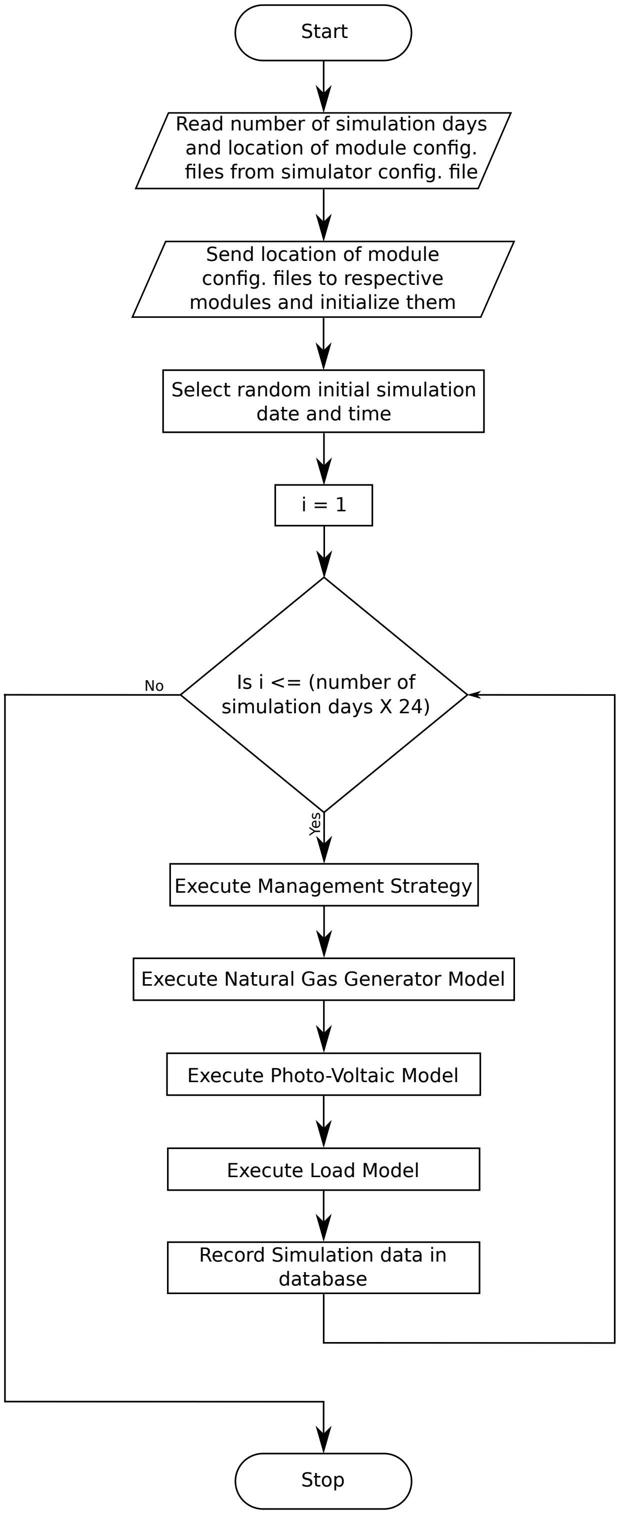

Figure 3.12: Flow-chart representing Main Simulation Routine

Step 4 Execute Steps 5, 6, 7, 8 and 9 until simulation is carried out for the number days specified in the variable read from the configuration file.

Step 5 Execute management strategy, illustrated in Figure 3.10.

Step 6 Execute Natural Gas Powered Generator Model, illustrated in Figure 3.4.

Step 7 Execute Photo-Voltaic Model, illustrated in Figure 3.6.

Step 8 Execute Load Model, illustrated in Figure 3.8.

Step 9 Record simulation data, described in sub-section 3.6.1, in the database.

3.7 Summary

This chapter primarily dealt with the structure and functions of the adaptable and configurable microgrid simulation framework, which is part of the microgrid testbed. The overall modular design of the **architecture of the simulation framework** and the designs of all the modules which are part of the current version of the simulation framework were described.

The software module which simulates the **natural gas powered generator** makes use of a computer model, which is based on the relationship between the hourly fuel consumed by the generator and its percentage operating point. The values power generation capacity of the generator and the fuel storage capacity to be used in the simulation can be specified through a **configuration file** for the module. The software module for the **photo-voltaic system** makes use of a computer model which outputs the power generated by the PV module, based on hourly weather data and the electrical characteristics of the PV module being simulated. The **software**

load module uses archival hourly load data for the Province of Ontario and scales it down the magnitude to that of the specified load values in the microgrid.

The **software management module**, representing the energy manager of a functional microgrid, contains the **management strategy**. The management module sends set point values and control signals to the other modules in the simulation framework. PV power and load values need to be predicted if the management strategy is to schedule dispatch of microsources and loads ahead of time. Prediction strategies used in the current version of the simulation framework have been presented. A sample management strategy has also been described and the internal structure of the management module has been shown. The **simulator module**, which contains the main simulation routine for the framework has been described, with the aid of a schematic of its internals and a flow chart was presented to describe its functioning.

Chapter 4

Analysis Tool and Testbed Demonstration

The software testbed of a microgrid requires means of visual analysis of simulation data in order to gain insight into the behaviour of the management strategy and computer models, in turn, aiding their improvement. The *Analysis Tool* is part of the software testbed and it enables graphical analysis of data generated by executing a simulation in the simulation framework. It receives a command from the user, and depending on the user's command, retrieves appropriate data from the databases and creates plots using the data. This software tool is composed of a collection of routines, one for each user-command supported. The analysis tool is *expandable*: Routines to handle more user-commands can be easily added to accommodate future analysis needs. The current commands supported are designed to demonstrate the usefulness of the analysis tool in visualizing the behaviour of computer models and management strategy. This chapter includes the description of the structure of the analysis tool and demonstrations of its capabilities.

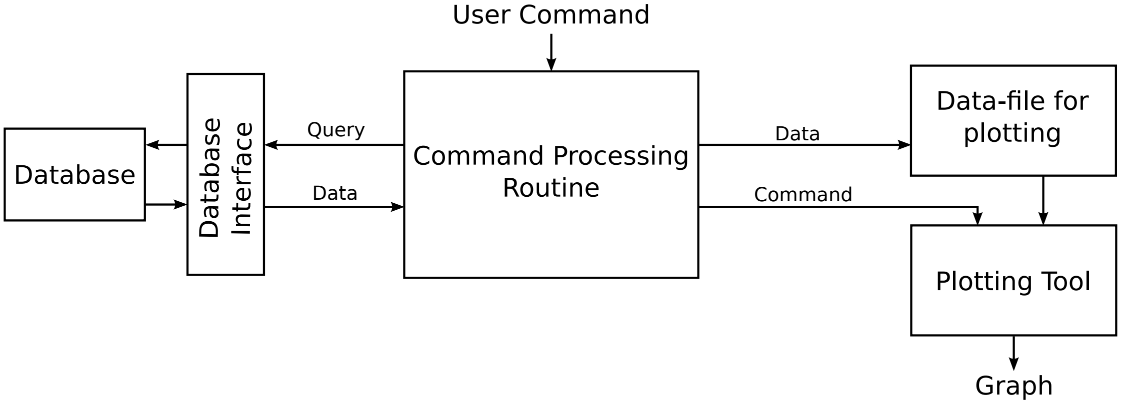

Figure 4.1: Architecture of Analysis Tool

It is to be noted that a graph can be obtained with any possible combination of data values retrieved from the database. The routines currently implemented are a sample and represent a small set of routines which the author believes would be useful for developing and improving management strategies.

4.1 Analysis Tool Structure

Figure 4.1 shows the architecture of the analysis tool. The components which constitute the analysis tool can be observed in the figure. Each of those components is discussed below.

4.1.1 Command Processing Routine

The *command processing routine* is the main routine in the analysis tool. It receives the user command, sorts them to find the relevant sub-routine, which then retrieves the appropriate data for the analysis and invokes the plotting tool to obtain a graph. Figure 4.2 shows a flow-chart representing the flow of the command processing routine,

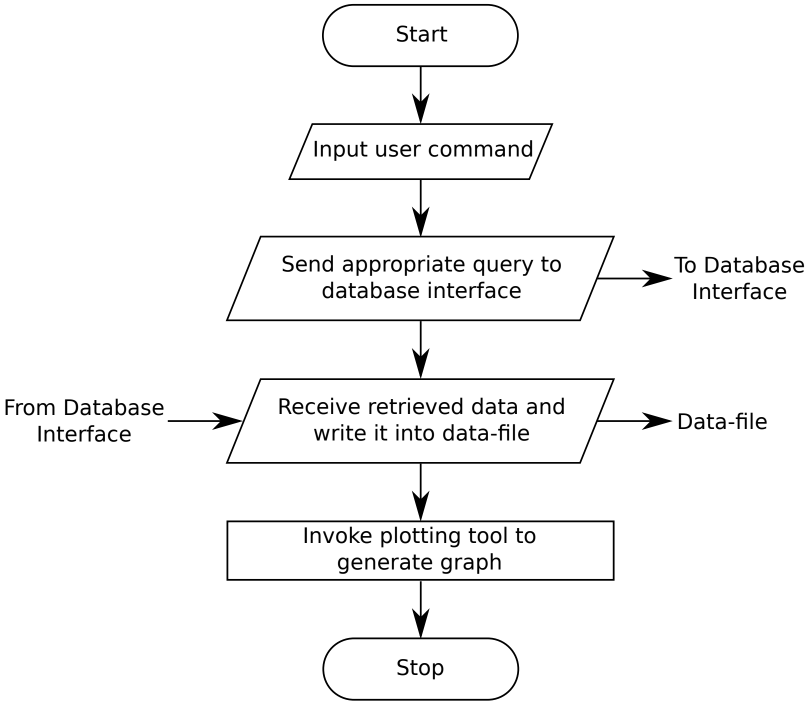

Figure 4.2: Flow-chart representing the flow of the command processing routine

which can be described in a few steps, as follows:

Step 1 Receive command from the user.

Step 2 Send relevant query to the database interface, depending on the command received.

Step 3 Receive retrieved data and write it into data-file.

Step 4 Invoke plotting tool, sending the location of the data-file and type of plot desired, to generate plot.

4.1.2 Database Interface

The database interface provides a means to communicate with the database by providing an interface between the programmer and the database querying language. It receives queries from the command processing routine and retrieves the appropriate set of data from the database and sends it to the routine. It makes use of the MySQL libraries to connect and query the database.

4.1.3 Plotting Tool

The plotting tool is made use of to generate graphs. The tool receives a set of commands and specifications regarding the type, range, the data-file to be used etc. from the command processing routine. It, then generates a graph using the data from the file according to the specifications. The plotting tool employed currently is *Gnuplot*.

4.2 Testbed Demonstration

In this section, simulations and analyses of management strategies and models used are presented. Following are descriptions of two different simulations which differ slightly from each other in the functioning of their management strategies and specifications of the micro-sources used. This, along with the analyses of the simulations, constitute a demonstration of the microgrid, illustrating the usefulness of the testbed. In particular, the demonstration brings out the capabilities of the analysis tool in providing the means for a visual aid for decisions and improvement in the design management strategies and computer models.

Attribute		**Simulation I**	**Simulation II**
Number of Simulation Days		300	
Photo-Voltaic Module	*Maximum Power*	1.5 MW	3.0 MW
	Temperature Co-efficient of Power	-0.0043	
	Irradiation at STC	$1000\,\mathrm{W/m^2}$	
	Temperature at STC	25 °C	
Natural Gas Generator	*Maximum Power*	10.5 MW	
	Maximum Fuel Storage Capacity	$200000\,\mathrm{m^3}$	
Maximum Load in MicroGrid		10.5 MW	

Table 4.1: Values of various attributes in the demonstration simulations

4.2.1 Simulation Settings

Table 4.1, shows the configurations for Simulation I and Simulation II of all the attributes of the simulation framework which can be modified through the configuration files. It can be seen that the settings for both simulations are identical except for the power capacity of the Photo-Voltaic module. There are two other differences between the two simulations, both, in their respective *management strategies*: the criteria used for buying fuel for the natural gas powered generator and the load prediction methods are different from one another.

Simulation I uses the same management strategy as that described in Section 3.5 and illustrated in Figure 3.10. However, the management strategy used in Simulation II is different and is illustrated by the flow-chart in Figure 4.3. It can be seen from the figures that, in simulation I, the process of making a decision on fuel purchase is:

```
if $Fuel\ Available \leq 0.3 \times Max\ Fuel\ Storage\ Capacity$ then
    $Fuel\ Bought = Max\ Fuel\ Storage\ Capacity - Fuel\ Available$
```

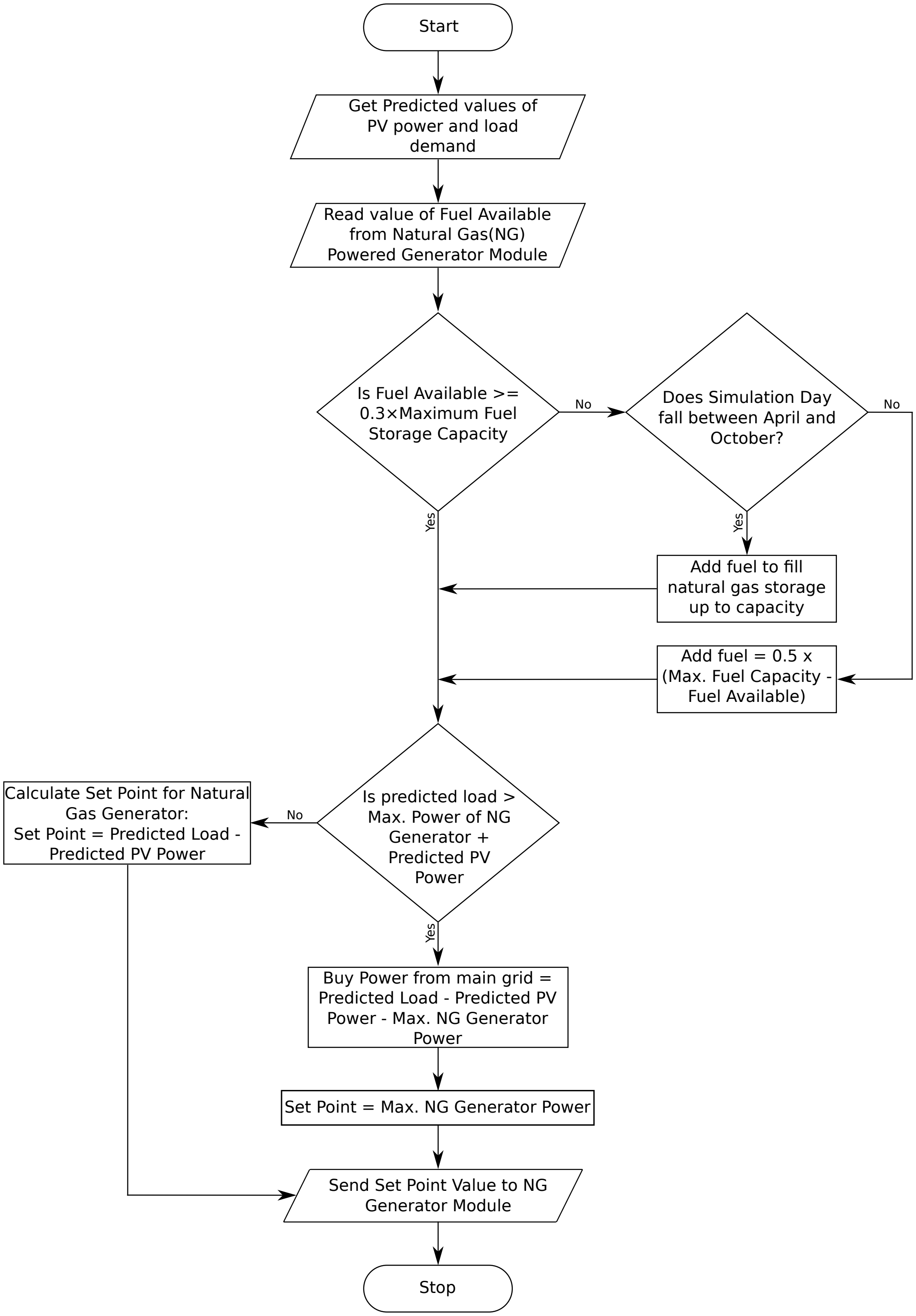

Figure 4.3: Flow-chart representing Management Strategy used in Simulation II

```
else
    $Fuel\ Bought = 0$
end if
```

And in simulation II, the decision making strategy for fuel purchase can be summarized as follows:

```
if $Fuel\ Available \leq 0.3 \times Max\ Fuel\ Storage\ Capacity$ then
    if $simulation\ day\ falls\ between\ months\ April\ and\ October$ then
        $Fuel\ Bought = Max\ Fuel\ Storage\ Capacity - Fuel\ Available$
    else if $simulation\ day\ falls\ between\ months\ November\ and\ March$ then
        $Fuel\ Bought = \frac{1}{2} \cdot (Max\ Fuel\ Storage\ Capacity - Fuel\ Available)$
    end if
else
    $Fuel\ Bought = 0$
end if
```

The fuel purchase strategy used in simulation II ensures that, during winter months, when the demand for natural gas is at its peak due to heating needs, purchase of fuel in large quantities is avoided. Instead, smaller purchases are made at more frequent intervals so as to ease the burden on the fuel supplier during peak demand period.

In simulation I, the load prediction method used is that used in the sample management strategy as described in Section 3.5. It is defined by the relation 4.1, reproduced here from the previous chapter. The relation assumes that the predicted load values deviate from the actual values by up to 5%.

$$\begin{aligned}\frac{Peak\ Demand_{\mu-grid}}{Peak\ Demand_{province}} \cdot Load\ Demand_{province} \leq Load\ Demand_{\mu-grid_{pred}} \\ \leq \frac{Peak\ Demand_{\mu-grid}}{Peak\ Demand_{province} \cdot 1.05 \times Load\ Demand_{province}} \qquad (4.1)\end{aligned}$$

The load prediction method used in simulation II is described by equation 4.2. This method uses the arithmetic mean of the corresponding provincial load data from two preceding years to arrive at a prediction for the value of load demand.

$$\begin{aligned}Load\ Demand_{\mu-grid_{pred}}(n) \ = \ & \frac{1}{2} \times \frac{Peak\ Demand_{\mu-grid}}{Peak\ Demand_{province}} \\ & \times \Big\{ Load\ Demand_{province}(n-1) \\ & + Load\ Demand_{province}(n-2) \Big\} \qquad (4.2)\end{aligned}$$

where,

$Load\ Demand_{\mu-grid_{pred}}(n)$ is the predicted load value for a given simulation day and time in the same year as the one used for simulating load demand in the load module

$Load\ Demand_{province}(n-1)$ is the provincial load value for the corresponding date and time in the year preceding the one used for simulating load demand in the load module

$Load\ Demand_{province}(n-2)$ is the provincial load value for the corresponding date and time in the year two years prior to the one used for simulating load demand in the load module

In both of the simulations described above, the provincial load data for the load module was obtained from the Independent Electricity System Operator's(IESO) data archives. In these particular simulations load data for Ontario from the year 2007 were used. The weather data used for simulation and prediction are from the Canadian Weather year for Energy Calculations(CWEC) data sets, as described in Chapter 3.

4.2.2 Analyses

The simulations carried out with settings described above provide a good platform to illustrate how the analysis tool enables the visual analysis of the performance of computer models and management strategies. Analyses of these simulations, using the built-in routines currently implemented in the analysis tool, will be presented here. These analyses will constitute a demonstration of the capabilities and the functioning of the simulation framework. Explanations will be provided, with the aid of plots of various parameters recorded during simulations, as to how the analysis tool enables visualization of the performance of the management strategies and computer models used and thus serve to aid their improvement.

It is to be noted that in many of the graphical plots presented below, data-smoothing was performed so as to obtain discernible curves. The necessity for data-smoothing arises since, in both simulations, each parameter is recorded 7200 times, one for each simulation time-step and including each of these data-points in a curve would lead to a plot which looks congested. Data-smoothing, whenever used, was performed by the use of the cubic spline smoothing option available in the gnuplot plotting tool.

It should also be noted that, all time parameters which appear in ensuing plots represent simulation time and not real-life time. For instance the time value *May '00* in a plot represents the month of May in the 0^{th} simulation year.

Performance of Computer Models

The analysis tool can be used for the testing, validation and verification of computer models used in the various software modules of the simulation framework. If one wishes to validate the functioning of a computer model, the real-life data used to simulate the corresponding software module can be plotted alongside the outputs of the computer models to check whether or not the relationship between the two follows from the expected behaviour of the computer model.

In the simulations performed for demonstration, computer models of interest are those used in the photo-voltaic and load modules. In the computer model used in the PV module, the power output of the PV system has a directly proportional relationship to the incident solar radiation. With this in mind, one can verify that the computer model is working as is expected of it, by plotting the PV power output and incident radiation alongside each other in a graph. Such a plot is shown in Figure 4.4. It can be seen that the curve for PV power generated follows the exact same trend as that for incident solar radiation, thus confirming that the computer model works as expected.

In Figure 4.4, one can observe that there are certain time periods spanning over a simulation month when the values of PV power output and incident radiation are very low, close to zero. This is not realistic and is a result of the cubic spline data-smoothing performed while plotting the data. However, in our simulations, there are large fluctuations in the values of simulation data within very short simulation

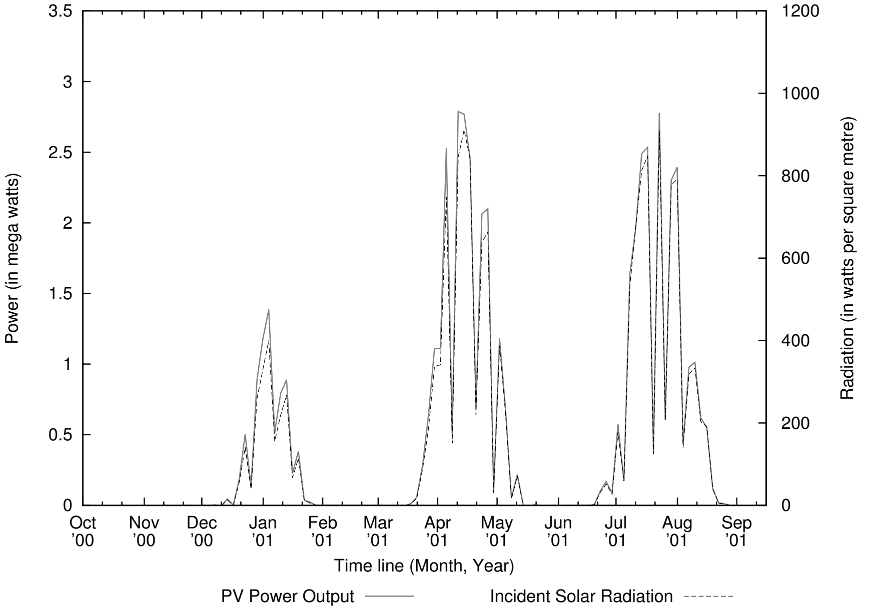

Figure 4.4: This figure shows a plot of power output of the PV module, represented by the solid grey line and that of incident solar radiation, represented by the dashed black line against simulation time for simulation II. Cubic splines data-smoothing was performed while plotting this graph. The values of incident solar radiation were obtained from the Canadian Weather year for Energy Calculations data-set.

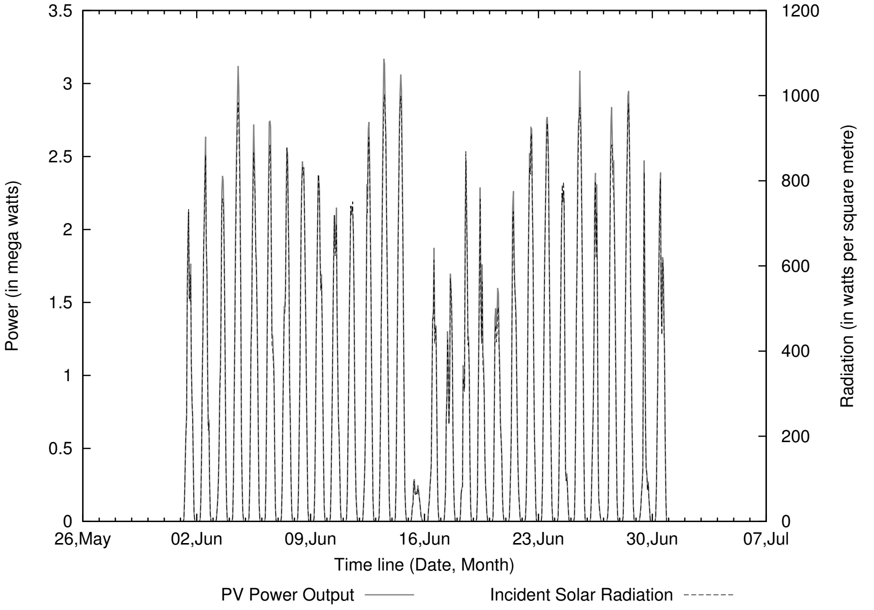

Figure 4.5: This figure shows a plot of power output of the PV module, represented by the solid grey line and that of incident solar radiation, represented by the dashed black line against simulation time in simulation II for the simulation month of June. No data-smoothing was performed while plotting this graph. In this figure, one can observe the daily fluctuations in the PV power generated, caused by the daily fluctuations in incident irradiation.

time intervals. This necessitates data-smoothing while plotting these data over large simulation time periods in order to achieve plots in which the trends of the simulation data in question are discernible. This can be better understood by observing the plot of the same simulation parameters over a shorter simulation time period, plotted without employing any data-smoothing technique. Figure 4.5 shows the plot of PV power generated and that of the incident solar radiation, in simulation II over a shorter simulation time period, the simulation month of June, without data-smoothing. Here, one can observe the daily fluctuations in the weather data and the corresponding fluctuations in PV power generated.

The computer model used in the load module of the simulation framework, scales down the magnitude of the load demand values obtained from the provincial(Ontario) load demand data-file, to arrive at the load demand values in the microgrid, so that the fluctuations in the load demand values of the microgrid follow those of the province of Ontario. Graphical plots can be used to verify that the computer model performs this task as expected. A plot of the provincial load demand, from the load data-file is plotted against time in Figure 4.6 alongside the microgrid load demand values.

As with the plots of the PV power output and radiation data values, the plots in Figure 4.6 were obtained by performing data-smoothing to smooth over short term data fluctuations, which render their trends unrealistic, but serves to make them discernible. Figure 4.7 shows a plot of load demand values for the province of Ontario and the microgrid for a shorter time period, the simulation month of June, without data-smoothing. The daily variations in the profiles of both the load demand curves are observable in this figure. From Figures 4.6 and 4.7, it can be seen that the computer model for the load module implemented in the current version of the

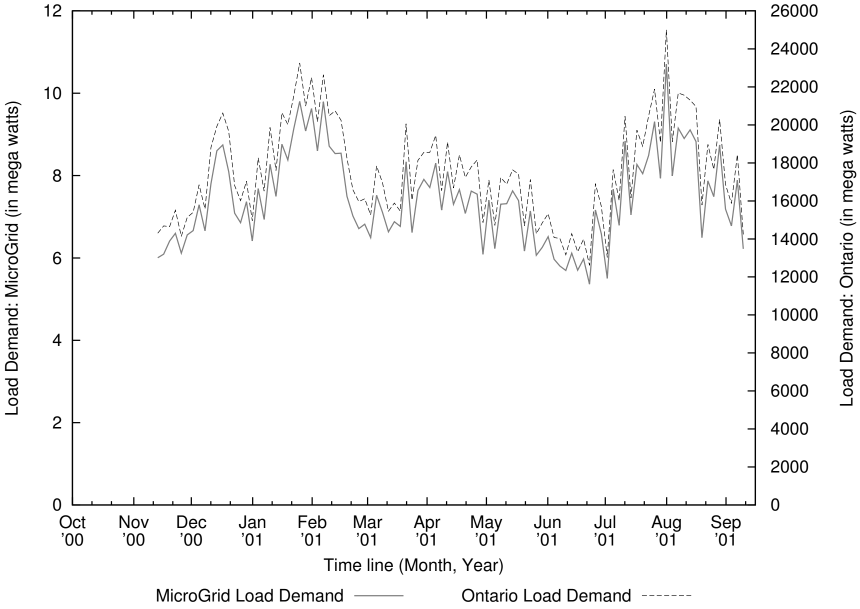

Figure 4.6: This figure shows a plot of the load demand for the microgrid, represented by the solid grey line and that for Ontario, represented by the dashed black line against simulation time for simulation I. Cubic splines data-smoothing was performed while plotting this graph. The values of Ontario load demand were obtained from the Independent Electricity System Operator's archival load data-set for the year 2007.

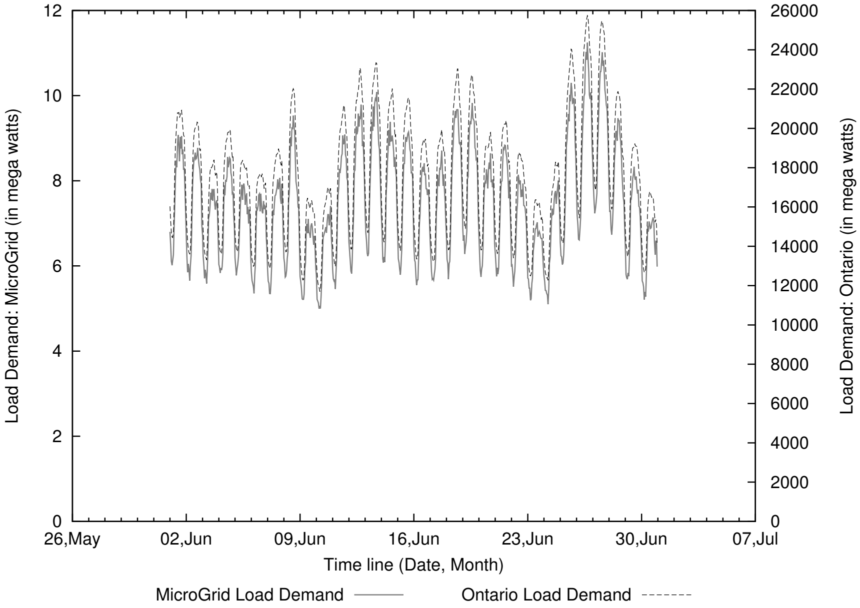

Figure 4.7: This figure shows a plot of the load demand for the microgrid, represented by the solid grey line and that for Ontario, represented by the dashed black line against simulation time in simulation I for the simulation month of June. No data-smoothing was performed while plotting this graph. This illustrates the daily fluctuations in the microgrid load demand values, which follows those in the provincial load demand data.

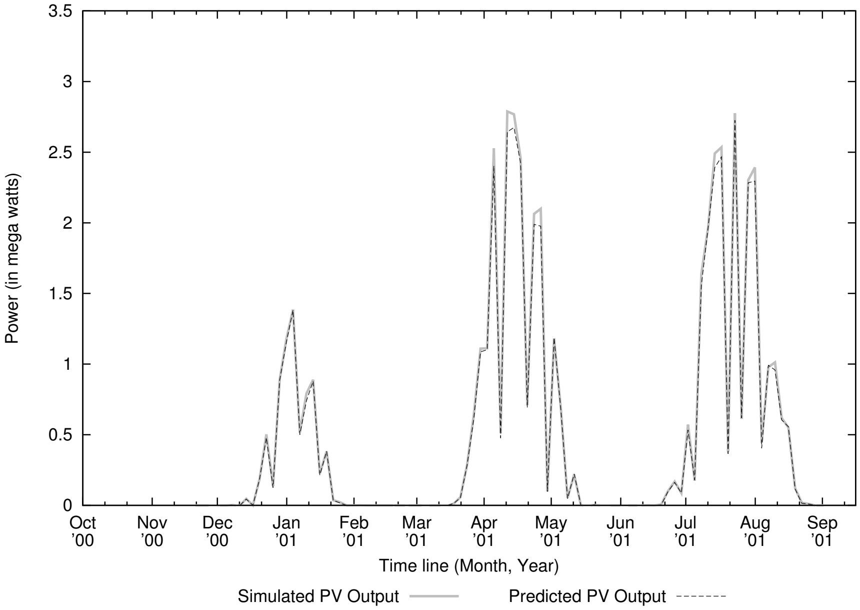

Figure 4.8: This figure shows a plot of the power generated by PV module, represented by the solid grey line and of predicted values of PV power generation, represented by the dashed black line against simulation time for simulation II. Cubic splines data-smoothing was performed while plotting this graph. It can be seen that the predicted values are fairly accurate and the values are slightly under-predicted, in keeping with the relation 3.7

simulation framework works as expected

Analysis and Comparison of Performance of Prediction Components and Management Strategies

Management strategies make use of prediction components to predict the future values of parameters essential to their decision making, such as the future load demand and power outputs from temperamental microsources like PV modules. Hence, the accuracy of prediction methods are vital in determining the overall performance of the management strategy. The analysis tool can be used to plot the values of PV power and load demand predicted by the prediction components, along with the values which result from the simulation of PV and load modules, in order to determine how accurate the methods used for predictions are.

Figure 4.8 shows the plots of the predicted values of power generated by the PV module, calculated using the relation 3.7 against simulation time, alongside values of PV power generated by executing the computer model in the PV module in simulation II. Cubic splines data-smoothing was performed while plotting this figure. It can be seen that the prediction is fairly accurate and that the predicted values are always slightly lower than that of the output of the PV module. This corroborates with the nature of the relation 3.7, which dictates a cautious approach to prediction, that is, the kind of prediction must always be under-prediction and that the deviation in the predicted values must utilize weather data values which lie within within 5% of the values obtained from the weather data-file.

In Figure 4.9, the plot of predicted values of microgrid load demand for simulation I, against simulation time are shown along with that of the microgrid load values obtained by running the computer model in the load module of the simulation framework. It can be observed, from the figure and from the relation 4.1, that similar to the predicted values of PV power, the prediction method dictates that the prediction method uses a value that deviates at most 5% from the values obtained from the load data file. However, in this method, load values are always over-predicted.

Simulation II uses a different approach for prediction; it uses provincial load values from two years immediately preceding the year, whose load values are used in the computer model of the load module to simulate microgrid load demand. This method is described by the relation 4.2. Figure 4.10 shows a plot of the predicted values of load demand in simulation II against simulation time along with the microgrid load

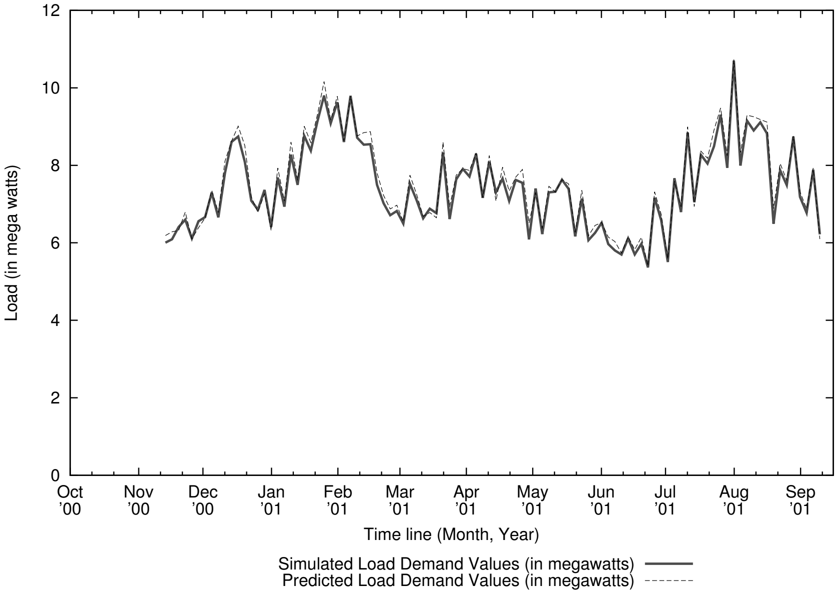

Figure 4.9: This figure shows a plot of the load demand, represented by the solid grey line and of predicted values of PV power generation, represented by the dashed black line against simulation time for simulation I. Cubic splines data-smoothing was performed while plotting this graph. It can be seen that the predicted values are fairly accurate and the values are slightly over-predicted, in keeping with the relation 4.1

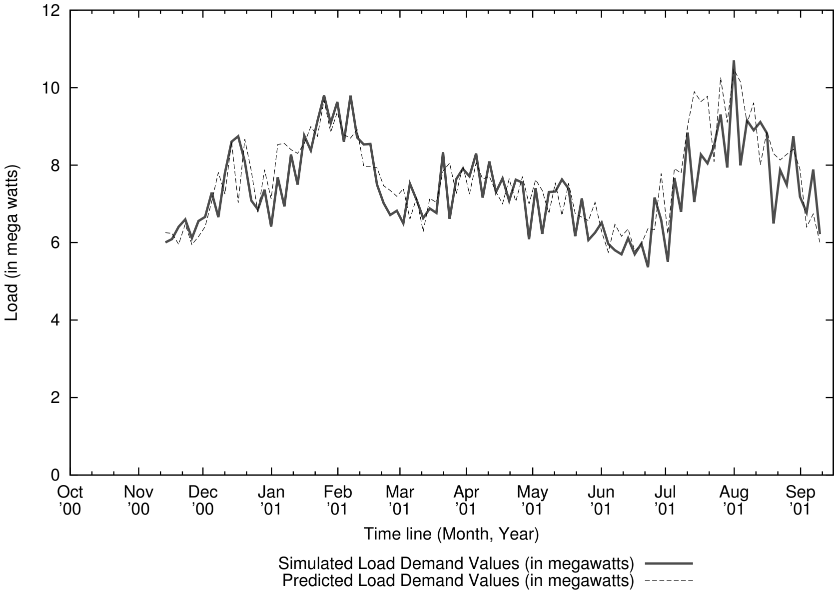

Figure 4.10: This figure shows a plot of the power generated by PV module, represented by the solid grey line and of predicted values of PV power generation, represented by the dashed black line against simulation time for simulation II. Cubic splines data-smoothing was performed while plotting this graph. It can be seen that the predicted are not as accurate as those of simulation I, and are at times higher than the simulated value and at other times, lower. The prediction method used here is summarized by the relation 4.2

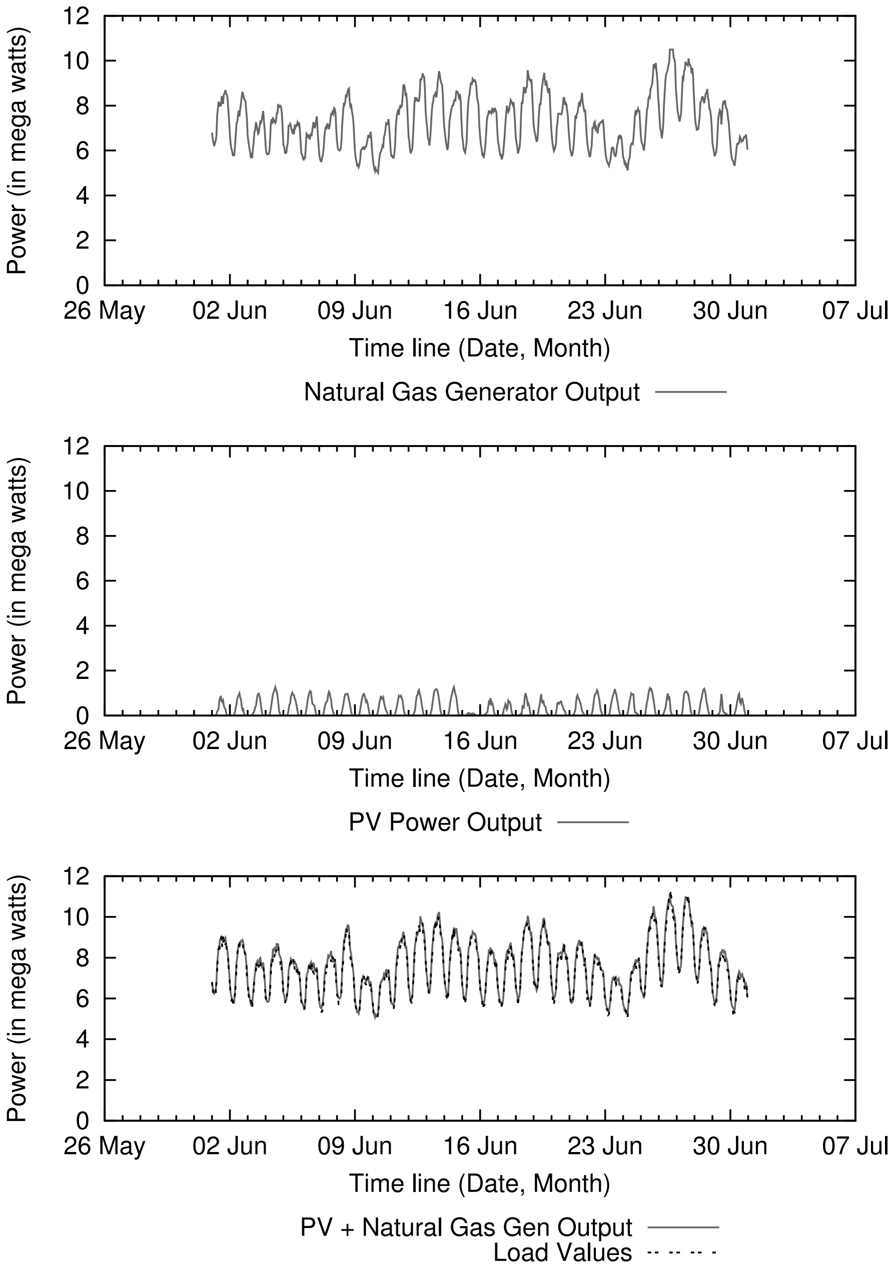

Figure 4.11: This figure shows three plots, all of which are for the simulation month of June in Simulation I. **Top**: Plot of power generated by the natural gas powered generator against simulation time. **Middle**: Plot of power generated by the PV module against simulation time. **Bottom**: Plots of the combined power generated within the microgrid, represented by the solid grey line and that of load demand in the microgrid, represented by the dashed black line against simulation time for simulation I. No data-smoothing was performed while plotting these graphs. It can be seen that, since the predicted load demand values are fairly accurate for simulation I, the load demand is matched by power generated within the microgrid.

values simulated by the execution of the load module's computer model. It can be seen from the figure that the prediction method used in simulation II is not as accurate as that used in simulation I. There are large deviations both higher and lower than the simulated values of load demand, during different periods of simulation time.

Inaccuracies in prediction methods affect the efficacy of the management strategy's capability to balance power supply and demand within the microgrid. The management strategies, in this case, make use of the predicted values of load demand and PV power to calculate set points for the natural gas powered generator so that load demands are sufficiently met. If the predicted values are not accurate, balancing load and power supply cannot be achieved without unforeseen power selling and purchase to and from the utility grid.

The effects of inaccuracies in load demand prediction are illustrated in Figures 4.11, 4.12, 4.13 and 4.14. Figures 4.11 and 4.12, for simulation I and II respectively, contain 3 different plots each. The first plot in each shows the power generated by the natural gas powered generator against simulation time. The second plot shows power generated by PV module against simulation time. The third plot shows the load demand and cumulative power generated by the PV module and natural gas generator against simulation time. It can be seen that since the prediction for load demand is fairly accurate in simulation I, the load is matched by the power generated within the microgrid. However, in simulation II, it can be seen in Figure 4.12 that the load demand and power generated by sources within the microgrid are not balanced. This results in unforeseen needs to purchase power or sell power. This is illustrated in Figures 4.13 and 4.14.

Figures 4.13 and 4.14 show plots of the predicted estimate of the amount of power

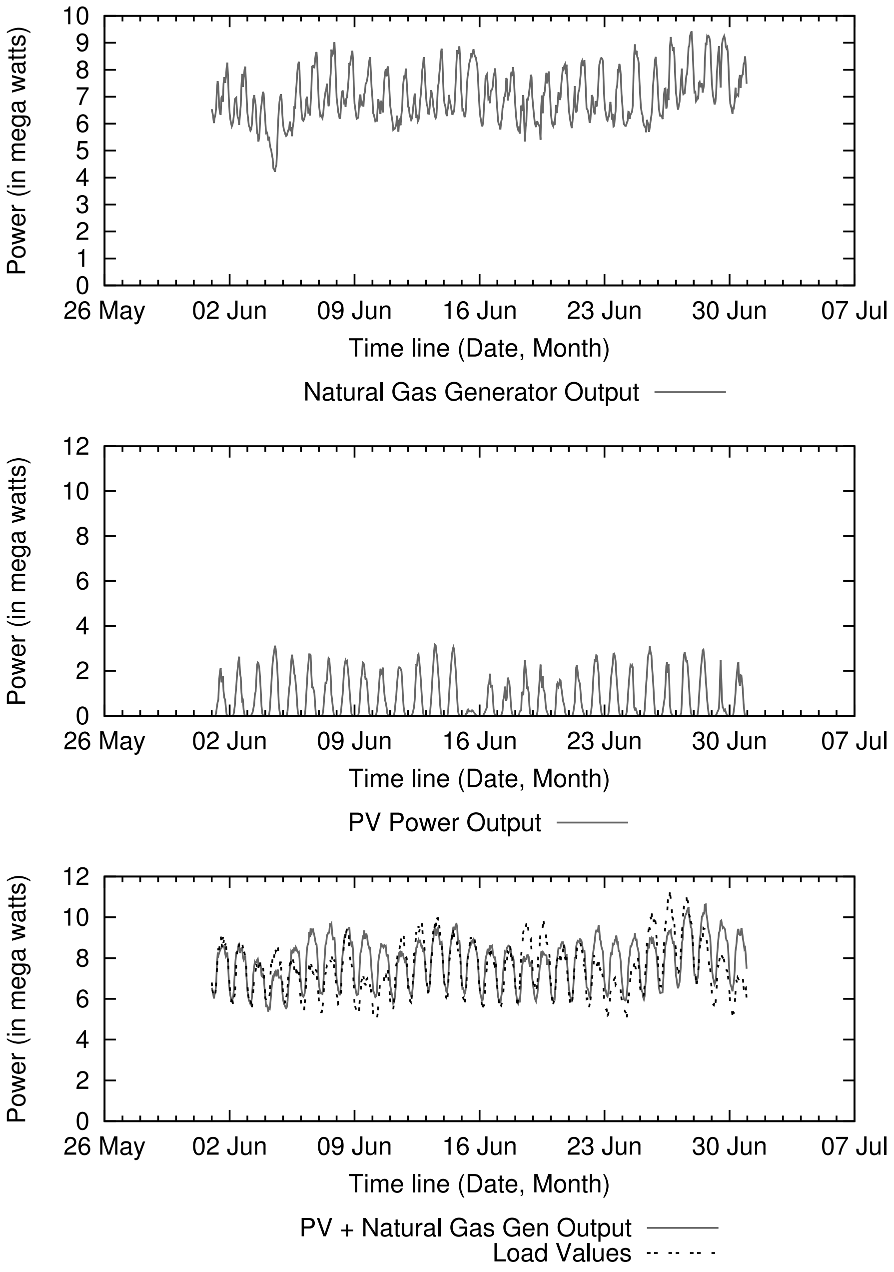

Figure 4.12: This figure shows three plots, all of which are for the simulation month of June in Simulation II. **Top**: Plot of power generated by the natural gas powered generator against simulation time. **Middle**: Plot of power generated by the PV module against simulation time. **Bottom**: Plots of the combined power generated within the microgrid, represented by the solid grey line and that of load demand in the microgrid, represented by the dashed black line against simulation time for simulation I. No data-smoothing was performed while plotting these graphs. It can be seen that the load demand and power generated by sources within the microgrid are not balanced. This results in unforeseen needs to purchase and sell power to and from the utility grid. This is illustrated in Figures 4.13 and 4.14

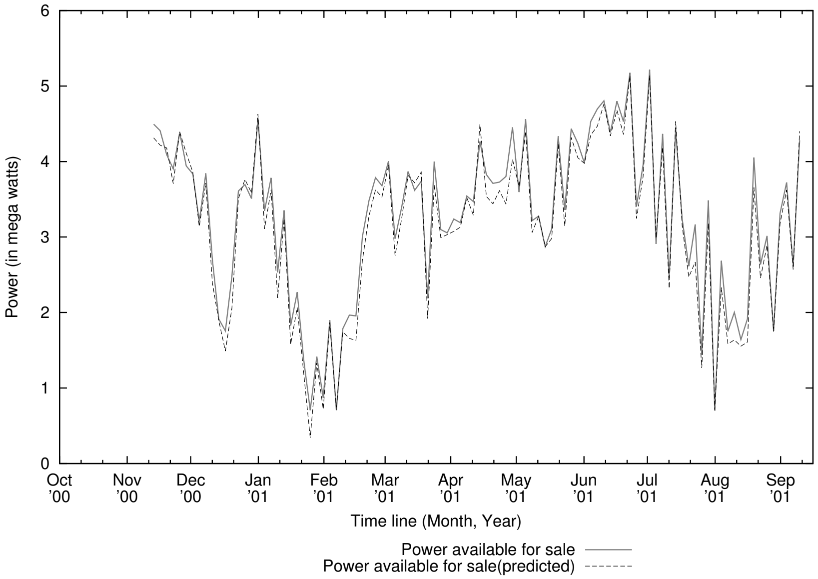

Figure 4.13: This figure shows a plot of the power available for sale in the microgrid, represented by the solid grey line and of predicted values of PV power generation, represented by the dashed black line against simulation time for simulation I. The power available for sale is calculated by subtracting the value of load demand from the total power generation capacity in the microgrid, which varies from time to time by virtue of the temperamental nature of the PV module. Cubic splines data-smoothing was performed while plotting this graph. It can be seen that the predicted values are fairly accurate. The simulated values are slightly higher than the predicted values, due to over-prediction of load demand and under-prediction of PV power.

that could potentially be sold, which is determined by the management strategy based on predicted values of load demand and PV power generation, alongside the actual reserve power in the microgrid that could be sold, which is calculated from simulated values of load demand and power generated by PV module, for simulation I and II respectively. It can be seen that in simulation II, the estimated values of the amount of power that could be sold are inaccurate due to inaccuracies in the predicted values of load demand. The analysis tool can also be used to verify and compare the functioning of different aspects of management strategies. For instance, in simulation I fuel for the natural gas powered generator is purchased once the fuel available in

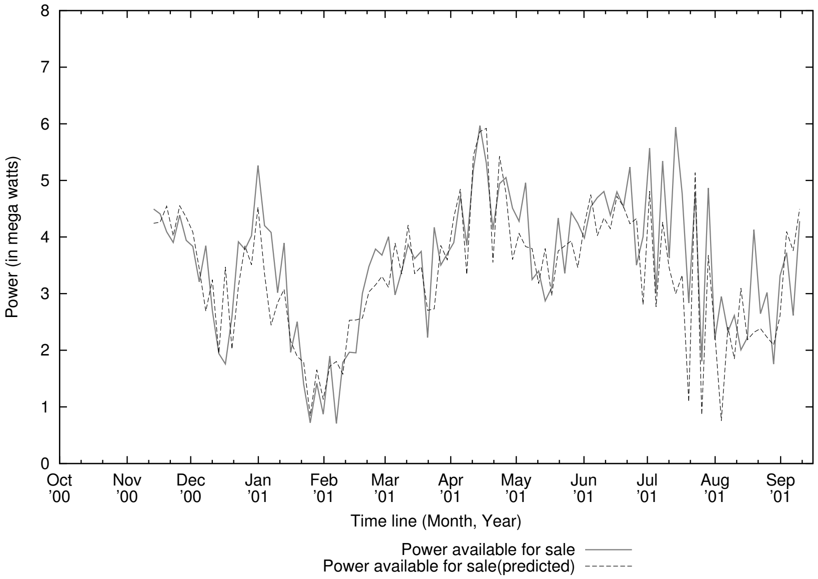

Figure 4.14: This figure shows a plot of the power available for sale in the microgrid, represented by the solid grey line and of predicted values of PV power generation, represented by the dashed black line against simulation time for simulation II. The power available for sale is calculated by the same method as described in Figure 4.13. Cubic splines data-smoothing was performed while plotting this graph. It can be seen that the predicted values are not as accurate as those in simulation I, due to the inaccuracies in load prediction in simulation II, illustrated in Figure 4.10.

storage is at a minimum specified level. Figures 4.15 and 4.16 show plots of the fuel available in storage and fuel bought, in cubic metres, for the natural gas powered generator in simulations I and II respectively. Here, one can notice an unmistakable difference between the figures in that, fuel is bought in smaller quantities but at more frequent intervals during certain simulation months in the plot for simulation II. This is due to the difference in fuel purchase policies in the management strategies used in simulations I and II, in order to lessen the burden on natural gas fuel suppliers, when the demand is at its peak, due to increased heating demands.

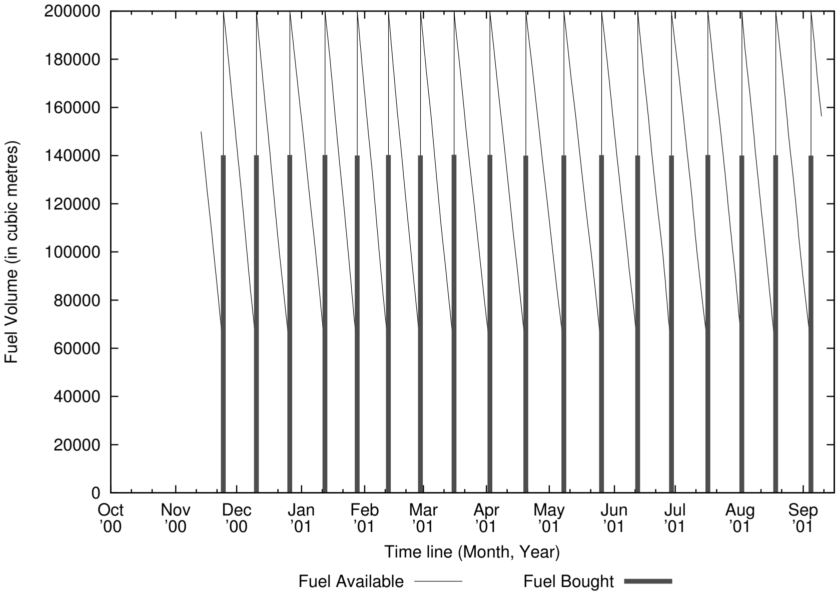

Figure 4.15: This graph shows the plot, in simulation I, of the fuel available for use in the natural gas generator's storage facility against simulation time, represented by the solid black line, along with that of the amount fuel bought against simulation time, represented by impulses, which are thick and grey. Location of occurrence of the impulse on the time axis represents the simulation time at which fuel was bought and its height, the amount of fuel bought. It can be seen that in simulation I the strategy for fuel purchase is the same for the entire simulation time period.

Tracking Individual Simulation Parameters

In addition to the different kinds of analyses presented above, the analysis tool equips the user with the ability to track individual simulation parameters recorded in the simulation database. This facility would be useful if one wishes to analyze the behaviour of just one parameter, which for instance is suspected to cause issues in the functioning of management strategies or computer models. Figure 4.17 shows the plot of fuel consumed by the natural gas powered generator against simulation time for simulation I. Similar plots can be obtained for every parameter recorded in the database during simulations.

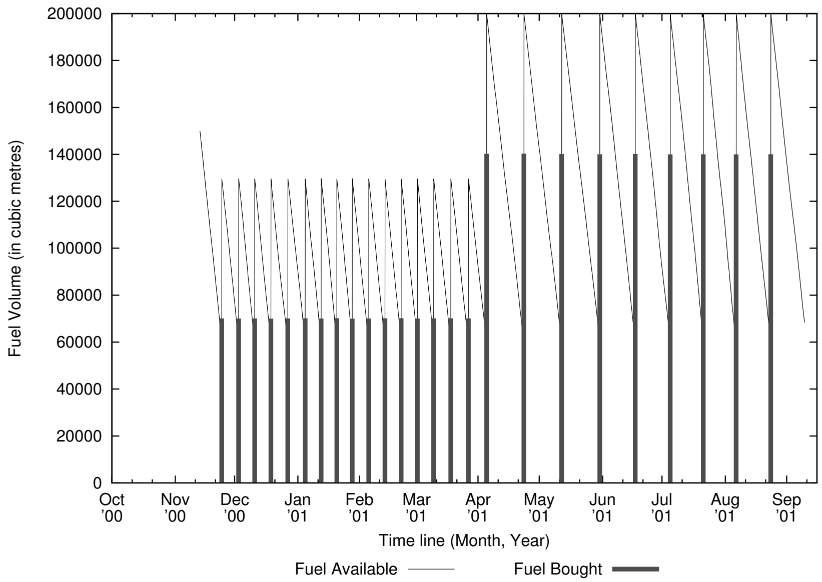

Figure 4.16: This graph shows the plot, in simulation II, of the fuel available for use in the natural gas generator's storage facility against simulation time, represented by the solid black line, along with that of the amount fuel bought against simulation time, represented by impulses, which are thick and grey. The characteristics of the impulses represent the same things as they do in Figure 4.15. It can be seen that in simulation II the strategy for fuel purchase is different for winter months, ensuring that more frequent purchases of smaller quantities are made to lessen the burden on the suppliers, when the demand for natural gas is at its peak.

4.3 Summary

The software testbed needs a means to facilitate visual analysis of simulation data in order for the designer to get an intuitive picture of the working of computer models and the management strategy. The analysis tool provides this means. The structure and functioning of the analysis tool was presented in this chapter.

A demonstration of the testbed's capability to simulate the microgrid and the usefulness of the analysis tool in aiding the improvement of the computer models and management strategy used in the testbed is also presented in this chapter. Two

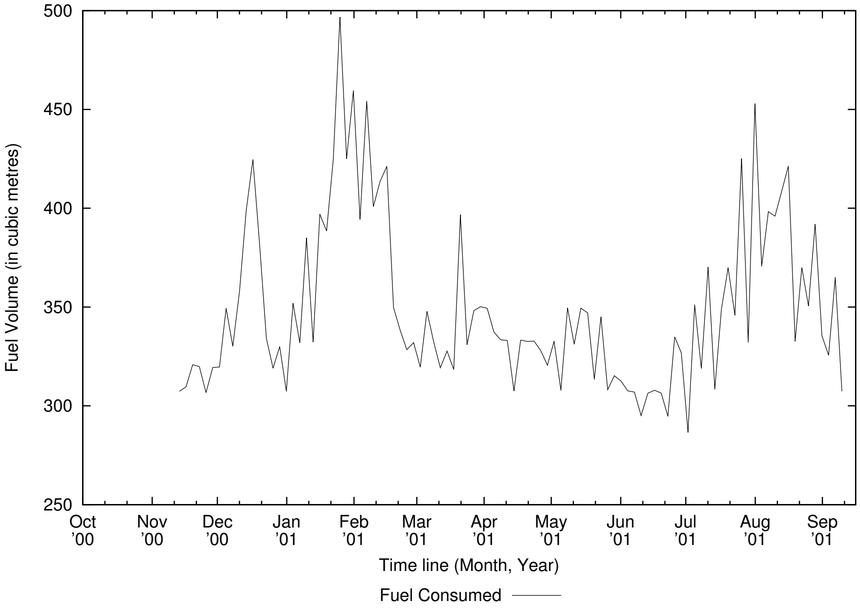

Figure 4.17: This figure shows the plot of fuel consumed by the natural gas powered generator, against simulation time for simulation I. Cubic splines data-smoothing was performed while plotting this graph. This is a graph which tracks a single simulation parameter throughout simulation time. This type of graph can be used to track the fuel consumption, in case it is suspected that there is an anomaly in the performance of the computer model of the natural gas generator, for instance.

simulations with different simulation settings and management strategies were performed using the simulation framework to aid the demonstration. It was shown that the analysis tool enables visual analyses of simulation data such as fuel and energy purchase and consumption, etc., which would enable improvement and optimization of the management strategy. It was also shown how the combination of simulation framework and analysis tool can be used to analyze and compare management strategies with a view to improve them. It was illustrated through the analysis tool, how prediction plays an important role in the performance of management strategies. The analysis tool's capability to aid the verification and testing of computer models used in the simulation framework was also demonstrated.

Chapter 5

Conclusion and Future Research

5.1 Summary

With increasing acceptance of microgrids as the potential future of electric distribution system, intelligent energy management in microgrids has become a vital research topic. With the recent advancements in Cognitive Dynamic Systems, application of its research principles in the design of energy management strategies of microgrids would be desired. However, due to the difficulties associated with testing new algorithms and schemes on a functional system such as a microgrid, one must resort to the development of simulators for testing.

This thesis presents a flexible and versatile microgrid testbed, designed for the purpose of testing management strategies for microgrids. The initial design of the microgrid structure, explained in Chapter 2, was done keeping in mind resources currently available at McMaster University. However, the testbed is flexible enough to accommodate the use of microgrids with other configurations.

The microgrid testbed consists a *modular* simulation framework. Modularity is achieved by designing the simulation framework using Object Oriented Programming principles. With the help of this framework, simulations of various configurations, differing in the type and capacity of microsources and loads used, the management strategy employed to manage demand-supply balance and the duration of simulation time, can be performed. The computer models, the prediction techniques and management strategy used in the current version of the simulation framework were presented in Chapter 3.

The analysis tool, the topic of Chapter 4, provides the designer with the ability to visually analyze the results of simulations run with the help of the simulation framework. The analysis tool consists of various routines which produce different kinds of plots of parameters recorded during simulations. Apart from this, the tool also allows addition of new routines to perform different analyses in case a new module is added to the microgrid being simulated or a different perspective on simulated data is desired. The capabilities of the microgrid testbed are demonstrated in chapter 4, with sample analyses of two simulations with different configurations. These demonstrations showcase the testbed's capability to simulate and aid analysis of the performance of computer models, prediction techniques and management strategy used.

5.2 Contributions to the Literature

The author's research contributions are listed below.

- Design of a microgrid structure for use in a microgrid testbed for energy management

- Design and implementation of a software testbed of microgrids
- Design and implementation of a flexible, modular and customizable software simulation framework for microgrids
- Design and implementation of a an analysis tool, to aid visual analysis of microgrid simulation data
- Demonstration of the analysis, model verification and testing capabilities of the software testbed

5.3 Future Research Directions

In this section, possible future research directions, which build on the work presented in this thesis are discussed.

5.3.1 Cognitive Controller: A Cognition Enabled Energy Manager

Cognitive Dynamic Systems(CDS), described by Haykin (2007), are engineering systems which try to mimic the cognitive functions of the human brain, viz., *perception*, *attention*, *intelligence* and *memory* to perform an *action* on their environment. The neuro-scientific background on these cognitive functions and the *perception-action cycle*, the powerful mechanism which is the core of CDS operation are explained in great detail by Fuster (2005).

The need for accurate and reliable prediction of certain parameters in the microgrid, demonstrated briefly in Chapter 4 and the need to optimally schedule dispatch of microsources and loads by the energy management strategy, among other requirements, provide the perfect opportunity for application of CDS design principles. With knowledge of principles and methods for development of theory and design framework for CDSs such as the Cognitive Radar, by Xue (2010) and Cognitive Radio, by Setoodeh (2010), the design of a *Cognitive Controller* for microgrids: a cognition enabled energy management strategy, would serve to improve microgrid performance. Hence, it is proposed to apply the best principles learnt from the design of Cognitive Dynamic Systems to develop the next generation energy manager for microgrids.

5.3.2 Implementation of a Functional MicroGrid

Once sufficient testing on the testbed has been done and the management strategy found to be satisfactory, implementation a functional microgrid using a cognitive energy management strategy, described above is mooted. As already mentioned, the McMaster University campus has microsources which can be integrated to form a microgrid. However, in order to provide heterogeneous quality of service within the campus, electric contracts have to be revised and priorities assigned to loads, in order to facilitate the energy manager to curtail and reschedule certain loads. With the proximity of buildings in the campus and the existing heat distribution infrastructure, combined heat and power and chilling facilities, the energy manager can be used to manage space and water heating and cooling as well. The implementation of a microgrid on campus, controlled by a cognitive energy management strategy would serve to improve the overall efficiency of energy use and result in savings in energy bills for the University.

Appendix A

Microsource Technologies Considered for Proposed MicroGrid Structure

In this appendix, different microsource technologies considered for inclusion during the design of the microgrid structure for the software testbed are introduced. A brief description about each of them is given, along with references for further reading on their technology and modelling.

A.1 Renewable Energy Microsources

This section will cover microsources which convert renewable natural resources such as wind, sunlight, water etc. into electricity.

A.1.1 Wind Turbine Power generators

Wind turbines use a rotor, usually with three blades, as a prime mover. The rotor rotates when wind blows and this rotary motion is trasmitted to an electric generator through a gearbox. The rotor assembly is usually mounted on top of a tower made of steel and there is a mechanism so as to enable the rotation the rotor assembly, around the tower's axis, so that the blades face the desired direction from which the wind blows. The generator is usually equipped with an anemometer to measure wind speed and direction. Utilization of wind turbine generators in urban areas poses unique challenges. Winds are usually slower, more turbulent and with more directional variations in cities. The noise and vibrations associated with the rotation of blades would may not be acceptable in many buildings, since wind turbines are usually mounted on rooftops. There have been several different rotor and blade designs proposed for use of wind turbine technology in urban locales.

The turbine, generator, their performance, operation and integration into the electric power system are explained in detail by Stiebler (2008). Dynamic models and simulations of wind turbines, connected to various kinds of generators are presented by Ekanayake *et al.* (2003), Muljadi *et al.* (2005), Slootweg *et al.* (2001), Sudrià *et al.* (2005) and Mansouri *et al.* (2004).

A.1.2 Photo-Voltaic Power Generators

Photo-voltaic(PV) generators make use of the photo-electric effect to generate electricity. Most modern cells have a semiconductor p-n junctions and the semiconductor substrate is usually made of either silicon or gallium-arsenide. These cells are arranged together in photo-voltaic modules. A solar array consists of several modules connected together. The energy conversion efficiency of modern day photovoltaic arrays are around 10% to 16%.

Krauter (2010) gives a detailed introduction to photo-voltaic technology, production of PV modules and heat and energy yield modelling of PV modules. A good model for simulating output voltage and current values of a PV cell is presented by Sze and Ng (2007). Dynamic sumulation models of PV systems are presented by Hansen *et al.* (2000), Marion (2002), Joyce *et al.* (2001), Altas and Sharaf (2007) and Sukamongkol *et al.* (2002). Li *et al.* (2009) consider the problem of developing a power control strategy of a PV power system when connected to microgrids.

A.2 Non-Renewable Energy Microsources

This section will discuss microsource technologies which use non-renewable sources of energy as primary fuel.

A.2.1 Fuel Cells

Fuel cells(FC), like batteries, produce electricity from electrochemical reactions. Fuel, usually gaseous fuel like hydrogen, is oxidized and the ions created during the electrochemical process flow between the anode and cathode; in the outside circuit, electrons produced at the anode flow towards the cathode through electrical loads. In batteries, fuel is stored, but, in fuel cells fuel and oxidants are fed into the electrodes continuously. Hence, fuel cells do not need to be recharged. There are different kinds of fuel cells such as alkaline fuel cells, molten carbonate fuel cells, phosphoric acid fuel cells, proton exchange membrane fuel cells and solid oxide fuel cells. Certain types of FCs such as the molten oxide fuel cells operate at high temperatures and can be used in combined heat and power applications. Borbely and Kreider (2001) and Wood (2008) provide good introductions to fuel cell technologies. Lasseter (2001) and Hatziargyriou *et al.* (2004) present dynamic models of many different microsources including fuel cells.

A.2.2 Microturbines

Microturbines are small, mechanically simple devices, which usually make use of natural gas as their fuel. Single-shaft microturbine is the most commonly used type. Compressed air and fuel are mixed and burnt, producing hot flue gases which rotate a turbine. An introduction to microturbines is presented by Borbely and Kreider (2001). Haugwitz (2003), Aguiar *et al.* (2007), Nikkhajoei and Iravani (2002) and Mohamed (2008) present models and analysis of microturbines.

A.2.3 Reciprocating Engines

Reciprocating Engines have power generation capacities ranging from a few kilowatts to 5 megawatts and use hyrdo-carbon fuels. Internal combustion engines are a type of reciprocating engine. Fuel and air are mixed and ignited in an enclosed chamber. Expansion of hot gases caused by the ignition, accelerates a piston to produce mechanical energy. There are two types of reciprocating engines: spark-ignition Otto cycle engines which use natural gas as their fuel and compressed ignition diesel cycle engines which use diesel as their fuel. Reciprocating engines can be used in combined heat and power applications due to the amount of exhaust heat produced.

A.2.4 Combined Heat and Power

Combined Heat and Power(CHP) generators make use of the waste and exhaust heat generated from the process of producing electricity in devices such as reciprocating engines and high temperature fuel cells. In reciprocating engines only 30% to 40% of the energy available in the fuel is converted to electricity. One way of recovering heat is to pass exhaust gases through a heat recovery chamber to heat water. Ebullient cooling systems pass water through engines to cool them, thus keeping engines at their operating temperatures. Coolants at the outlet are usually at a temperature greater than 100°C. The hot water generated can be used for space heating. Absorption chillers are used to produce chilled water from exhaust of engines, using a chemical process involving lithium bromide and water solution. Borbely and Kreider (2001) explain technologies used in CHP systems.

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