

Smart Grid for Demand Side Management of Households by Integration of AMI and Solar PV Distributed Generators



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Declaration

I declare that this dissertation is my own, unaided work. It is being submitted for the degree of Masters of Science in Electrical Engineering at the University of Cape Town. It has not been submitted before for any degree or examination in any other university.

Signature of Author

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Abstract

This thesis focuses on demand side management (DSM) of households. The thesis proposes two power grid enhancement DSM techniques to form a smart power grid. The two techniques are: a) advanced metering infrastructure (AMI) and b) solar photovoltaic (PV) systems installed on households and connected to the main grid. The aim of the AMI is to provide a two way communication between the utility and the energy consumers. It brings energy awareness to households by providing them with more detailed energy consumption information which helps them manage their energy better. Integration of grid-connected solar PV supplements energy that households draw from the national grid. It reduces load catered by the grid. It can also shave peak demand and hence delay need for large investment into new power stations.

This thesis investigated important issues concerning implementation of the proposed DSM programmes. It was identified from review of literature that a huge gap exists in implementation of wide area communication networks for AMI. Therefore AMI section of this dissertation proposes and simulates a MPLS network implementation for backhaul communication networks. The simulation is done on OPNET network simulator. Communication networks support information dissemination between utilities and their customers in a smart grid. Smart grids are characterised by bi-directional flow of both data and power between utility and its customers. That is, utilities sell power to the grid hence customers need for smart meters to know how much power they buy, when do they buy it most and how much the power cost them. Utilities also buy energy from households who have grid-connected DGs such as solar PV systems; they therefore need smart meters which provide them with information about the energy they purchase from these independent power producers.

The proposed grid-connected distributed generators are notorious of bringing unwanted disturbance to stability of the main power system. Hence protection and control are important issues. The thesis studies economic and technical viability of implementing grid-connected solar PV microgrids. The viability study attempts to find how much it costs the households to own one of these solar PV systems. The technical study sets to find a feasible configuration of the home-based solar PV systems. Meshed solar PV microgrids were found to be a viable option. However, they pose more challenges on power quality issues. Hence protection and control

become harder. The thesis simulated differential protection scheme and proposed it as a good scheme for the meshed microgrids.

Keywords

Smart grids, Microgrids, Renewable Energy Technologies, Advanced Metering Infrastructure (AMI), Solar PV, Distributed Generators, Communication Networks, Protection of Microgrids, Multi protocol label switching (MPLS), Internet Protocol, Energy Metering, Viability of Solar PV Distributed Generators, and AMI backhaul network.

Terms of Reference

The topic of this thesis was proposed by A/Prof. SP. Chowdhury in collaboration with Dr. Simon Winberg, both from the Department of Electrical Engineering at the University of Cape Town. A/Prof. Chowdhury's area of expertise is focused on the fields of heavy current and renewable energy research background; while Dr. Winberg's expertise are in the fields of digital systems, communication networks and radar research. Their combined vision for this thesis was use of communication networks and renewable energy sources for energy management of households. The task was therefore to research and come up with an inter-disciplinary energy management system for energy management of households.

The supervisors specified the guidelines of this research to focus on:

- Energy management of households,
- Smart grid technologies,
- Intelligent electronic devices,
- Communication networks for smart grid's advanced metering infrastructure,
- Integration of home-based solar PV DGs into the main grid,
- Simulation of the proposed concepts,
- Discussion and analysis of the obtained results and
- Conclusions and recommendations drawn from the studies.

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Nomenclature

ACDs – Appliance Controller Devices
AMI – Advanced Metering Infrastructure
AMR – Automated Meter Reading
BS - British Standards
COE – Cost Of Energy
DA – Distribution Automation
DSM – Demand Side Management
EEPs – Energy Efficiency Programmes
EMS – Energy Management Systems
EVO – Efficiency Valuation Organisation
FECs – Forwarding Equivalency Classes
HAN – Home Area Network
HTTP – Hyper Text Transfer Protocol
IC – Initial Capital
IEC - International Electro-Technical Commission
IED – Intelligent Electronic Devices
IEEE – Institute of Electrical And Electronic Engineers
IP – Internet Protocol
IPMVP – International Performance Measurement and Verification Protocol
ISO - International Standards Organisation
ISP – Internet Service Provider
LAN – Local Area Network
LCoE – Levelised Cost of Energy
LER – Label Edge Router
LSP – Label Switched Path
LSR – Label Switch Router
M&V – Measurement and Validation
M2M – Machine 2 Machine

MAN – Metropolitan Area Network
MCAS – Microgrid Control Agent Server
MDMS – Meter Data Management System
MMS – Manufacturing Message Specification
MPLS – Multi Protocol Label Switching
NPC – Net Present Cost
NREL – National Renewable Energy Laboratories
NRS - National Regulatory Services
NSP - Network Service Provider
OPNET - Optimised Network Engineering Tools
PC – Personal Computer
PCC – Point of Common Contact/Coupling
PMO – Project/Programme Management Office
PMUs – Phasor Measurement Units
PV-DGs – Photovoltaic Distributed Generators
QoS – Quality of Service
REFIT – Renewable Energy Fit-In Tariffs
REMPLI – Real-Time Energy Management via Power Lines And Internet
RFP – Request For Proposals
SABS - South African Bureau of Standards
SAM – System Advisor Model
SCADA – Supervisory Control and Data Acquisition/System Control, Alert and Data Acquisition
SHS – Solar Home System
TE – Traffic Engineering
THD – Total Harmonic Distortion
ToR – Terms of Reference
UWB – Ultra Wide Band
VoIP – Voice over Internet Protocol
VPN – Virtual Private Network
WAMPAC – Wide Area Monitoring Protection and Control
WAN – Wide Area Network
Wi-Fi – Wireless Fidelity

1 Introduction

The essence of this dissertation is to investigate demand site management (DSM) for domestic households. This thesis presents a set of studies carried-out to determine how to achieve DSM through advanced metering infrastructure (AMI) and solar photovoltaic (PV) integration on domestic power distribution systems. The first part of this thesis is therefore finding a more efficient communication network design for AMI. The second part investigates design factors associated with integrating solar PVs on a distribution network. The AMI section studies alternative communication network technologies and simulation of the proposed design techniques that can be used for networking the components of the modern metering infrastructure that supports DSM. The grid-connected solar PV studies feasibility of the approach. The economic feasibility studies concentrate more on cost-benefit trade-offs of domestic PV integration in terms of DSM and peak demand shaving (PDS). The technical feasibility study investigates power quality disturbances and how these can be detected and mitigated. In addition, the thesis presents case studies on real-life implementation issues of AMI and solar PV systems. These case studies also delve into project management for implementation of the proposed DSM solutions.

1.1 Background and Motivation of the Research

'Going green' is the buzzword used globally by politicians, environmentalists and engineers alike. Climate change issues are no longer the future but the present as South Africa's renowned Bishop and peace Nobel winner Desmond Tutu once said. While political leaders are still struggling to come up with a solid framework on how climate change issues should be dealt with, at least everybody agrees that something needs to be done. As early as 1988, United Nations Environmental Panel (UNEP) and World Meteorological Organisation (WMO) formed the Intergovernmental Panel on Climate Change (IPCC) as a body that oversees scientific knowledge on global warming. It was the first report (titled: UN Framework Convention on Climate Change) from this organisation that concluded on an accord that climate change was caused by human behaviour [1]. Emission of greenhouse gases which cause global warming and global dimming effects have led to many humanitarian disasters. E.g., As far as 1970s and 80s, it was believed that the Ethiopian droughts were caused by global dimming while the 2003

European heat wave is attributed to global warming. Both of these events saw deaths of from thousands to millions of people [2]. Further findings identified means of energy generation from fossil fuels as a major contributor of greenhouse gases. In response to these discoveries, the trend has since been finding alternative sources of energy, mostly renewable sources. In addition to this, another identified solution is curbing energy usage by managing available energy and using it efficiently and effectively. This has motivated a lot of research into the fields of renewable energy generation, energy efficiency and thus energy management, hence the focus of my thesis. The scope of the work covered in this report is refined in Section 1.2 below.

1.2 Scope of this Thesis

There are many energy efficiency programmes that have been proposed globally. Most of them are designed to initiate and promote customer participation in generation and use of energy, e.g., Eskom's 49m campaign [3], and the USA's Weatherization Assistance Program [4]. DSM programmes comprise a subset of these. There are two classes of these programmes: 1) power network infrastructure based programmes; and 2) non-network initiatives. This dissertation concentrates on the network based DSM programmes. The dissertation focuses specifically on two types of network enhancement DSM programmes: firstly the enabling communication network technology of advance metering infrastructure, and secondly integration of solar PV distributed generators (DGs) based on power utility customer's homes. Power network infrastructure based DSM programmes are those that entail enhancing the power grid to support energy efficiency while non-network initiatives are basic incentives in the form of time of use price reduction etc. that motivate customers to use less energy without the utility needing to invest in the network infrastructure to support such. Most of these types of initiatives come as policy instigated by regulators. It must be noted that most of the ideas discussed in this dissertation are influenced by South African needs and experiences. However, most of the ideas are applicable globally. Detailed objectives of the thesis are outlined in Section 1.3 which follows below.

1.3 Objectives of the Research

The main objective of this thesis is to investigate application of advanced metering infrastructure (AMI) and grid integration of home-based PV DGs as power grid enhancement DSM programmes. AMI has three important facets which can be investigated. These are the smart meters, the appliance control devices, and the communication networks. On the other hand, PV DG integration can be looked at from various design challenges point of view, possible negative

impact on power quality, protection synchronisation, and distribution feeder operations [5]. The work pursued in this thesis ruminates on implementation of these DSM programmes. The thesis proposes an integrated energy management system that combines consumption monitoring infrastructure (AMI) and conventional energy source supplement (solar PV DGs). In the light of the above mentioned possible areas of study, the focus of this thesis is divided into the following four main sub-objectives:

- Investigating integration of AMI into conventional power grids,
- Studying domestic PV systems design and how power quality issues related to their integration into the national power grid can be detected and mitigated through protection schemes,
- AMI project implementation: Case study, and
- Solar PV installation project: Case study.

The investigation on integration of AMI will chirp on the following:

- It studies currently used approaches to AMI technologies.
- It determines how communication networks infrastructure of AMI can be implemented.
- It discusses design challenges and how they can be overcome.
- It presents design of an efficient communication network that caters for all smart grid applications.

The PV integration section of this dissertation will present

- Viability study of domestic solar PV systems,
- Feasible design of a microgrid of solar PV systems, and
- Protection, monitoring and control of the solar PV microgrid systems.

The case studies will look at

- Project Management practices for implementation of AMI,
- HOMER software based design for a real-life off-grid PV system for a household, and
- Project Management practices used in implementation of a solar PV project.

The expected outcome of this research is therefore recommendation of the most suitable AMI communication protocol for the backhaul (Wide Area Network - WAN) network. The solar PV simulations give an insight into design of protection schemes for grid-connected systems and feasibility of solar PV integration as a DSM programme. The design of protection scheme study

will show that differential protection scheme is suitable for protecting the point of common coupling (PCC) in grid-connected solar PV systems. It will also validate viable solar PV microgrid systems design for use as DSM programme. The case studies on project management theories will give an insight into how real-life projects of DSM and smart grids are realised.

1.4 Plan of Development - Thesis Outline

This report mainly focuses on an investigation on applying advanced metering infrastructure and integration of PV DGs as DSM programmes. The report can be divided into three parts: review of literature, simulations and case studies. The review of literature section discusses general concepts involved in demand side management, advanced metering infrastructure and solar PV distributed generators' integration into the main grid. The simulations covered are: 1) AMI communication networks, 2) feasibility of solar PV systems, 3) solar PV to main grid PCC differential protection, and 4) Metropolitan Area Network for control, monitoring and protection of the microgrids. The two case studies focus on real-life implementation of AMI and solar PV systems.

The flow of the chapters is such that the title of the research and plan of development of the report are introduced in the first chapter. The second chapter reviews pertinent literature. This is followed by a description of the approach used to achieve the goals of the thesis. After describing the methodology used in the investigations, design of the software models used in the research is presented in Chapter 4. The results from experimental investigations are presented and analysed in Chapter 5. This chapter is followed by case studies presenting real-life implementations of both solar PV systems and AIM systems. Chapter 6 discusses and analysis AMI project planning case study. A case study on design, planning and implementation of a solar PV project is discussed in Chapter 7. Chapter 8 concludes the thesis and gives recommendations. Some concepts related to the theme of the thesis and yet lie outside the scope of the report are also presented in Chapter 8 as work that can be done in the future. This brings the number of chapters in this dissertation to eight.

The figure below summarises the funnel-like development process which the structure of this thesis inherits. The report starts with introduction of the three concepts which form the core of this thesis: DSM, AMI and solar PV systems. A review of literature on these concepts narrows the scope and leads to simulations and results on specific areas of the proposed DSM

programmes. These are further filtered to case studies on real-life implementation of these programmes.

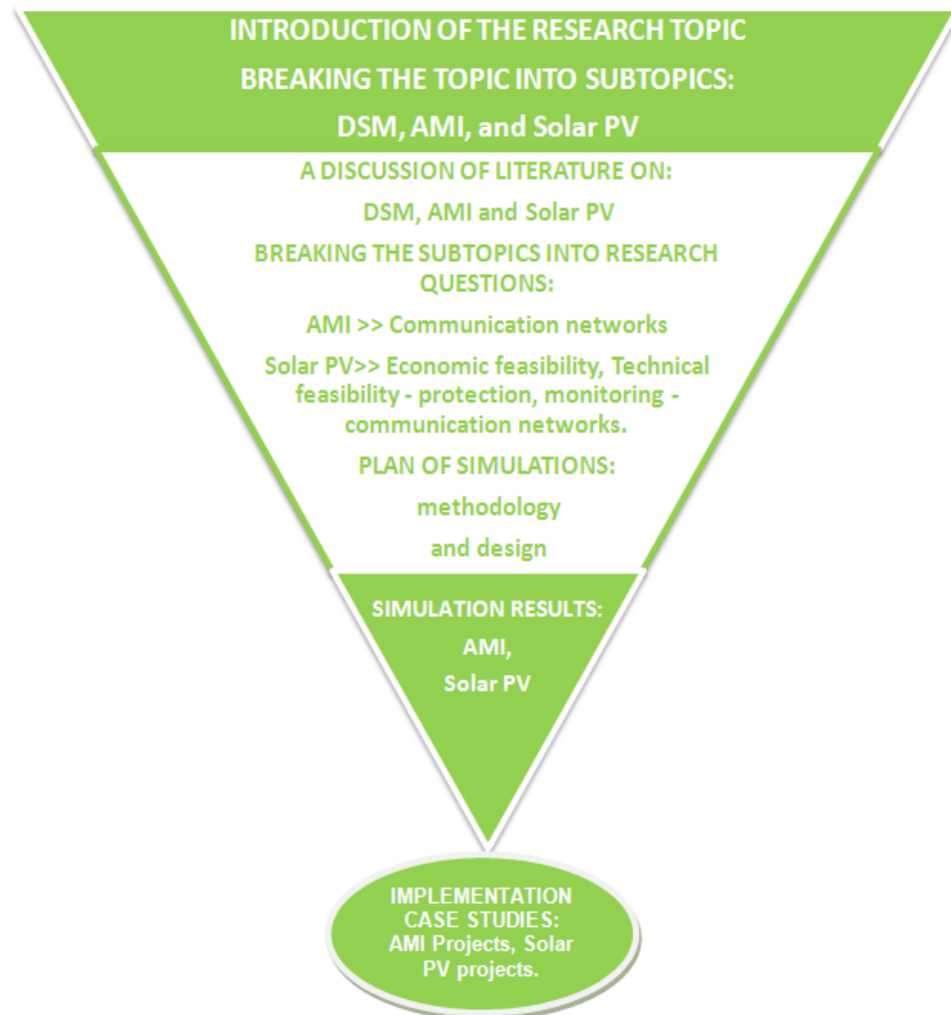


Figure 1-1. Thesis development process structure.

This section concludes with a detailed breakdown and flow of chapters below:

Chapter 1. “Introduction”

Introduction is the first chapter that establishes the work presented in this dissertation. It highlighted the background and motivation of the work. It also gave the scope of the report and objectives of the simulations performed for this thesis. It has laid a foundation for the other chapters of the thesis which are explained below.

Chapter 2. “Literature Review”

The *literature review* chapter introduces and sets the theoretical context related to the demand side management, advanced metering and solar PV systems. This chapter discusses existing approaches to DSM and energy management. It compares conventional power networks to future power networks (smart grids). Viability of integrating solar PV system to distribution networks as one approach to DSM is discussed. The chapter concludes by looking at the REMPLI which is an ongoing project aimed at building a DSM system for smart grids.

Chapter 3. “Methodology”

Methodology chapter presents a procedure followed to gather relevant facts, data and graphs which are the results of the study. The methods presented are for the following studies performed in this dissertation: 1) OPNET Simulation of wide area network for AMI. This simulation is done on OPNET communication network simulation platform. 2) HOMER simulation for feasibility studies of the proposed grid integrated solar PV system. 3) MATLAB differential protection scheme simulation applied to grid-connected solar PV studied. 4) OPNET Metropolitan Area Network (MAN) simulation for control and monitoring of the solar PV microgrid. 5) The fifth procedure presented is for gathering data for the two case studies: the AMI and the solar PV real-life projects. The different activities and simulations carried out were part of the unified effort towards achieving the goals of this thesis (that is, using AMI and solar PV as DSM programmes for households). The chapter describes the tools and techniques used; how data was collected and how it is analysed.

Chapter 4. “Design of the Simulations”

The *design* chapter gives the gist of simulations and practical work performed for this thesis report. This chapter describes how the simulations were planned and executed. Furthermore, the chapter explains the models that led to the simulations performed to obtain the results presented in chapter 5 introduced below.

Chapter 5. “Results and Discussions”

This chapter presents the results from the simulations. The four sets of results presented are from: 1) the wide area AMI network simulation using OPNET, 2) the viability study of domestic solar PV microgrids done on HOMER, 3) the MATLAB simulation of differential protection used at the point of common coupling of grid-connected solar PV microgrid and the main grid, and 4)

the OPNET simulation of a wireless MAN network proposed for monitoring, control and protection of the point of common coupling.

Chapter 6. “Case Study 1: AMI Project Implementation”

Chapter 6 is a special chapter that presents a real-life AMI project implementation. The chapter discusses AMI implementation from the project management point of view. It presents the resources necessary to bring the project to life.

Chapter 7. “Case Study 2: A Solar PV Project Implementation”

Chapter 7 presents a real-life solar PV systems project design and implementation. HOMER is used for system design. The chapter discusses this implementation from the design stage to project management activities necessary to bring the project to life using the real-life scenario.

Chapter 8. “Conclusions, Recommendations and Future Work”

In Chapter 8, conclusions drawn from the results and discussions are presented. These conclusions led to recommendations also presented in this chapter. The chapter also deliberates on future research work that can be spawned from this research. It makes recommendations for alternative methods that can be used to better achieve the objectives of this thesis.

2 Literature Review

This chapter reviews available literature that will help in building a foundation for the work presented in this thesis. The main objective of this thesis report is to discuss a study performed on demand side management. The work sets to investigate two power grid enhancement approaches to DSM. The first approach involves “smartening” the power network through addition of a layer of smart technologies called advanced metering infrastructure. The second technique proposed involves integration of PV DGs installed on customers’ homes into the power network. As a result, this chapter reviews literature on demand side management. The review will form a thread of discussions whose core centres on how a conventional power grid can be evolved and enhanced into an intelligent grid through integration of AMI and PV DGs with the aim of supporting DSM programmes.

The literature review commences with a description of the concept of demand side management in Section 2.1. This section clarifies the perspective from which the thesis treats this topic. Conventional power grid is reviewed thereafter. Conventional grid review is followed by sections describing future power grids (smart grids as they are known) and their applications. The concept of metering is introduced in Section 2.5. This sets the floor for three cornerstone topics affiliated with modern metering: tiered billing, AMI and wide area monitoring, protection and control (WAMPAC). Tiered billing and AMI are discussed in Sections 2.6 and 2.7 respectively. WAMPAC is discussed in subsection 2.10.4 as AMI technology that supports DGs. AMI is one of the characteristics of smart grids which is discussed in depth as it is core to DSM programmes. Tiered billing is a DSM incentive supported by AMI.

WAMPAC is one of the applications of AMI discussed in detail. WAMPAC becomes an important issue in this thesis because of the second proposal of grid enhancement – integration of domestic PV DGs. These DGs need solid protection, control and monitoring to operate successfully. Section 2.8 highlights the notion of distributed generation (DG) with focus placed on photovoltaic systems (PVs). This is followed by a review on viability of PV microgrids in Section 2.9. Moreover, a discussion of protection and control of the proposed grid integrated PV microgrids follows in Section 2.10. The chapter is concluded by reviewing a REMPLI system

which is an existing system that performs most of the functions performed by the AMI grid enhancement proposed in this thesis.

2.1 Demand Side Management

It was highlighted in the introduction in Chapter 1 that the core discussion of this thesis is demand side management (DSM) through integration of solar PV and AMI into the conventional grid.

2.1.1 Background to DSM

DSM refers to a series of initiatives designed to manage efficient use of electrical energy. It was highlighted that DSM consists of network based and non-network based initiatives. These initiatives are carried out to avoid power failures due to momentarily overloaded power network due to sharp peak demand. They also curb hazardous emissions to the environment via supporting efficient use of energy. Furthermore, the DSM initiatives defer investment into new substations, transmission lines, and distribution lines infrastructure. Peak demands are very sporadic. However, whenever they occur, they put substantial pressure on the network especially under emergency conditions [6]. For instance, in South Africa we experience grid-straining peak demands seasonally during cold winters. In other countries, hot summer seasons put the power grid under pressure due to need for air conditioners for cooling. The ultimate aim of DSM is to improve power grid reliability and integrity by controlling peak energy demand [7]. Therefore the two main drivers for DSM programmes are reducing greenhouse gas emissions and delaying need for capital investment into grid expansion.

There are several programmes which utilities instigate under the auspices of DSM. The programmes are differentiated according to the target load types and sizes. Load types can be classified into residential, commercial and industrial load. Certain DSM programmes are more effective for a certain type of load than they are for other types. Large energy consumers such as industries are more attractive options for implementation of DSM programmes. These programmes aim to achieve energy efficiency, peak pruning, peak shifting, and rebates/price incentives.

There are two mechanisms used for DSM in a smart grid: Direct Load Control (DLC) and Indirect Load Control. With DLC, the utility is able to disconnect some of consumer loads remotely to avoid widespread blackout due to strained network. These interventions lower operating and maintenance costs. On the other hand, with Indirect Load Control, consumers are

given information which motivates them to control their loads themselves by considering incentives such as current energy prices [8]. The subsection below describes DSM programmes pursued in South Africa.

2.1.2 DSM Initiatives in South Africa

There are several DSM initiatives that are being implemented in South Africa. They are classified into three types: 1) Behavioural change programmes; making households energy aware and advising them to change their energy consumption habits, 2) Low cost programmes; the most successful of these programmes is the efficient lighting where tungsten filament bulbs from households across the country were replaced with energy efficient LED or compact fluorescent lamps (CFLs), 3) Medium to High cost solutions; solar water heaters and heat pumps at households, insulation of buildings, etc [9]. Most of the programmes are in their infant phases. A good number of them target energy efficiency at households. The overall goal of these programmes is to reduce energy demand by 12% by 2015 [10].

Clearly, none of the envisaged DSM programmes are about smartening of the power grid through AMI and DGs such as solar PV. Hence this dissertation presents this approach within the South Africa context. It discusses how a conventional power network can be transformed to a smart grid. The section below reviews conventional power systems.

2.2 Conventional Power Grid

Conventional power networks were known to be hierarchical. Electrical energy was generated from massive power generation stations located close to sources of energy and then transmitted through high voltage transmission lines to areas where it can be supplied to customers. The grid was energised from different types of fuels. These were mainly fossil fuels: coal, natural gas and petroleum. The high-voltage transmission networks carried voltages ranging from 115 kV to 800 kV [11].

The transmission lines are connected to distribution lines which deliver the electricity to consumer homes and businesses. Figure 2-1 below illustrates the hierarchy of the structure of conventional power networks. The top of the structure is the central power generation station. Utility power generators voltage output ranges from hundreds of volts to 30,000 volts [12]. Power is generated at 60 Hz (US system) and 50 Hz (UK system, used in South Africa). The top-down hierarchy consists of four layers: generation, transmission, distribution and consumption. There is a transformer between each of these layers.

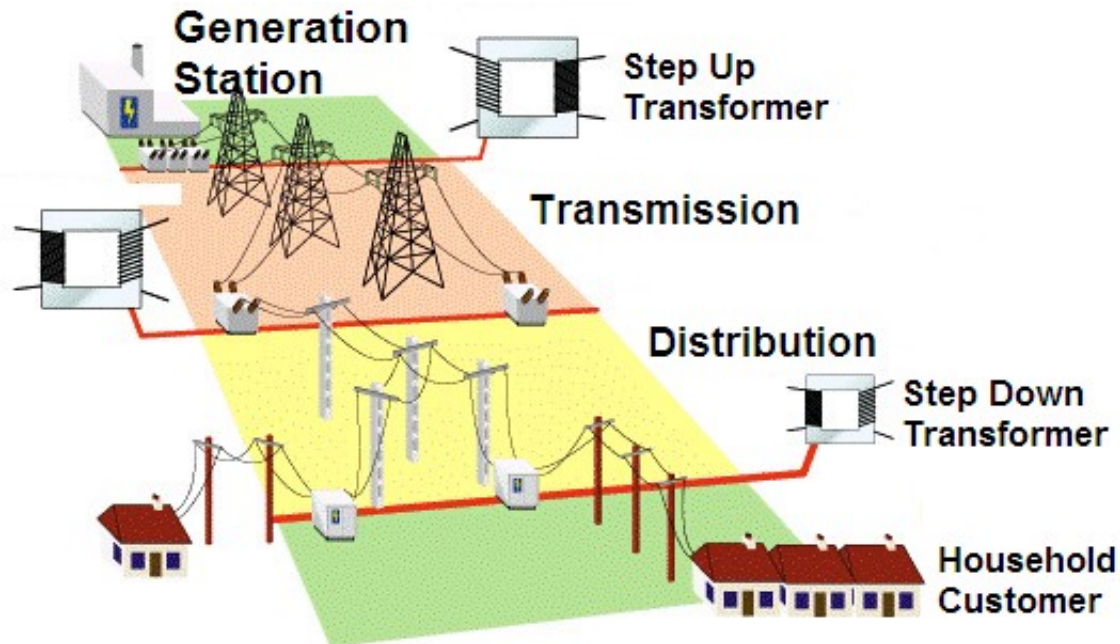


Figure 2-1. Hierarchical structure of a conventional power grid – picture adapted from [13].

The generation station and the transmission lines are connected by step-up transformers which convert low generation voltage to higher voltages (mentioned above) suitable for transmission through long distances. The transmission network and the distribution network are interconnected by step-down transformers. High distribution voltages are about 132 kV, medium distribution voltage is 33 kV while low distribution voltage is 11 kV [14]. These voltages are further stepped down to supply voltages to suite different customer needs. Other than minimal control and protection components, the grid was plain with no ad hoc intelligence features available in smart grids as described below.

2.3 Future Power Grid: Smart Grids

There is considerable amount of research channelled towards smart grids. Main drivers behind the research in smart grids hence the supporting communication networks are pressure from global environmental regulations that foster need to enhance power efficiency.

In the United States, the Department of Energy defines smart grid as a system that incentivises customer participation in the energy markets. It is a system of technologies that enable utilities to improve performance by creating a two-way communication between a utility and its customers in real-time [15]. The future grid is achieved by incorporating advanced information technology systems, communication networks, sensors and smart meters into the conventional power grid. The resulting system is advanced metering infrastructure.

AMI is a subset of smart grid programmes which provides a two-way communication between the utility and its customers (industries, households and commercial). AMI is thus the main component of a smart grid that interlinks metering data management systems (MDMS) with smart meters in consumers' households or businesses. This interlinking is achieved through communication networks as discussed further in this dissertation. Communication networks are thus the enabling core of smart grids and energy management systems. They provide a two-way integrated communication between the utility management and sensing devices, grid self-healing capability devices and demand side management (DSM) systems [16].

Figure 2-2 is an illustration of the futuristic power grid described above. It consists of heterogeneous sources of energy. In the figure these sources are the plug-in hybrid electric vehicle (PHEV), wind turbines, domestic solar photovoltaic systems and energy storage devices. The whole system is monitored by a dynamic systems control/data management system. As depicted in the figure, the future power system is integrated. Distributed renewable sources are connected to the main grid and are controlled by a smart system.

Achieving this smart grid system will capacitate future power grids to meet the applications discussed in Section 2.4 below.

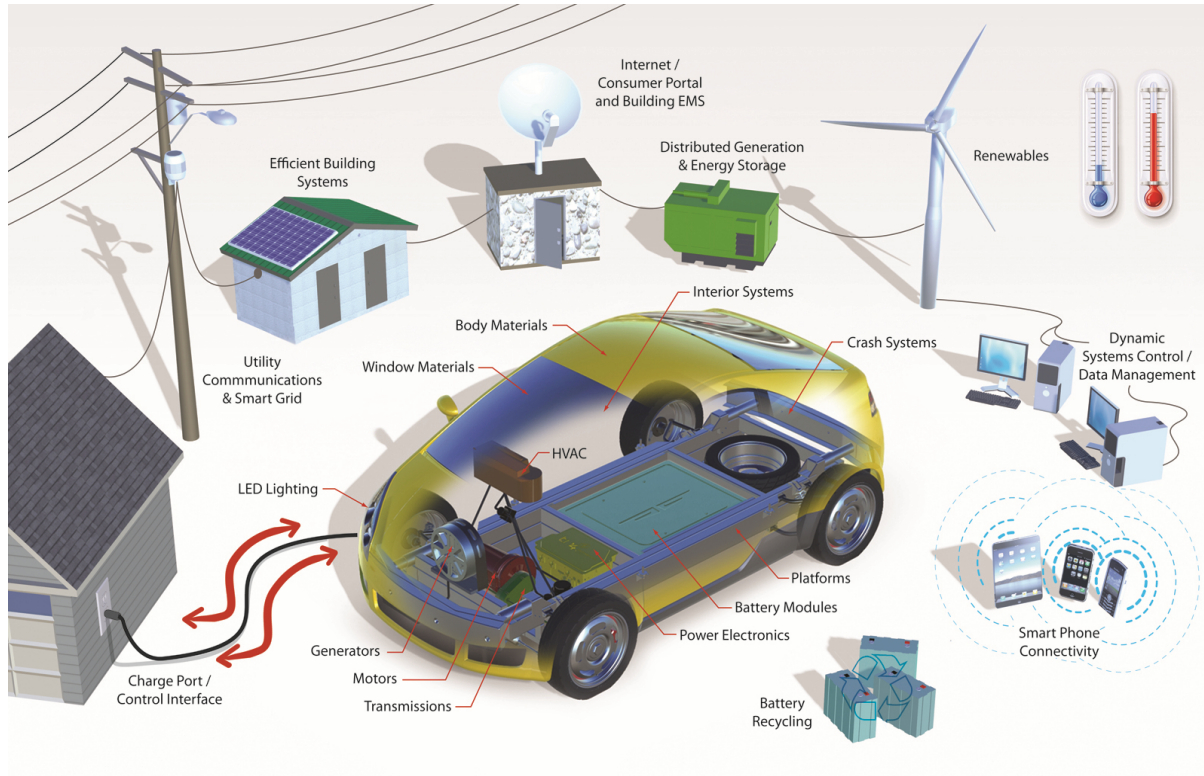


Figure 2-2. Structure of a future power grid with active distribution network [17].

Table 2-A is a comparison of smart grids and conventional grids. It highlights the main differences in order to indicate how the power network has evolved.

Table 2-A. Comparison of conventional grid to smart power grid.

Conventional Grid	Smart Grid
Centralised/Hierarchical	<i>Decentralised with DGs</i>
Directional power flow	<i>Bi-directional from DGs</i>
Directional utility to customer communication	<i>Bi-directional communication</i>
Power generated mainly from fossil fuels	<i>Power generated from distributed renewable sources</i>
No energy management	<i>Energy efficiency management</i>
Passive customer participation	<i>Active customer participation</i>

2.4 Smart Grid Applications

In designing an integrated network for smart grid energy management systems, requirements of smart grid applications need to be understood. This thesis, discusses the following applications

which portray heterogeneous network quality of service (QoS) requirements of smart grid applications:

- Advanced metering infrastructure (AMI),
- Automated demand response,
- Tele-protection,
- Distribution automation and
- Microgrid management [18].

AMI is a system of technologies that support smart metering. The sole purpose of smart meters is to measure customers' energy consumption and send the data periodically to the meter data management system (MDMS) located at utility's back-office. Smart metering initiatives are commonly the first phase in the grid evolution which many utilities seem to be focusing on [19]. This is because smart meters are the prime link between a utility and its customers. Thus deploying the metering application first allows for automated demand response (ADR). ADR refers to any measure taken by the customer in response to utility directives or incentives offered to incentivise reduction of consumption during peak demand periods. Moreover, distribution automation and microgrid management refers to applications of a network of intelligent electronic devices (IEDs) used to monitor the state of the power grid. A new application of IEDs is the use of phase measurements units (PMUs) to monitor and synchronise voltage and current phases. This area combined with tele-protection, has been extended to wide area monitoring, protection and control (WAMPAC).

These applications are meant to support the smart grid to achieve a certain set of functions. The functions can be summarised in terms of three basic business applications. The three business perspectives are energy delivery optimisation, demand optimisation, and asset optimisation. Delivery optimisation focuses on efficiency and reliability of the power network. Demand optimisation is about empowering utility customers by giving them more control over the energy they consume. Furthermore, utilities want to draw optimum benefit from their asset investment. Hence need for asset optimisation implemented within smart grid. Thus a revolutionary migration into smart grid thwarts the purpose of smart grid. Therefore a solution is to find a way to unify the legacy communication networks infrastructure as presented in Section 2.7.4 below. Before going further, Section 2.5 below thrashes out the all important concept of smart grids – metering.

2.5 Metering

Metering is the process of measuring the amount of power consumed by an electrical load. Electricity metering has been in practice for a long time. There are three types of Electricity meters. These are single rate meters, multi-rate meters and pre-payment meters. Meters are also classified according to their accuracy. There are four of such classes: the class 2, class 1, class 0.5., and class 0.2 [20]. Other ways of classifying energy meters is by frequency of meter reading. In this case, there are half-hourly (HH), no-half hourly monthly (NHHm), and non-half hourly quarterly (NHHq) class of meters [21].

Energy meters evolved from mechanical meters to electromechanical types of meters. These have also been faced out by electronic meters. Electronic meters brought certain advantages to the metering sphere. These advantages can be summarised as: improved accuracy, ability to measure energy consumption by low power factor equipment, ease of calibration, anti-tempering protection, advanced billing capabilities (time of use, and pre-paid), and automatic meter reading [22]. Evolution of energy meters is demonstrated by Figure 2-3 below. Motivated by the relevance of metering to the work discussed in this thesis as explained above, detailed aspects to do with metering are pursued further in the subsections below.

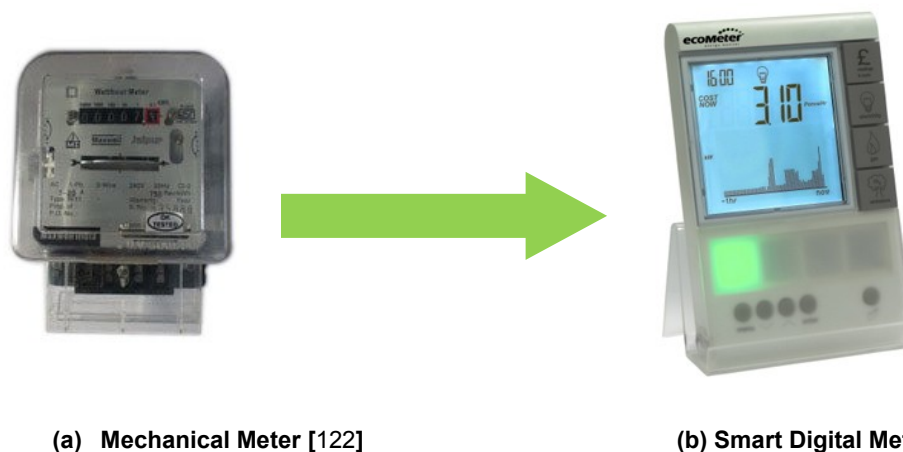


Figure 2-3. Evolution of energy meters.

2.5.1 Metering techniques

Energy consumption metering involves two processes: measuring voltage and measuring current. Power meters therefore consist of voltage sensors and current sensors. Power consumed is measured in watts and is calculated as a product of the sensed current and voltage [22] [23]. Energy used then becomes a time integral of the product of voltage and current [24]. There are two types of electrical loads: linear loads and non-linear loads. In linear

loads, current is directly proportional to voltage at any time whereas current and voltage are not proportional in non-linear loads. Linear loads have unity power factor while non-linear loads have lower power factor.

Mechanical meters were able to measure both voltage and current for linear loads sufficiently. However, many loads today such as washing machines, refrigerators, driers etc are non-linear. Determining energy consumption of these loads requires measuring power factor. This leads to a complicated measurement not easily achievable by mechanical or electromechanical meters. Electronic meters have made it possible to measure both linear and non-linear components of the power consumed. This has therefore improved customer accountability – utilities are able to bill customers for reactive and active power.

2.5.2 Energy Metering and Management Standards

There are several standards bodies that have defined guidelines that energy meters should meet. A few of the renowned bodies are International Electro-technical Commission (IEC), Institute of Electrical and Electronic Engineers (IEEE), and American National Standards Institute (ANSI). ANSI and IEEE have a working relationship through standards development organisation (SDO). IEEE is a member of the ANSI accredited SDO. Thus, common standards used are the IEC 620 and ANSI 12 series of standards.

The standards are being evolved as new technologies arrive. These standards focus on safety of the utility customers and accuracy of the meters. They provide guidelines for different types of meters in terms of methods of metering, display/housing, mounting, voltage and frequency, current classes and test amperes and other general requirements [25]. Some standardise approach to certain conditions in the power system. An example of such is the IEEE 1459 standard which provides definitions for the measurement of electric power quantities under sinusoidal, non-sinusoidal, balanced, or unbalanced conditions [26]. Table 2-B below summarises a set some of IEC standards for energy meters. This is not an extensive list as there are many more parts of the standards not listed. The table shows what the standard was called (old standard) and what it is now. It also shows the type of measurement instrument which the standard covers.

Table 2-B. Summary of watt-hour meter IEC standards [27].

Old Standards	New Standards	Type of Measurement Instrument
IEC 60521	IEC 62052-11 and 62053-11	Mechanical (induction) watt-hour meter
IEC 60687	IEC 62052-11 and 62053-22	Electronic (static) watt-hour meter, class 0.2 s and 0.5 s
IEC 61036	IEC 62052-11 and 62053-21	Electronic (static) watt-hour meter
IEC 61268	IEC 62052-11 and 62053-23	Var-hour meter

Two concepts in metering have been discussed thus far: metering techniques and standards that guide development of energy meters. One of the core aspects of DSM is energy measurement and management. Energy meters discussed above are tools used to achieve this measurement. Section 2.5.3 below explains the concept of energy measurement and management.

2.5.3 Energy Measurement and Management (Smart Metering)

Energy meters are very important DSM enabling devices as they provide information about energy usage. When information is available management of energy becomes possible. This section deals with concepts of energy management. There are several reasons necessitating energy measurement. Principles and motives of energy usage measurement are:

- Measuring energy consumption of utility clients to determine
 - How much energy a household/business uses.
 - When exactly is more energy being used? This is determined in terms of the days of week and time of day.
 - Power factor consideration – holding customers accountable by billing both active and reactive power drawn from the utility.

Measurement serves a tool that informs energy management interventions. The aim of these interventions can be explained as thus:

- Identifying and correcting serious energy inefficiencies.
- Determining how to best reduce consumption and

- Measuring the impact/effectiveness of energy management interventions. That is, measuring and validating energy saving programmes.

There is currently no standard guideline that utilities and energy consumers can follow in order to achieve energy efficiency. Utilities have no standard means of measuring and verifying the impact that energy efficiency programmes are making. It is in response to this gap that Efficiency Valuation Organisation (EVO) was formed. EVO's mandate is measurement and validation (M&V) of energy saving intervention programmes. M&V refers to accurately identifying and verifying the direct effect/impact of energy efficiency programmes. This is done by identifying all variables affecting energy consumption before energy efficiency programmes (EEPs) are effected and then monitoring usage of a household. The EEP is then implemented and measurements on usage are monitored. Removing the irrelevant variables identified before instigation of EEPs will then lead to a realistic evaluation of the EEPs. EVO is a non-profit consortium consisting of practicing energy engineers. It is currently the biggest body focusing on developing M&V guidelines for EEPs [28] [29]. The USA Department of Energy created a directive for M&V plans prompted by the State's energy facilities. The 17 year old guideline is called the International Performance and Measurement Verification Protocol (IPMVP) [30].

IPMVP documents good practise in M&V particularly for purposes of energy savings reporting. It stresses the importance of separating changes in conditions of energy usage and savings brought about by the EEPs. The three volume IPMVP documents cover both energy and water savings. The volumes are as thus: Volume I – Concepts and options for determining energy and water savings, Volume II – Indoor environmental quality issues, and Volume III – Applications. Volume I explains and proposes good practise for documenting impact of energy and water efficiency projects. Volume II presents guidelines on energy efficiency project designs that take into account the effects it has on indoor environmental quality issues. Volume III defines guidelines for specific application manuals of ideas in Volume I such as new buildings construction [31].

Apart from measuring efficiency, metering is also used for monitoring and control of the power systems. This is achieved through application of wide area measurement systems (WAMS). The section below further discusses the ideas related to use of WAMS to achieve wide area monitoring, protection and control (WAMPAC).

2.5.4 Power Grid Monitoring and Control (WAMPAC)

WAMPAC is of interest in this thesis as it is one of the applications of AMI that ensure availability of the power system and its ability to meet energy demands of customers. In the previous sub-sections, metering and measurement discussed looked at monitoring consumption through energy meters to ensure that energy demands are met by existing supply. The concept pursued in this sub-section ensures that the energy needs are consistently met by monitoring the quality of power flowing in the power systems. Instead of measuring energy consumption by consumers, WAMS are devices that measure and monitor certain properties of power in the grid. WAMS in common use are phasor measurement units (PMUs) or synchrophasors as they are sometimes called. Synchrophasors are devices which extend the functions of RTUs that were used in conventional power networks. Their functions are to measure voltage and current phase vectors [18]. PMUs form part of a list of new devices and components added to conventional power grids to “smarten” them. This set of devices is called intelligent electronic devices (IEDs). They are enabling technologies of the tele-protection application of smart power grids mentioned in Section 2.4 above.

At this stage, the report focuses on two metering concepts that support DSM: tiered billing and automatic metering achieved through AMI. Advanced billing capabilities of smart meters are the core of DSM programmes’ incentives for households. Automatic metering is also an important function of advanced metering infrastructure which is one of the bases of this thesis. Thus, these subjects are presented in Sections 2.6 and 2.7 below starting with the concept of tiered billing.

2.6 Tiered Billing

Tiered billing refers to a form of energy pricing where prices fluctuate and discriminate on the basis of some variable. The basic goal of these pricing strategies is to incentivize consumers to manage their use of energy sparingly. The common variables usually used to determine energy prices are time-of-use, size of income of the consumer and location of the consumer. The other model used by the City of Cape Town discriminates energy prices depending on the consumer’s monthly total consumption.

Time-of-use billing structure usually has three tiers: off-peak, standard, and peak. In this case, utilities define energy prices differently for times they consider off-peak, standard and peak hours and consumers experience different charges depending on the time of the day they use energy. The aim of this structure is to motivate consumers to use energy during off-peak hours

and to switch-off appliances during peak hours. Figure 2-4 illustrates Eskom's defined time-of-use periods. The red colour shades peak hours, the yellow colour shades standard while the green colour shades off-peak charge periods. This billing structure uses hour of day and day of the week as discriminators of energy cost.

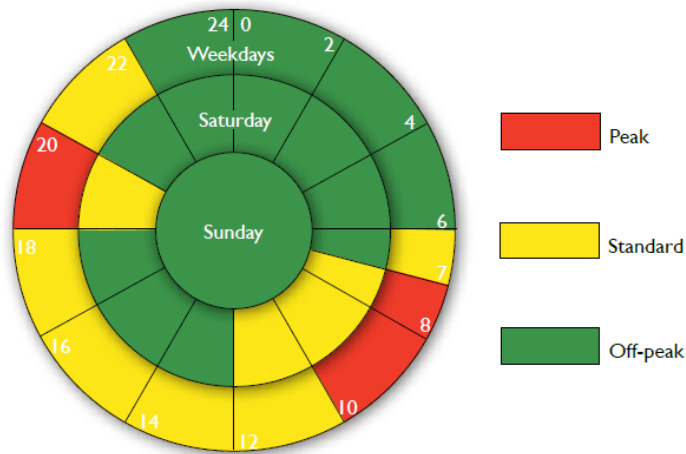


Figure 2-4. Time-of-use periods defined by Eskom [32].

Table 2-C below shows energy prices in ZAR/kWh for the three different time of use periods mentioned above.

Table 2-C. Time-of-use energy charges.

Energy charge (R/kWh)		
Peak	Standard	Off Peak
1.89	0.49	0.26

Table 2-D below illustrates a tiered billing structure that combines time-of-use and consumer location. In this case rural areas incur higher charges as they are sparsely populated, hence expensive to connect to the grid.

Table 2-D. Time of use combined with consumer location [32].

	Energy charge (R/kWh)		
	Peak	Standard	Off Peak
Urban Residential	1.9717	0.57	0.26
Rural Residential	2.97	0.76	0.4009

The other pricing model mentioned above is the one that discriminate users based on their total monthly consumption. Residential billing in Cape Town is divided into lifeline and domestic sections. Each section has blocks defining the range of consumption and charge per kWh for that range. Table 2-E below illustrates pricing strategy used by the City of Cape Town metro.

Table 2-E. City of Cape Town's billing structure for residential consumers [33].

Billing Block	Consumption Range	Charge (c/kWh)
LIFELINE (<450 kWh)		
Block 1	0 -150kWh	61.60
Block 2	150.1 – 350kWh	81.04
Block 3	350.1 – 600kWh	107.43
Block 4	> 600kWh	118.06
DOMESTIC (>450 kWh)		
Block 1	0 – 600kWh	107.43
Block 2	> 600kWh	118.06

It is important to note that it is not possible to support the tiered billing structures described above in conventional power grids. The tiered billing functions are only supported in digital meters which implement the discriminatory smartness. Tiered billing is effective if consumers are well informed about their energy usage patterns so that they can take actions to manage these patterns. It is this need for information that prompts our discussion of AMI as an important tool for DSM. Section 2.7 below discusses AMI as a tool that can support both consumers and utilities to achieve energy savings by managing consumption.

2.7 AMI

Modern utilities are faced with increasing energy demands. South African power utility, Eskom faces greater challenges due to growing economic activities in the country [34]. While electricity

demand is increasing, reserve margins are continuously diminishing. In some cases, demand surpasses installed generation capacity [35]. The utility needs to implement energy management programmes on the grid to ensure efficient use of electricity by customers. The future grid is achieved by incorporating advanced IT, communication networks, sensors and smart meters into the conventional power grid. The resulting system is advanced metering infrastructure (AMI). AMI is a subset of smart grid programmes whose focus is to provide a two-way communication between the utility and its customers. AMI is thus the main component of a smart grid that interlinks metering data management systems (MDMS) with smart meters in consumers' households or businesses. This interlinking is achieved through communication networks as discussed further in this thesis. Communication networks are thus the backbone of smart grids. They provide a two-way integrated communication between the utility management and sensing devices, grid self-healing capability devices and demand side management (DSM) systems [16]. Smart grid and AIM concepts are broad. They include, but are not limited to, the devices mentioned above. This section focuses on AMI.

2.7.1 AMI penetration in South Africa

AMI is a relatively new field in South Africa. AMI is a successor of automated meter reading (AMR). AMR focuses on automatic collection of consumption data and does not include intelligence such as DSM which is driven by these data [36]. The first standard to govern the envisaged AMI implementation was released in 2008 in National Regulatory Services (NRS) 049 document. NRS specifications are documented by NRS Project Management Agency in collaboration with South African Bureau of Standards (SABS) for Electricity Suppliers Liaison Committee [37]. USA conceived and developed AMI since 2003. This led to drafting of their famous 'Grid 2030' visionary document [38]. It is currently the global leader accounting for 56% of the world's AMI market. China constitutes 23.9% of the market [39]. Following in the footsteps of these leaders, developing and implementing the NRS 049 standard in power distribution networks is the first step for South Africa's realisation of AMI. The standard proposes two architectures for the AMI systems for use in South African markets [40].

It appears that most AMI architectures are proprietary which hinders flexible interworking of components from different vendors. Without standard AMI design principles, utilities face inflexible choice of system components. Furthermore, this inflexibility makes it harder and more costly to support this type of equipment design approach. Standardisation and collaboration is important to ensure interworking of equipment from heterogeneous manufacturers. Applying standardised principles in design of interfacing and communication technologies used to

interconnect the AMI components promotes interworking of systems [41]. To start with, subsection 2.7.2 below gives a detailed description of AMI functions.

2.7.2 AMI Functions

According to Henri Groenewald (Chief Engineer, Measurements at Eskom), the proposed AMI system should provide a two-way communication between the customer and the utility [40]. The system should be self-healing; the meter should know when there is a power cut. The utilities will be able to fix network problems automatically without customer intervention [42]. The system should provide a load switch which will enable utilities to connect and disconnect appliances in customers' households (load limiting capability). Display of real-time energy consumption and provision of a means for customers to manage their load is another requirement [43].

Having looked at the functional requirements of the components, Section 2.7.3 below delves into reviewing components of the AMI system.

2.7.3 AMI Components

Figure 2-5 below shows one of the common architectures of the AMI system. The system consists of the Head office workstations, AMI Master Station, the Communication network, the AMI Concentrator, and AMI Meters distributed in households and businesses. The AMI meter has functional support components. These are the Customer interface unit (CIU), Appliance controller devices (ACDs) and an optional Water meter [44] [40] [45]. The second model is similar; but it excludes the concentrator. In this model, AMI Meters connect directly to the master station via a communications network. A brief overview of each module of the AMI system is described in the subsections that follow below. This report will discuss the components at an abstract level and then deepen further into implementation details of communication networks for AMI.

1. AMI master station

The Master station houses all remote control features of the network. From the master station, the control personnel will be able to connect and disconnect loads, manage and monitor load, detect tamper on the equipment, investigate faults, and monitor quality of supply. The station will also incorporate time-of-use (ToU) billing system and electricity vending system. It functions as a data warehouse for the utility. Configuration (firmware updates) of the meters will be performed remotely via the master station.

2. AMI smart meter

The meter is connected to the master station through a concentrator (shown in Figure 2-5 below) or directly to the master station. The main function of the meter is to register power consumption information of the customer. It also stores ToU billing information which can either be retrieved by the master station or by the CIU. Moreover, it keeps an account of tampering events identified. It records power supply outages, and under/over voltage conditions. It executes disconnect/connect commands send by the master station during events such as load limiting and control.

3. Customer Interface Unit (CIU)

This unit is connected to the meter to display information to the customer. It enables the customer to see power consumption data and billing information. It displays alarms and load control history.

4. Appliance Controller Device (ACD)

These devices switch controllable appliances on and off according to the time-of-use pattern which will depend on the ToU billing system. Common controllable devices are appliances that are ZigBee Standard compliant [46]. That is, they are controlled by 'connect and disconnect' instructions send by the master station through the AMI meter via a ZigBee Home Area Network (HAN).

The definition of AMI above stressed that AMI is achieved not only by integration of sensors and smart meters but also communication networks and information technologies. Some authors describe AMI as provision of a two-way communication between customers and utilities [47]. Thus communication networks are important to AMI. Hence the subsection below will receive greater attention in this thesis.

5. Communication network

Nogil Myoung et al (2010) and many other authors say that information and communication technologies are the core of smart grids [48] [49]. The communications network is the spine medium of transmitting information between meters and the master station. Between the AMI meter and the CIU and AMI meter and the ACD, the model proposed in Figure 2-5 proposes power-line carrier (PLC) and radio frequency communication networks [40]. The four areas of the communication network to be studied are local area network (LAN) at utility data centre, wide area network (WAN) for backhaul communication, metropolitan area network (MAN) of

smart meters at commercial and residential areas and home area network (HAN) within customers' premises.

Standardisation of communication technologies plays a key role for interoperability of AMI subsystems from different equipment manufacturers. Before sinking into the discussion on implementation of these in AMI, it is important to highlight some of the leading bodies involved in drafting AMI standards. South African AMI standard was first released in NRS 049 in 2008.

USA has taken a leading role as one of the countries that have enacted smart grid guiding principles in its Energy Independence and Security Act (EISA) 2007 [50]. USA power utilities formed a consortium called Utility Standards Board (USB) in 2007. This is one of the advances that accelerate standardisation of smart grid and AMI equipment in USA. National Institute of Standards and Technology (NIST) of USA formed the Cyber Security Coordination Task Group (CSCTG) through its Smart Grid Interoperability Panel (SGIP). Furthermore, another set of standards in the USA have been developed by American National Standards Institute (ANSI). ANSI has defined application layer standards that describe messaging services for communication of AMI devices. ANSI, IEEE and Measurement Canada (MC) collaborated to develop the standard known as Utility Industry End Device Data Tables [51]. China and USA private sectors have teamed-up to form a USA-China Energy Corporation Program (ECP) within which there is a Smart Grid Working Group [52].

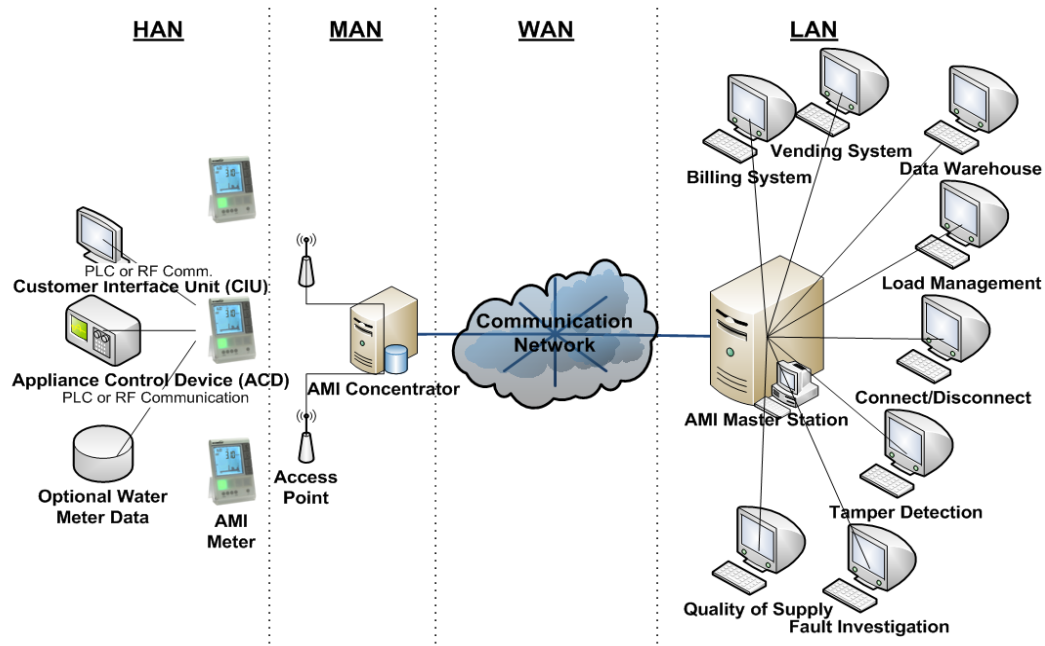


Figure 2-5. Architecture of AMI as proposed in NRS 049.

The European Committee for Electro-technical Standardization (CENLEC) through European Telecommunication Standards Institute (ETSI) is another smart grid and AMI standards developing body based in Europe. CENLEC has instituted a Smart Meter Coordination Group (SM-CG). In Netherlands, smart meter standard specifications have been released in Dutch Smart Meter Requirements (DSMR) report.

Furthermore, there are other international standards developed by International Electro-technical Commission (IEC). IEC substation automation standards are old standards on which new AMI standards can be built. A further discussion on AMI connectivity is presented in subsection 2.7.4 below.

2.7.4 AMI Connectivity: The South African Context

Communication networks and information technology form an imperative component of smart grids [49]. The USA's Department of Energy defines smart grid as a system that promulgates customer participation in the energy markets [15]. A smart grid cannot be defined without mentioning need for high-speed, reliable, and secure two-way communication network [53]. This visionary definition is achieved through many applications that were outlined in Section 2.4 above.

Many telecommunications researchers have dealt with the topic of communication networks in smart grids. In [48], the authors compared communication requirements of distribution automation system (DAS) and advanced metering infrastructure (AMI). The paper has determined that DAS applications have more stringent communication requirements such as QoS and latency. A field area network (FAN) based on carrier-class Ethernet (CE) is proposed in this paper. Four fibre cores ring topology network is used. To cater for the stringent requirements, the authors propose use of high availability seamless redundancy protocol (HSR) for DAS and AMI. HSR is a very robust protocol designed with distribution automation (DA) and control in mind. However, cost of fibre optics, particularly at distribution level has not been considered in this paper. The approach does not consider reuse of and interoperability with legacy networks.

In [51], technical requirements for application layer standards for IP-based AMI network are discussed. The authors realise the need for IP network that supports a wide range of applications hence interoperability. In general, much of the research work done look at specific solutions for each of the seven layers of the OSI model. Most of this work looked at higher level services without considering detailed challenges of implementing the proposed technologies

[18]. The work discussed in [48] concentrated on physical media while [51] compared two application layer protocols: C12.22 and session initiation protocol (SIP) running over an IP network.

The discussion of standardisation bodies above indicates the importance of standardising AMI communication network technologies. AMI communication network should conform to the existing trends of evolution in communication networks design. The evolution trend in communication networks is moving towards convergence. Therefore standardisation of network services and interfaces. There are several interfaces that need to be standardised within AMI systems. This thesis investigates communication networks for these interfaces in four areas. This is the approach used by Coalton Bennett et al (2008) [54].

There is a vast range of networking technologies that may be considered for smart grid applications for each of the different areas of the network. Figure 2-6 below illustrates some of the proposed communication networks that can support connectivity of AMI. Options shown in the figure are power line carrier (PLC), M-Bus, radio frequency (RF) networks, IP and mobile broadband networks such as General Packet Radio Service (GPRS). These networking technologies are more suitable for certain parts of the four areas of the AMI communication network. Geographic area covered by the network is usually used as the main determining factor of suitability of the network. The areas to be considered below are the LAN, WAN, MAN, and HAN. The WAN of the AMR projects being implemented in South Africa uses GPRS. A typical GPRS architecture is discussed in [55]. The experiments and simulations in this thesis will pursue the WAN to show how the South African energy management market can approach backhaul connectivity.

In this subsection, work done on standardisation of communication technologies of metering infrastructure is reviewed first. It is followed by a presentation of technologies for each of the four aforementioned AMI network areas. A comparative study that reviewed communication standards used in existing proprietary AMI technologies is looked at in subsection 2.7.5 below.

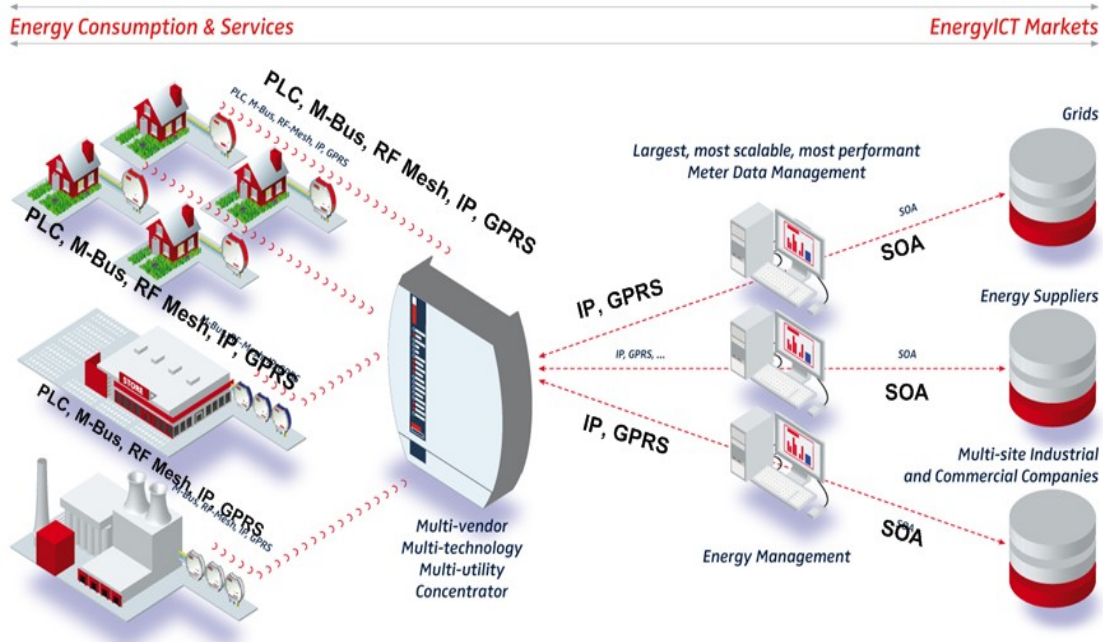


Figure 2-6. Smart grid communication networks for energy management system.

The four areas of the network have been portrayed and demarcated by dotted lines in Figure 2-5 above. The first area is the home area network (HAN). The other areas are local area network (LAN) within the utility's head office, wide area network (WAN) spanning long distances connecting head office network with a network of smart meters. The network of AMI meters or intelligent electronic devices (IEDs) forms the fourth area which is metropolitan area network (MAN). The proposed networks are assumed to be IP-based. IP-based networks are preferred for broader interoperability and inherent legacy security associated with them [51].

A. HAN

A HAN is a network of smart energy devices and home automation appliances that make a smart and energy efficient home. This network consists of the following end-devices: smart meters, CIU, ACD, and controllable appliances (programmable thermostats). Radio frequency networks (IEEE 802.15.4 – ZigBee, IEEE 802.11 – Wi-Fi, IEEE 802.15.1 – Bluetooth, and IEEE 802.15.3a – Ultra wideband) and PLC have been suggested in Figure 2-5.

Wi-Fi is suitable for large area networks that demand higher data rates. Thus it is recommended for MAN as discussed in B below. The primary disadvantage of using Wi-Fi in HANs is that its transmission power is higher since it covers larger areas, making it inappropriate for HAN devices. On the other hand, Bluetooth is appropriate in HANs because it supports low power

and low data rates wireless communication applications. It is a short range peer-to-peer network. It uses an idea of small size networks called “piconets”. Each *piconet* consists of a maximum of eight devices. Of the eight devices, one of them has to be a master. The master device synchronises connection and communication between the other devices. Its proliferation in smart grid HANs is limited by the use of master-slave architecture as this aided connection and synchronisation increases communication latency. Ultra wideband (UWB) is another alternative radio frequency technology that can be used in HANs. It is also characterised by high data rates. Hence high power demands which renders it impractical for machine to machine communication (M2M) applications in HANs. Moreover, the task group that developed the protocol got dissolved and no further developments are being done on the protocol [56]. Nevertheless, as further discussed below, ZigBee compliant standards have been designed specifically for HAN of energy metering applications.

ZigBee smart energy protocols are the most adopted. ZigBee-compliant equipment is used in Smart Energy products [57]. The equipment is ZigBee-Certified. This means that it can interwork with other ZigBee-Certified components from other manufacturers [58] [59]. As the key requirements when designing communication media for sensor networks are long battery life, small footprint, low cost, and mesh networking for supporting numerous devices that interwork, ZigBee standard has been specifically designed to meet these requirements [60]. These therefore make it the most attractive solution. ZigBee operates in the 2.4 GHz free frequency band. It supports a smart energy profile (SEP).

The SEP which is under development, is an application layer platform that is expected to standardise communication between power utilities and smart energy devices. It is being developed by an alliance between the following independent alliances: ZigBee, HomePlug, HomeGrid and Wi-Fi. Its main objective is to foster utility customer participation in energy saving programmes [61]. The SEP 2.0 protocol specification defines device behaviour in function sets. The specified sets are energy metering, demand response and energy pricing.

Another new development in networking smart energy devices in HANs is 6LowPAN. 6LowPAN is IPv6 low power devices personal area network. Thus it is a network layer protocol designed for power constraint devices such as smart meters, building automation devices, phones etc. It is built over IEEE 802.15.4 wireless radio network. It has lower bandwidth compared to ZigBee and Bluetooth. The HANs described above link to the power utility network via MAN and WANs. Subsection B below reviews MAN connectivity.

B. MAN

This subsection discusses metropolitan area network (MAN) of the smart grid. The proposed solutions are based on wireless network technologies. Wireless networks are proposed because of relative ease of deployment for supporting smart grid applications. These network technologies are less prone to theft of equipment. They remove need for costly cabling which also attracts vandalism and theft problems.

The MAN solution considered here is Wi-Fi. The section looks at a proprietary implementation of Wi-Fi called Firetide® meshed wireless network. These are the networking technologies that can be considered for both AMI and monitoring, control and protection of microgrids/distributed generators. The discussion starts with general Wi-Fi concepts and then presents Firetide® mesh.

i. Wi-Fi

Wi-Fi is proposed as a data link layer protocol for MAN of smart meters in customers' homes or a set of IEDs in a microgrid protection and control network. It is an IEEE 802.11 protocol suit which transmits data over the air using radio frequencies. This protocol suit has been defined in many different variants. The early versions of the protocol are 802.11a and 802.11b. These versions were released in the late '90s. The known short comings of both of these early versions are security and interference proneness. The IEEE 802.11b uses the 2.4GHz free frequency spectrum. This spectrum is used in many applications such as microwave ovens, cordless phones and other home and medical applications. Therefore Wi-Fi 802.11b based on this spectrum is very interference prone.

There are newer developments which address the challenges facing the protocol suit as explained above. The new IEEE 802.11i is one such advancement which can be boosted with security measures implemented in the network layer to achieve acceptable security levels for SCADA applications as discussed further in this section. Wi-Fi security has been the main issue limiting its proliferation in security critical applications such as control of power systems. Data security in Wi-Fi networks can be enhanced to assure safety for SCADA systems.

As seen on Figure 2-5, the proposed AMI network uses Wi-Fi as a wireless MAN and the Internet for backhaul communication (WAN). Similarly, Figure 2-12 shows the suggested microgrid protection and control system which uses this architecture. The control client and server applications are based on manufacturing message specification (MMS). All the three

protocols have known security shortcomings. MMS was not designed with data security in consideration [62]. The current implementation of MMS has access control list objects defined. However, this implementation has all but two access control functionality identifiers set to OPTIONAL. The code snippet shown below demonstrates MMS security definition. Only *name* and *accessControl* have been defined. It is therefore very important that all the other functions are defined to enhance security at application layer. Any system based on MMS has to impose security measures at lower layers.

```
ACCESS-CONTROL-LIST ::= CLASS {
    &name Identifier,
    &accessControl Identifier,
    &readAccessCondition    [0] AccessCondition OPTIONAL,
    &storeAccessCondition   [1] AccessCondition OPTIONAL,
    &writeAccessCondition   [2] AccessCondition OPTIONAL,
    &loadAccessCondition    [3] AccessCondition OPTIONAL,
    &executeAccessCondition [4] AccessCondition OPTIONAL,
    &deleteAccessCondition  [5] AccessCondition OPTIONAL,
    &editAccessCondition    [6] AccessCondition OPTIONAL,
```

Figure 2-7. A code snippet showing access-control-list function definition for MMS [62].

On the other hand, early versions of Wi-Fi were made of very security blemished encryption technique called Wire Equivalent Privacy (WEP) [63]. The WEP used Rivest Cipher 4 (RC4 – Named after its designer Prof. Ronald Rivest [64]) encryption algorithm that had a 40 or 104 bits secret key. The key would be combined with an initialisation vector (IV) to encrypt a packet P and its checksum (Integrity Check Value -ICV). The receiving node (IED or smart meter) would then recover the packet using the following formula.

$$R_p = [P \parallel ICV(P)] + [RC4(K \parallel IV)]$$

Equation 2-1. A decryption formula for RC4 encoded packet.

R_p in Equation 2-1 above is the recovered packet. P is the sent packet. ICV is the checksum, K is the secret key, IV is the initialisation vector and RC4 is the encryption algorithm. (\parallel) represents a logical operator AND, \parallel represents concatenation and + represents XOR. An important variable in this formula is the initialisation vector. The problem with the early versions of WEP-based Wi-Fi is that the IV was send with the message as plain text! Even worse, IV value was the same for all packets [65]. If the IV was to be sniffed, critical control messages can be interrupted, recovered and modified easily by anyone. This therefore left security measures to be considered in other upper layers.

Nevertheless, Wi-Fi security enhancements have evolved in recent years. IEEE 802.11i and its original version, Robust Security Network (RSN) have introduced enhanced security measures for Wi-Fi via implementation of IEEE 802.1x authentication protocol (originally used in wired networks), data integrity and privacy as well as reliable key distribution [63] [65]. The security protocol was released as Wireless Protected Access 2 (WPA2). Therefore sending unencrypted MMS payload over RSN or IEEE 802.11i Wi-Fi is no longer a dangerous approach as it originally was. The RSN or IEEE 802.11i lower level protocols implement necessary security measures. Below is a discussion of Firetide's proprietary implementation of Wi-Fi network.

ii. Firetide meshed wireless network

Firetide® has implemented the above mentioned Wi-Fi protocols in their wireless network equipment. They have made additions to the conventional Wi-Fi network protocols with their proprietary auto-mesh routing protocol which manages load and flow of traffic in the network [66] [67]. Thus the differentiating factor between the conventional Wi-Fi and Firetide's implementation is the meshed architecture. Conventional wireless networks created localised hotspots forming hub-spoke architecture whereas with meshed wireless networks, the localised hotspots are integrated to form a wireless meshed "hot region". This region covers wider areas such as campus-wide networks or metropolitan area networks. The meshed architecture creates a reliable and scalable network which can suitably be used for smart grid MAN. Figure 2-8 below illustrates a structure of a meshed Wi-Fi network. The figure shows two meshes: Mesh 1 and Mesh 2. Mesh 1 is a linear mesh of outdoor access points. On the other hand, Mesh 2 is a bonded meshed that is connected to the Internet through an Internet gateway. Also shown in the figure are intelligent electronic devices and AMI meters which will be Wi-Fi clients in an energy management application in question. What differentiates this architecture from a normal Wi-Fi network is the ability of the access points to be inter-connected to form a seamless mesh.

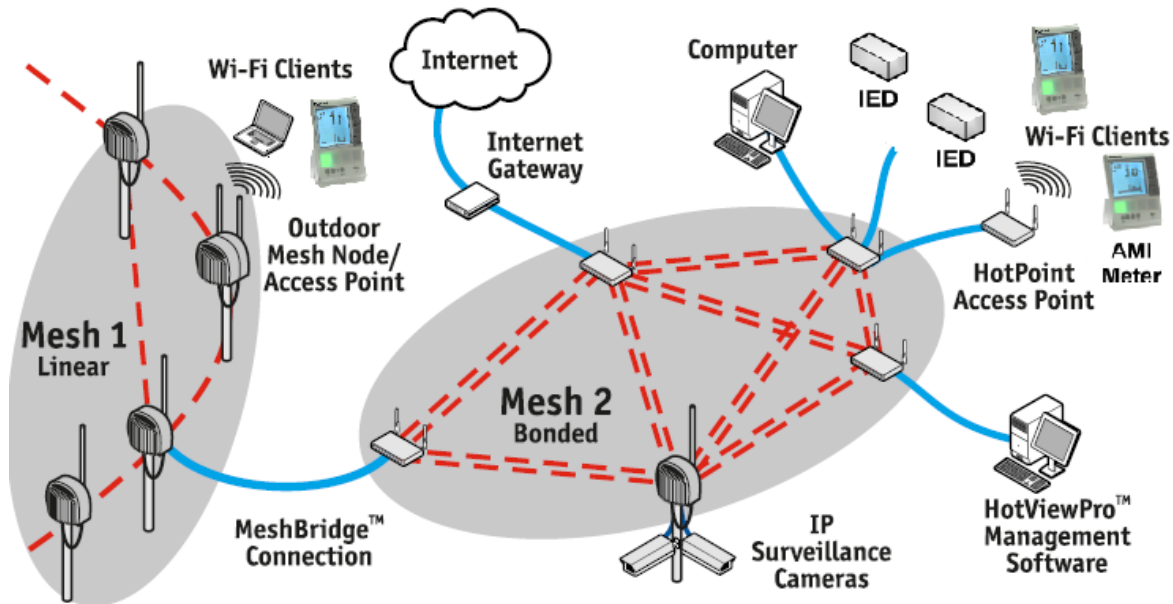


Figure 2-8. A Firetide meshed network architecture. Adopted from [68].

Worth mentioning at this point are the reasons why wireless networks are suitable for WAN and MAN. In the past, Wi-Fi was dreaded because it was interference prone and less secure for use in critical applications. Nevertheless, Wi-Fi security enhancements have evolved in recent years as explained above. The most notable advantage that wireless networks have is that they allow metering data to be geo-referenced; bringing location awareness and smartness to the network. Without needing special global positioning system (GPS) chips to be installed in the meters, triangulation methods that make use of signal strength at each transmitting AMI meter can be used to calculate estimated geographical location of each meter. Plotted on a map, the geo-data will represent the location of each smart meter. This information will become very important for maintenance and control personnel in knowing exactly which parts of the power network need attention. In the following section, an economical approach of implementing a backhaul network for AMI is discussed.

C. WAN

Power utilities can use their legacy communication networks to evolve their power grids into smart grids. This would be an economically sensible approach. However, smart grid applications are not a commonplace in the existing communications infrastructure equipment. This makes it a challenge to design high reliability and availability networks. Hence there is need for “workaround” techniques to make a smart grid implementation an evolutionary and economically friendly process as opposed to a costly revolutionary undertaking. The proposed

techniques use gateways and protocol converters to implement interoperability between new and old technology. Another method which can facilitate an evolutionary design process is implementation of unified communication networks. Nevertheless, the challenge that remains with adoption of these techniques is whether the designed networks will meet stringent quality of service (QoS) requirements (low latency, high security and availability) of tele-protection and other smart grids applications. This section reviews some of the design considerations which help to answer this question.

Communication networks for smart grids have to support a vast range of applications. This range presents a challenge in the design of these communication networks. The situation is aggravated by the differing quality of service (QoS) requirements that these applications have. Meanwhile, legacy communication network infrastructure has been optimized to meet QoS requirements of certain applications such as voice [69]. On the other hand, financial constraints necessitate the need for an evolutionary design approach. Thus power utilities prefer to re-use their legacy infrastructure. It is economically sound for them to overlay new smart grid applications on existing infrastructure. The fact that there are many options of technologies and that some options are more suited for certain areas while others are plausible only for certain areas indicates the necessity for ability to integrate data from the differing protocols and standards.

Therefore this poses three questions that need to be answered: how can heterogeneous applications that may use different protocols be integrated as one communication network?, how can legacy communication networks be used for energy management system applications?, what can be done on these legacy networks to ensure that they satisfy the QoS requirements of these applications? The essence of this thesis is to answer these questions. The scope through which these questions will be looked at is discussed further below.

In this dissertation, as seen on Figure 2-5, I propose implementing a smart grid network with Internet as the backhaul network. This approach has traditionally been seen as security flawed and therefore dreaded by power utilities. By introducing a new technique that incredibly enhances security of data over the Internet, this section shows why internet is no longer a “no-go” area for SCADA and energy management applications. Critics of use of the Internet for power utility applications were rightfully concerned with exposing grid network to cyber warfare. Nevertheless introduction of IPsec based VPN has dealt with many if not all security concerns of running critical applications over the Internet. As will be illustrated on Figure 2-12, VPN

consists of creating a virtual tunnel (security association) between distributed power grid control networks and the central control network. A VPN is an IP-based network which enables sharing of backhaul network resources on a single or multiple physical networks. It enables the geographically dispersed MANs to communicate securely with central server (at utility's head office control room) over a shared backhaul network.

IPSec offers three security services to VPN. It comprises encapsulating security payload (ESP), authentication header (AH), and internet key exchange (IKE). ESP supports data integrity, confidentiality and authentication through use of algorithms that produce unique packet identifiers that serve as signatures of each individual packet. ESP provides encryption support to IPSec protocol. Drawbacks of ESP are that it does not encrypt the ESP header and the ESP authentication, but only the payload [70]. However, this is not an absolute loop-hole since the ESP processed datagram from the network layer will become encapsulated as payload if tunnel mode security association (SA) is used.

AH provides similar services as ESP. It has an added option of anti-replay included. Furthermore, IPSec provides IKE protocol for exchanging of keys between the sender and the receiver during a SA setup. The protocol manages the keys and ensures that they are sent and received by legitimate nodes [70]. Combining this security services with quality of service (QoS) agreement defined in the service layer agreement (SLA), utilities can be assured of a visible way to use ISPs for SCADA, advanced metering infrastructure (AMI), and energy management systems.

The propositions made above are additions to the original Internet Protocol. If adopted they can make a pure IP network suitable for use by power utilities. Original IP was about addressing of nodes in the network. The logical addressing of devices and networks is done with IP address. IP protocol also focussed on identifying each device in the network (through the devices' media access control (MAC) address) and routing data from source nodes to destination nodes. Address resolution protocol (ARP) is used to translate the logical IP addresses and map them to specific device MAC addresses. Thus pure IP protocol defines means of using IP addresses and routing protocols to transmit data across a large network of interconnected networks (Internet). It made no provision for special handling of critical data. It is known as a best effort protocol. Meaning that it does all it can to get data from source to destination, but with no guarantee that the data will actually get to the destination. However, as mentioned above smart

grid applications have special characteristics which require certain quality of service from the network.

Multiprotocol Label Switching (MPLS) VPNs provide differentiated services that cater for quality of service. As its name suggests, MPLS is suitable for combining and transmitting data carried by different protocols from different physical media. A VPN concept supports the ability of the network to logically create a virtual extension of the power utility's secure network over public Internet. This thesis will discuss how MPLS protocol running over an IP network may be utilised to create a VPN for supporting the utility's smart grid. This builds on the ideas about using IPsec to create secure VPN which were presented above.

MPLS is favoured for its ability to create switched virtual circuits between the source node and the destination. With MPLS, designated paths (label switched paths - LSPs) are assigned between the sending node and the receiving node. Data may be transmitted on each virtual path according to its QoS and latency requirements. The data with similar requirements is classified into forwarding equivalency classes (FEC) that form traffic trunks which are transmitted to the MDMS at the utility's head office over the same LSP [71].

D. LAN

The local area network (LAN) shown in Figure 2-5 consists of the ordinary network that the utility company may have in their head office. The network usually consists of wired Ethernet LAN and Wi-Fi depending on the size of the company. In addition to the normal network services that the network has, it will support smart grid/AMI applications. As it is a normal practice, the LAN will be connected to the Internet core network via an Internet Service Provider (ISP).

The discussion above has focused mainly on the specific practical details of currently available implementation approach. Nevertheless, there are futuristic communication network technologies whose conceptualisation needs to cater for AMI. Machine to machine (M2M) communication protocols are part of new developments considered for bringing an "Internet of things". Further developments being done are in the spectrum of convergence in the form of IP Multimedia Subsystem (IMS) as opposed to IP/MPLS discussed above. Another interesting development which can be seen as the future enabling technology for energy management infrastructure such as AMI is the Evolved Packet Core (EPC). It is dearly important that conceptualisation of these technologies takes into account and supports AMI and its sub-applications.

Also presented above are options for networking the four areas of an energy management system of a smart grid. The MAN and WAN are the most critical network areas of the smart grid system. Thus, this thesis report will take them further and propose ideas for implementing smart grid devices communication network in these areas. At this stage, the report reviews existing AMI systems in the subsection below.

2.7.5 A Review of Proprietary AMI Systems

The review of existing AMI architectures and proposed models revealed that interesting aspects which foster interoperability of AMI sub-systems are architectural model semantics, syntax of exchanged messages, communication and interfacing profiles and network security management [72].

Many companies have developed different AMI solutions with more or less common features. This review discusses three different AMI solutions from different vendors. The systems are real solutions that were studied in an experimental setup used in an exhibition during the March 2011 African Utility Week conference held in Cape Town, South Africa [73]. The data summarised in Table 2-F was provided by the equipment vendors themselves. The solutions studied were from Iskraemeco, Nuri Telecom, and Kamstrup. Table 2-F depicts features of the AMI as proposed in the NRS 049 document. In this review, for anonymity of the vendors, these product names are abstracted as Product 1 (P1), Product 2 (P2), and Product 3 (P3) in no particular order from the previous list of actual names (as shown in Table 2-F). The systems developed by three leading manufacturers are evaluated against functional requirements established in the NRS 049 document. The following sub-sections will describe each product in detail from P1 through to P3.

Table 2-F. A comparison of three AMI solutions from different vendors [41].

Feature	P1	P2	P3
MASTER STATION			
• Billing System	☺ Yes	☺ Yes	☺ Yes
• Vending System	☹ No	☺ Yes	☺ Yes
• Data Warehouse	☺ Yes	☺ Yes	☺ Yes
• Load Management	☹ No	☺ Yes	☺ Yes
• Tamper Detection	☹ No	☺ Yes	☺ Yes
• Fault Investigation	☹ No	☺ Yes	☺ Yes
• Quality of Supply	☹ No	☹ No	☺ Yes
AMI METER			
• CIU	☹ No	☺ Yes	☺ Yes
• ACD	☹ No	☺ Yes	☺ Yes
• Load Switch	☹ No	☺ Yes	☺ Yes
COMMUNICATION			
GSM/GPRS	☺ Yes	☺ Yes	☺ Yes
PLC	☹ No	☹ No	☹ No
ZigBee	☹ No	☺ Yes	☺ Yes
TCP/IP	☺ Yes	☺ Yes	☺ Yes
PSTN/IDSN	☺ Yes	☹ No	☹ No

A. Product 1

Product 1 is called ‘Energy Measurement and Management’ (EMM) system. As the name suggests, it is a system that focuses on automatic meter reading (AMR) and therefore does not meet most AMI functions described in subsection 2.7.2 above. It is important to note the difference between AMR and AMI. While conception AMR can be traced back to the ‘80s, the idea of AMI only came in 2005 [74]. AMR concentrated on automatic meter reading and billing only. AMI is a combination of systems and networks for measuring, collecting, storing, analyzing, and using energy consumption data for managing load, power network failure, and managing and balancing demand with capacity [45] [75].

The EMM’s master station functions as a billing and data warehouse tool. The meter is a standard “dumb” instrument for reading energy consumption. The additional feature that sets it

apart from “our-everyday” meters is the ability to communicate energy readings to a distant server. However, the EMM system supports many backhaul (WAN) communication networks. It has an option of either using public switched telephone network (PSTN), integrated services digital network (ISDN), Internet protocol (TCP/IP) and general packet radio service (GPRS).

B. Product 2

Clearly, Table 2-F shows that P2 meets most of the standard requirements stipulated in NRS 049. The only important functionality that seems to lack is monitoring quality of supply. That is, keeping both phase and frequency of the distributed power in-check by reporting discrepancies back to the utility control centre [40] [76].

The AMI meter in P2 also has all the components in the proposed standard. It satisfies an important requirement for a Demand Side Management (DSM) system: a two-way collaborative and interactive communication between the utility, the consumer and the controllable electrical load [46] [77]. On the communications side, P2 supports GPRS and TCP/IP for WAN link and ZigBee standard for short range communications (HAN). In its architecture, P2 system incorporates a utility data centre and supports internet or mobile broadband network for linking the data centre to the concentrators (or cellular modems). The concentrators link to AMI meters which connect to smart homes via ZigBee-compliant HAN.

C. Product 3

Product 3 is called Demand Side Management (DSM) system. It is fully compliant with NRS's proposed standard. P3 system supports two networks for backhaul communication: GPRS and Internet (TCP/IP). In both architectures, ZigBee is supported for HAN. Ethernet is also used for HAN. P3 is capable of performing load switching and load control. For load control, the system uses ZigBee relays which act as ACD to monitor appliances. The DSM AMI meter is also equipped with a connect/disconnect feature for isolating customers (in the event of bill payment default) [78]. The switch is also meant to isolate customers who exceed their consumption threshold (load limiting threshold) [79].

The Internet based architecture system incorporates customer mobile phone applications and personal computers web interface. These therefore enable consumers to monitor their energy usage through their cell phones and via their internet browsers.

At this stage, this report moves on to review the second proposed DSM programme – distributed generation. The report elaborates on the concept of distributed generation and

microgrids. It focuses on solar PV DGs that form meshed microgrids. The discussion idles on challenges of implementing microgrids. It reviews viability and grid protection issues which are core to success of the proposed DSM intervention.

2.8 Distributed Generation and Microgrids

Chen Jian *et al* (2011) describe distributed generation (DG) as installation of small power generators designed to supply and meet demand of specific customers and supplementing operation of main distribution networks [80]. Distributed Generation systems (DGs) are miniature sources of energy connected directly into distribution networks close to the point of consumptions. At its extreme level, the concept of distributed generation involves each household generating its energy from photovoltaic cells. This approach is particularly suitable in rural electrification projects. The DGs can be configured to form a meshed grid of DGs that service a load as one system. The integrated system of DGs is referred to as a microgrid. A microgrid is defined as a power system consisting of DGs and loads that are considered as a mini controllable subsystem of the distribution network. This is an attractive solution for energy generation and sharing in domestic electrification projects.

Distributed generation systems (DGs) forming a microgrid and their integration into the utility grid are the talk of the day in the alternative energy research world. The main advantages of microgrids are environmentally friendly distributed power generation technologies and peak demand shaving [81] [82] [83]. Depending on the abundance of the renewable resource being harnessed, DGs can defer need for investment in new power plants and transmission lines; which are usually costlier than these DGs.

There are two types of DG technologies: non-renewable and renewable energy technologies. Renewable energy technologies are receiving greater attention because of their less impact on the environment. The five renewable sources of energy shown in Figure 2-9 below are wind, solar, hydrogen, biomass, and hydro energy (micro-turbines). The figure also illustrates technologies that are used with these sources. Solar photovoltaic technology for harnessing solar energy is the centre of this thesis because of its ease and applicability on domestic electrification. It is highlighted in green on the figure.

This thesis focuses on implementation of islanded and grid-connected microgrids formed by solar systems installed in homes. Installation of solar photovoltaic DGs on households can provide an effective means to complement energy needs of households. In addition, excess

energy that may result can be sold back to the utility grid depending on the installed capacity. Nevertheless, DGs tender these benefits at a cost of adverse effects on the distribution network.

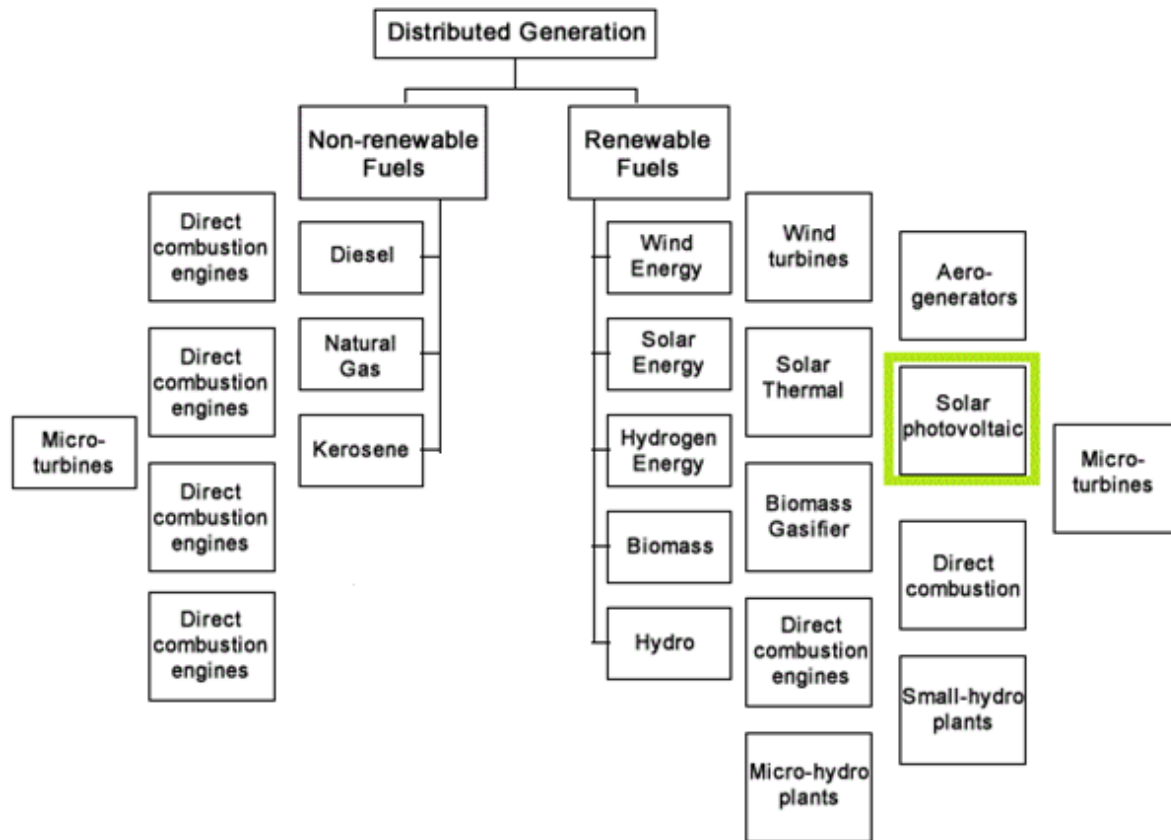


Figure 2-9. Non-renewable and renewable distributed technologies [84].

DG penetration changes the distribution network topology from radial structure to a meshed microgrid. Protection and control in a meshed microgrid network configuration is a challenge. This is true because unlike in radial architecture power grids, a mesh introduces more interconnections and interfaces which need to be protected. Furthermore, this is exacerbated by known effects of DGs on power quality such as transients, voltage sags and swells, under and over-current faults etc [81] [83] [80]. The challenges necessitate robust protection schemes supported by effective control and fault location identification. Section 2.10 below discusses these protection and control issues. Before delving into these technical issues, it important to assess viability of the proposed grid integrated PV solar systems.

2.9 Viability of solar PV DG Integration in South Africa

An all important question to address is; are grid-connected solar systems economically feasible for home-owners? This section attempts to answer this question by looking into available literature on solar PV integration from an economic perspective. Viability of the solar PV system depends on the following factors:

- i. Prices of the components,
- ii. Available solar irradiance at the proposed location,
- iii. Renewable energy feed-in tariff (REFIT), and
- iv. Load to be serviced.

Subsection 4.2.3 will discuss these crucial design factors in greater detail. The main components of the proposed PV system whose prices determine viability of the system are: 1. photovoltaic cells, 2. batteries, and 3. wiring. Available solar irradiance at the proposed location is a measure of potential solar energy that can be converted to electrical energy. Thus abundance of sunshine translates into greater potential for solar generated electricity. The other important factor is the REFIT. REFIT is a tariff that the country's energy regulator has approved for use by renewable energy generators. It is based on the levelised cost of energy (LCOE). LCOE is the price at which energy must be sold to break even. South Africa commenced research on REFIT in 2007. The first set of REFIT was published in 2009. The bar graph shown in Figure 2-10 shows this first set of REFIT compared to the current set. Large scale solar PV connected to the grid had the highest LCOE of R3.94 in 2009 compared to R2.325 established for 2012. Therefore the old set was repealed in 2011 with a new set [85]. The new set established in 2011 revised the 2009 set and included consumer price index (CPI). It also estimated 2013 REFIT values. The observed trend is that the costs are declining. In this thesis, interest is on the R2.325 value. Thus the system design must meet this constrained of LCOE. This is the most important economic feasibility factor. The section below reviews protection and control of solar PV microgrids as the most crucial technical feasibility issues.

2.10 Protection and Control of a PV microgrid

A power grid is vulnerable to contingencies caused by abnormal variations in the characteristics of supplied power as mentioned in the section above. A power system operates under harsh and abnormal conditions. Protection is needed for safety of electrical equipment and utility personnel. Functions of protection and control schemes are to mitigate, detect and recover from unpleasant incidents to continue service provision even when contingencies occur. Various

protection schemes have been proposed to deal with these contingencies. There are four characteristics which protection schemes must have: speed, reliability, cost, and selectivity. Therefore, a protection scheme must quickly select and reliably remove any faulty power system component in the most possible cost effective manner.

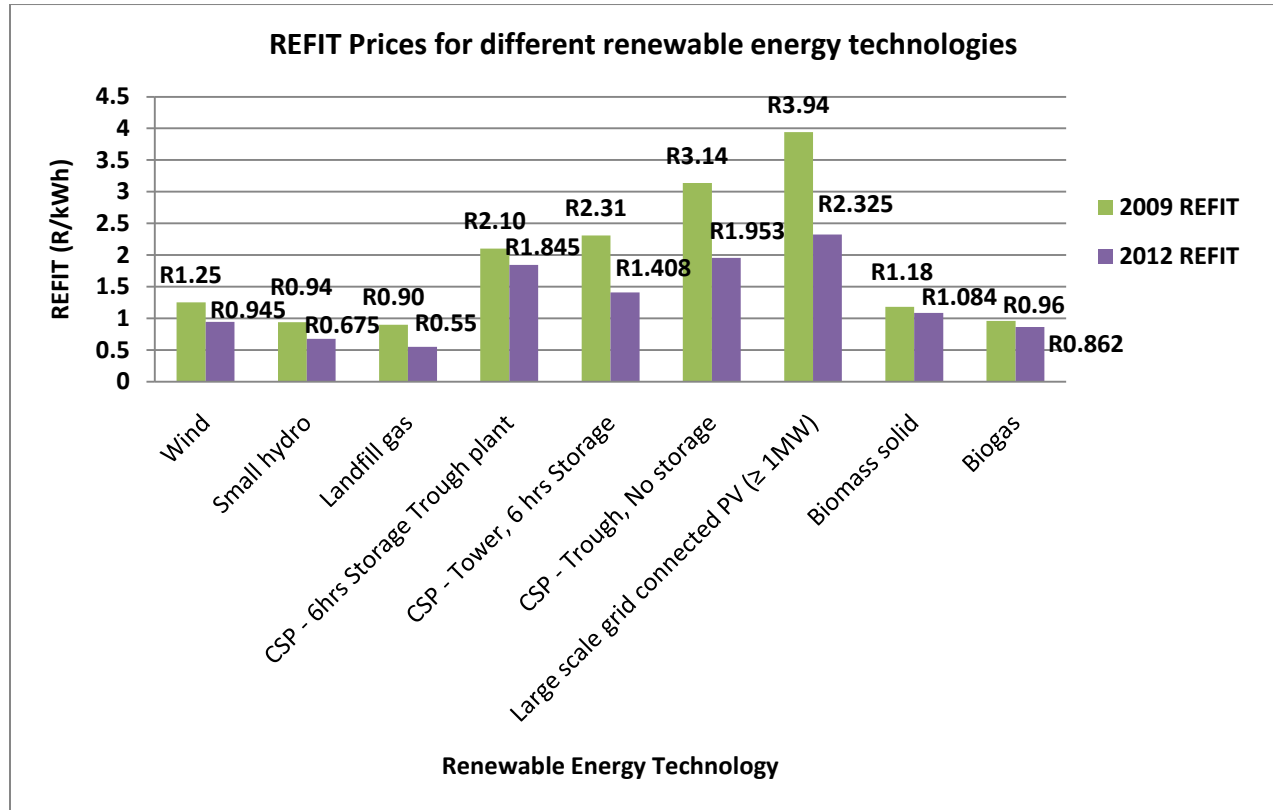


Figure 2-10. The first set of REFIT published in 2009 vs 2012 REFIT.

The schemes make use of protection devices installed on the power system. In a meshed microgrid, protection is achieved by guarding and monitoring each grid element individually. Grid elements are classified into protected zones or protected units. These units are: a *line*, a *source*, a *bus* and a *load* [86]. The zone boundaries are protection units: 1. Relays, 2. Instrument Transformers (current transformers (CTs), potential/voltage transformers (PTs)) and 3. Circuit breakers [87]. The relay circuits are powered from batteries (DC supply). There are also communication channels and control equipment.

In general, the protection process involves instrument transformers connected to either current and or voltage sensing devices close to the protected zone/unit. The current/voltage (I/V) on the protected unit is referred to as a primary current/voltage. The output current/voltage (I'/V') from

the transformer is the secondary current/voltage. The relationship between the primary values and the secondary readings is shown below.

$$I' = I \frac{1}{N} \quad \text{OR} \quad V' = V \frac{1}{N}, \text{ where } N \text{ is the conversion factor.}$$

Equation 2-2. Winding relationships of instrument transformer.

There are standards that determine the ratio of primary value to that of secondary values [87]. Different countries and utilities have different standards that they adopt depending on their policies and the type of equipment they have. Relay settings are based on this ratio. If the monitored value (current/voltage) falls out of the allowable margin, the relay gets excited and energises the circuit breaker which opens the circuit. The protected unit then gets isolated. Nevertheless, reality is that the dynamics of power flow in microgrids are complex and the simplistic protection scheme described above would not suffice. Hence the section below reviews these dynamics and issues concerning microgrid protection.

2.10.1 Protection issues in microgrids

In microgrids, contingencies occur during a change of mode of operation; going from grid connected to islanded mode. Most common disorders are transients, voltage sags and swells, over-voltage and under-voltage as well as under-current and over-current faults. It was in response to these problems that power electronic systems were employed to mitigate for faults and coordinate renewable sources (DGs) and loads. This formed an almost self-healing network called a microgrid. One of the aims of this thesis is proposing an optimal technique that implements adaptive control of the power electronic systems (protection devices) used in the interface protection of microgrids. The protection devices are intelligent electronic devices (IEDs): PMUs, and smart meters which need to communicate with the central control stations.

The adaptive control leads to the self-healing feature in microgrids. Protection schemes appropriate to microgrid network constraints and requirements are as equally important as the supporting communication network. It is therefore the focus of this thesis to review protection schemes of distribution networks integrated with microgrids.

The bi-directional power flow characteristic of microgrids makes conventional protection schemes used in radial architecture grids inapplicable for meshed microgrid [86]. Furthermore, conventional protection schemes used in radial distribution networks use load distribution, direction and magnitude of fault current, and characteristic architecture of the network. As

aforementioned, there is no predetermined direction of flow of energy in microgrids. A simulation performed in [86] shows that due to the jittering magnitude of fault current, traditional current protection schemes become irrelevant in microgrids. Fault current oscillates frequently and unpredictably as the system changes from grid-connected to islanded mode and vice versa.

Conventional inverter systems used with DGs have very low fault current. In islanded mode, the fault current is two times less than the nominal operative value set in conventional relays [80] [88]. This current requires very sensitive relays and may not cause a trip with conventional relays [80] [89]. Nevertheless, installing sensitive relays is not an absolute answer as these can lead to instability of the system by responding to spurious currents which may not necessarily affect system stability. In addition, in grid-connected operation, even load distribution is not predetermined since the microgrid can either be feeding just the local load or feeding the local load and the utility grid. It is therefore mandatory to device protection and control systems that adapt to the prevailing situation in the network. Differential current protection mechanism is seen as a plausible solution for current control. This will be pursued further in this report.

There are two types of control; hard programmed control and knowledge based control (referred to here as adaptive control). Hard programmed control also called hard wired control makes use of static relays. Static relays are programmed with hard-wired settings such as values for over-current protection. Foreseen deficiencies of fixing these values have already been indicated above. Subsection 2.10.2 below discusses an overview of these traditional protection techniques to further point out their shortcomings.

2.10.2 Developments in traditional protection schemes

The traditional power networks had fewer unpleasant contingencies as they were less complicated. The previous section painted a picture of complexity that microgrids bring to the power network. In the past, common contingencies were short circuits caused by failing insulation, over-voltages caused by lightening or current surge during switching operations, some mechanical and natural sources. Nowadays, catastrophic power failure events happen because the grid is under stress [87]. As explained before, this served as a motivation to this thesis; applying solar PV systems installed in homes to relieve the main power grid and to install smart meters in consumers' premises so that they can manage and reduce their consumption.

Protection systems have continued to evolve from decades to decades. So far there has been three generations of relays. These are electromechanical relays, solid state relays and now digital relay systems. Digital relays have brought the following advantages to protection:

1. Flexibility of settings – they can be programmed and reprogrammed with new settings.
2. Multiple functionality – they allow multiple protection schemes to be implemented.
3. Communication ability – they have build-in communication capability.
4. Adaptive protection system – they can be made to adapt to changing system conditions.

There are four common traditional protection schemes: over-current protection, directional over-current, distance protection scheme, and differential protection schemes. Over-current protection is the oldest scheme conceptualised as early as 1902. Challenges faced by the early schemes were to do with slow fault clearance times [90]. Figure 2-11 illustrates developments in power protection principles over years. It shows developments in types of relays and the protection schemes/principles used during the era of each of the types of relays.

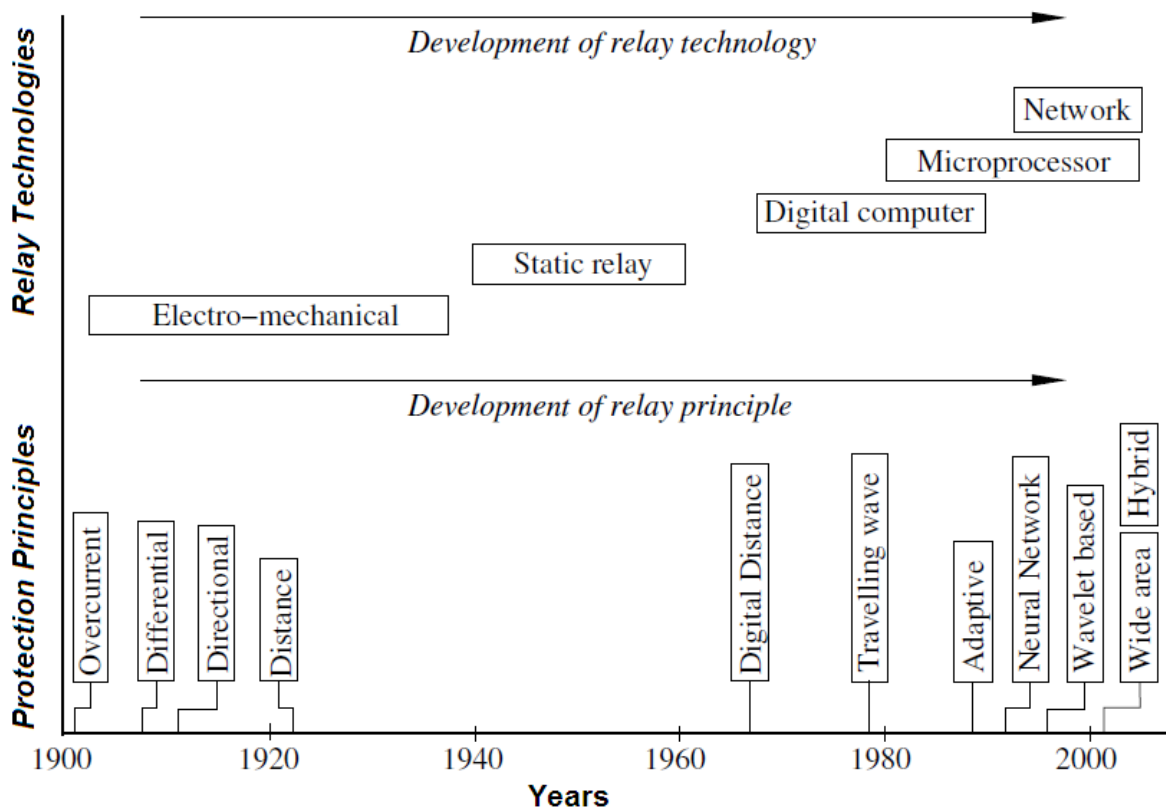


Figure 2-11. Developments in protection schemes, adapted from [90].

The evolution of protection equipment has assisted development of new protection schemes. Evolved microgrid protection schemes are discussed in subsection 2.10.3 below.

2.10.3 Evolved microgrid protection schemes

Some of the protection schemes proposed for microgrid protection are based on the evolved main grid protection schemes described above. Five categories of microgrid protection schemes have been proposed. The categories discussed in [80] are (i) improved current protection schemes, (ii) fault current limiter scheme, (iii) wide area protection schemes, (iv) Total Harmonic Distortion (THD) protection scheme, and (v) abc-dq transformation protection schemes.

The improved current protection schemes are simple over-current scheme and improved directional over-current scheme. They form part of the main grid protection schemes evolved and adopted for use in microgrids. The old main grid schemes were found to be insensitive to small fault currents which are characteristic to inverters used in microgrids. Another issue on which the simple over-current protection scheme fell short on is the bi-directional power flow in microgrids. Directional over-current scheme was designed to overcome this deficiency. The essence of the improved scheme is the ability to determine whether the fault in question is external or internal to the microgrid. This scheme applies communication between relays to determine direction and position of the fault. Nonetheless, this scheme does not meet all the challenges posed by the dynamic behaviour of DGs. That is, frequently switching on and off as well as changing fault current magnitude levels [80]. Another new variant of over-current protection scheme is the over-current scheme based on fault current limiter. The new scheme uses a current limiter to minimise current contribution from the microgrid. The current limiter is connected in series with the protected power lines.

Differential protection scheme is one of the oldest protection schemes to be adopted as shown in Figure 2-11 above. Many researchers improved and adopted the scheme for use in microgrids. The new scheme is known as symmetrical and differential current component scheme [91]. In this scheme, the grid is divided into protection zones with relays at the end of each zone. Zero-sequence current components indicate normal conditions in the network. Depending on the relay settings, negative-sequence current components may indicate that the faults are either downstream or upstream to the microgrid.

There are many other characteristics of the grid that can be monitored to determine the state of the network. The protection schemes presented use magnitude and direction of fault current. The amount of distortion of the harmonics in the output of inverters may also be used to predict the condition of the grid. Total Harmonic Distortion protection scheme uses this method in inverter-based DGs. As already highlighted, the schemes operate by communication between

relays. Hence the necessary support of communication network infrastructure in AMI is required for adaptive control and protection schemes of microgrids. The subsection below reviews the connection between AMI infrastructure and protection and control of microgrids.

2.10.4 Support of AMI network in DG Integration

Implementation of the proposed adaptive protection and control shares similar characteristics with AMI. Adaptive protection and control and AMI are applications of smart grids as discussed in Section 2.4. The system forms the WAMPAC reviewed in subsection 2.5.4. While the AMI discussion mainly focused on energy consumption management, protection and control focuses on ensuring continued transmission and distribution of good quality power. Knowledge-based protection and control uses intelligent sensors and advanced communication networks built in intelligent electronic devices (IEDs) to determine real-time conditions of the network, communicate the information to the control centre which invokes smart algorithms that determine informed decisions to take. In this way, control measures adapt to the situation at hand. In addition, this suggests a decentralized or agent based control system. The architecture of the protection and control network shown in Figure 2-12 below is similar the proposed AMI network architecture in Figure 2-5. The same MAN, WAN and LAN technologies proposed for the AMI network are applicable here.

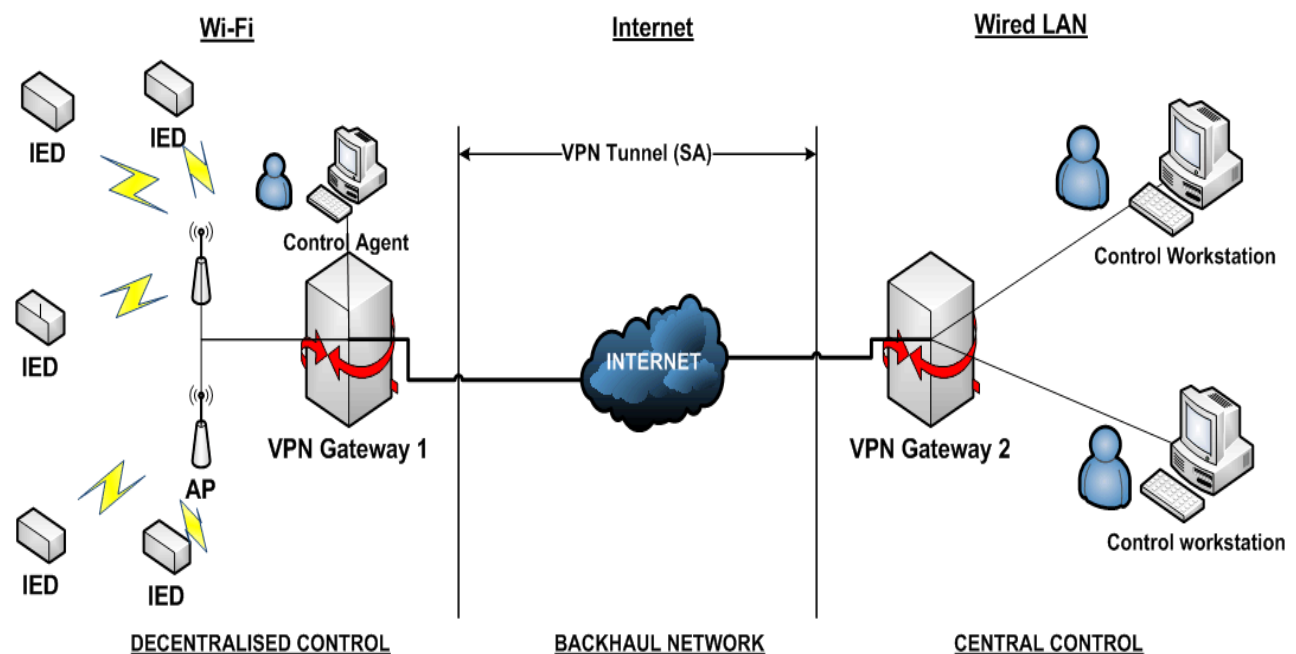


Figure 2-12. A Wi-Fi and Internet based microgrid control network.

The sections above reviewed existing literature about various concepts that can be combined together to build an energy management system. The review is concluded by looking at one existing energy management system that also combines various communications networking technologies. The REMPLI system reviewed below is one such system.

2.11 The REMPLI System

The acronym, REMPLI stands for **r**emote **e**nergy **m**anagement via **p**ower lines and **i**nternet. REMPLI is a project whose sole purpose was to design and implement communication infrastructure for energy management. The function of the REPLI's energy management system is to acquire data and support remote control functions of power grids. The project targets to build a communications infrastructure for remote metering and SCADA system. The system is based on PLC infrastructure [92]. Many currently existing prepaid electricity meters and SCADA systems are based on the similar technology pursued by REMPLI. An overview of the REMPLI system is shown in the figure below. The REMPLI project's task was to design and develop the REMPLI node, REMPLI bridge (coloured orange in the figure below) and access point. The access point nodes adapt the PLC infrastructure to work in the energy management environment and to interwork with other networking technologies.

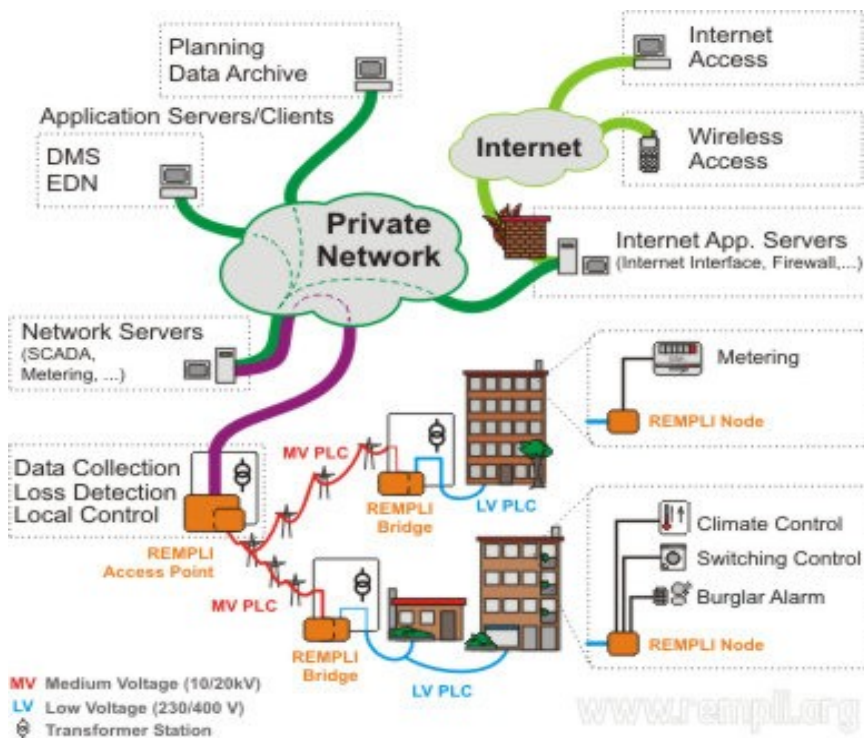


Figure 2-13. The REMPLI system overview [93].

The review in Chapter 2 above has set the context for the research to be pursued in this thesis report. It started by looking at the concept of demand side management. It then discussed power grids as they are known today. This discussion cleared stage for introduction of concepts involved in the future grid – the smart grid. Smart grid applications were presented thereafter. Of the applications, focus was placed on energy metering and billing; then protection and control issues coming with integration of solar PV alternative energy sources. Within the smart grid, the metering and billing applications are supported by advanced metering infrastructure (AMI). Hence it was discussed after presentation of the applications. AMI was thrashed out in greater detail, with a focus on connectivity of AMI components. AMI backhaul network connectivity is one of the centre discussions of this thesis.

One of the DSM approaches proposed is home based solar PV DG systems integration with the main grid. Literary concepts around distributed generation were also reviewed. Issues around viability of this approach to DMS were reviewed. This was followed by a detailed review of grid protection and control which mitigates a threat of low power quality brought by PV DGs. The chapter was concluded with a review of an existing energy management system, the REMPLI.

Chapter 3 below discusses methodology used in the experimental simulations performed to test the DSM solutions proposed in this thesis.

3 Methodology

This chapter explains how the objectives of this thesis presented in Section 1.3 were met by the research work. The chapter explains the overall methods used in conducting the research work being reported on. It describes how relevant information and data was collected and how the data addresses the said research objectives. Methods of analysis of the data are also described. Section 3.1 describes general research methods used. In Section 3.2, the procedure used to collect data is presented. Section 3.3 describes the data analysis methods used.

Two approaches of implementing DSM are proposed in this report. The first of the proposed methods discussed here is integration of AMI into the power grid. The second method is grid-connected and off-grid home based solar PV systems. While grid-connected systems are covered by the technical study on protection and the feasibility study, off-grid systems are presented in the case study in Chapter 7. Section 1.3 listed simulations performed under each of the proposed DSM programmes.

The simulations compare pure IP network and MPLS network to determine which networking protocol performs better in the backhaul network of the AMI. Methods used in simulating the proposed protection scheme for grid-connected solar PV system are presented. A differential protection scheme is simulated to determine its suitability of protection of point of common contact (PCC) in grid-connected solar systems. The feasibility study computes levelised cost of energy (LCoE) in grid connected and off-grid solar systems. It determines estimates of initial capital (IC) and net present cost (NPC) of these systems. The project management section discusses AMI and solar PV project implementation by looking at stages of project realisation and resources needed for real-life execution of projects involving AMI and solar PV. Having summarised the work covered by the simulations in this thesis, Section 3.1 below highlights general methods applied to achieve the said goals.

3.1 General Method of Conducting the Research Work

This thesis employs logical and empirical research methods. Therefore the research is designed in a manner that relevant literature was studied to determine the context of the objectives of this work in relation to what has been done by other researchers. The product of this approach is the

literature review presented in Chapter 2. Gaps in the existing knowledge in the area of DSM were identified from the extensive study of literature. This led to formulation of specific research questions pursued in this thesis. Hypotheses were formulated from the research questions. With the view of the expected outcome in perspective, the apparent question was ‘how were these hypotheses going to be validated?’ The procedure used is summarised by three stages shown in the figure below.

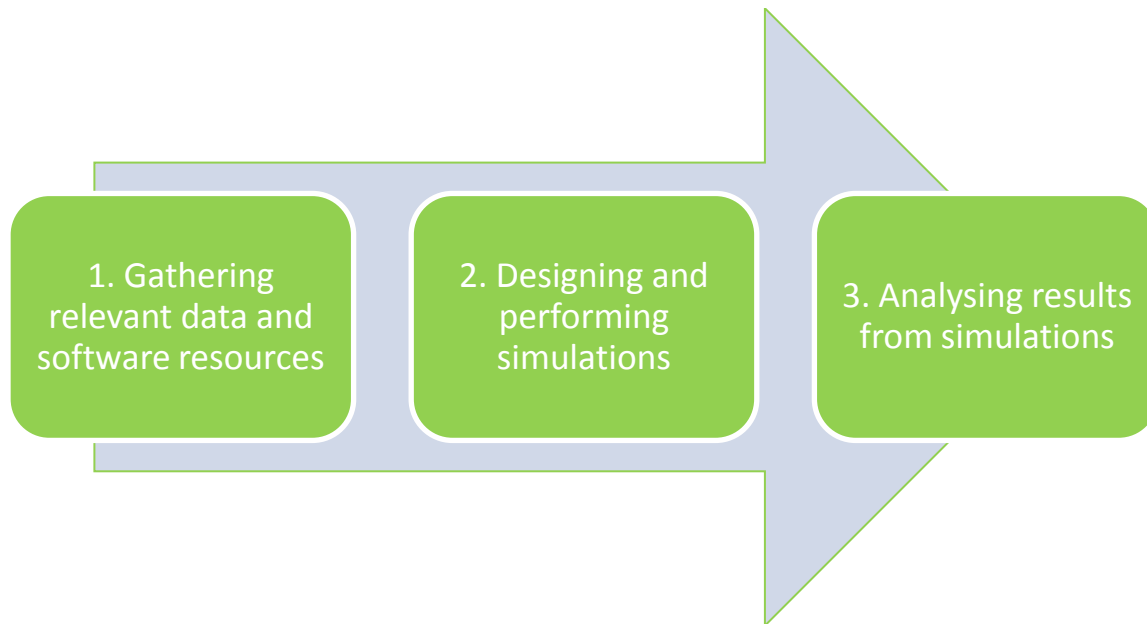


Figure 3-1. General methodology followed.

The thesis uses both real-life case studies and software modelling [94] for both AMI and solar PV system integration. Software modelling was chosen because it combines characteristics of the different types of modelling. Time and available financial resources were the influential countenances of the method used. Therefore case studies were used whenever it was cheaper and possible to access the information in a timely manner. Section 3.2 below gives a detailed account of the research methods used. An apparent problem with modelling as opposed to studying real-life system is the accuracy of the model. In order to prevent limitations of one model from affecting the objectives and accuracy of the results, the simulations will be supported by theoretical explanations and mathematical models that test and confirm their validity.

3.2 How relevant facts, data and figures will be collected.

This section explains how specific tasks in this research were performed. The proposed simulated DSM programme implementation consists of AMI, feasibility of integrating home-based solar PV into main grid, technical challenges (especially protection), and real-life project management activities. Thus the research was divided into the following five tasks:

- Simulation of AMI
- Feasibility of grid connected solar PV DGs
- Protection of grid connected solar PV DGs
- Case Study 1: AMI Project Implementation
- Case Study 2: Solar PV DG Integration Project Implementation.

Subsection 3.2.1 through to subsection 3.2.6 below describe how each of these tasks was fulfilled.

3.2.1 *Simulation of AMI network on OPNET*

OPNET Modeler V14.0 was used to build AMI simulations. OPNET is a simulation platform for designing and analysing communication network protocols, network applications, and devices [95]. It has models of different network nodes: routers, switches, PCs, servers etc. Most of these nodes are predefined. However, OPNET allows the network designer to configure and define certain characteristics of the network. It comes with many predefined network applications such as VoIP, video streaming, web-browsing (http), etc. It also allows the designer to define custom applications. This is a useful feature as smart metering application was configured as a custom application. OPNET supports many wired and wireless transmission media technologies: optic fibre, digital signal (DS0, DS1, DS2...) links, twisted pair, etc. OPNET is feature-rich and allows flexible design options and simulation scenarios. It allows the designer to build many scenarios of the same network using different protocols. Performance of the different scenarios can then be compared to determine the most optimum solution. This is the process followed to compare IP and MPLS network protocols for use in the backhaul network of the AMI.

The definition of AMI as given in Section 2.7 stresses the importance of communication networks for realisation of AMI. AMI is a communication network application. Thus OPNET was a suitable tool to use for simulating AMI as it was built for modelling communication networks applications. The useful features described above, and the fact that OPNET licence is free for academic purposes made it more suitable compared to other network simulation platforms.

Alternative simulation software was OMNET++. OMNET++ is open source software. However, OPNET was chosen over OMNET++ because of lack of documentation of OMNET++. It was harder to use OMNET++ as there were no tutorials related to MPLS simulation to refer to. The only disadvantage about OPNET was that it could not be used outside university network as the PC on which it is installed has to actively communicate with the licence server.

3.2.2 Simulation of feasibility of grid connected solar PV DGs on HOMER

The feasibility study of using solar PV systems to supplement traditional energy sources was simulated on HOMER. HOMER is a hybrid power systems optimisation and analysis tool. It uses optimisation and sensitivity analysis algorithms to assess viability and technical design of renewable energy systems. HOMER determines the size of a power system needed to meet a certain load profile defined by the designer. It requires the power system designer to define two variables as inputs: hourly, daily or monthly load profile that the power system is to service and energy resources available. The energy resources are solar irradiance, wind speeds, etc available to be harnessed at the location where the proposed system is to operate. The software uses these inputs to compute an optimised size of the resource harvester (solar panels, wind turbines etc.) and size of storage system that will meet the defined load.

The feasibility study considered in this thesis looked at home based solar PV systems at a new residential area in Cape Town. It is based on the study I presented in the paper titled “*Viability of grid-connected domestic solar photovoltaic systems in South Africa*”; which I co-authored [96]. The study used freely available satellite solar data source for solar irradiance estimates at the area. The load profile used is also an average energy consumption of a typical household in Cape Town. Load profile data was sort from City of Cape Town municipality. HOMER has an option that allows the designer to automatically download solar irradiance data directly (by giving it geographical coordinates of the location where the system is to be implemented, which is around 33.55 South,18.22 West for the Cape Town region used in this study) from the Internet into the project. The software automatically sourced the data from NASA satellite’s solar irradiance database.

The study in [96] focused on grid-connected systems installed in each household. This report presents a study which applies similar methods to pursue similar ideas; however the simulations considered here look at feasibility of meshed microgrids instead of individualised systems discussed in the paper. Meshed microgrid configurations are proposed because they can easily meet the 1MW capacity of the currently defined REFIT provisions for grid-connected DGs by

integrating more household PV systems into one microgrid [85]. Nevertheless, as in [96] the simulations will still focus on grid connected systems of capacities less than 100kWh which were only approved by NERSA on the 22nd September 2011 [97]. The reasons and advantages of the chosen design are detailed further in subsection 4.2.3.

The simulations compared feasibility of smaller systems as in [96] with the integrated meshed system proposed in this thesis. They attempted determine whether it is more economically feasible to have individualised household systems or to have meshed integrated systems. If integrating PV systems on three households is more economical than having a PV system serving one household connected to the grid, the findings will suggest that integrating more houses result in a more robust and economical system. Feasibility of the system was judged by its total net present cost (NPC) over a lifetime period of 20 years. NPC_{total} is the present sum of all costs incurred over the lifetime of the project, minus present value of all the revenue generated from the project. These costs are initial capital costs, replacement cost, operations and maintenance costs, emissions penalties, cost of power bought from the national grid, and fuel (where applicable). The revenues include electricity sold to the national grid and salvage value of the project.

NPC is calculated by HOMER as thus:

$$NPC = \frac{\text{Total Annualised Cost (\$/yr)}}{\text{Capital Recovery Factor}}$$

Total annualised cost is the sum of the total annual cost of each component of the system. Capital recovery factory (CRF) is a measure of present value of annual equal instalments of recovering the initial capital of the project. It is calculated as thus:

$$CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1}, \text{ where } i \text{ is interest rate and } N \text{ is the lifetime of the project (20 years in}$$

the case of the PV system in this thesis).

The expected shortcoming of using HOMER to download irradiance data automatically is that it connects to a database that sources data from satellites. An observed fact is that satellite data underestimates solar irradiance of a region. This translates to the overall required capacity of

the system being overestimated. Hence initial capital investments may seem to be higher than they really would be if ground data was used [98]. Nevertheless, the required accuracy of the calculations that seems to be affected by this method subjectively depends on what the design is to be used for. That is, whether it is to be used for attracting a potential investor, for academic purposes or for general investigation purposes. Thus for the purpose of the study undertaken here, the data was indicative enough to allow for reasonable conclusions to be drawn.

There were two other candidate alternative software simulation platforms that could have been used for the feasibility study. These are RETScreen4-1 and System Advisor Model (SAM 2010). RETScreen4-1 is a Canadian product designed to assist in evaluation of clean energy projects [99]. SAM 2010 is USA's National Renewable Energy Laboratories (NREL) product designed for performance evaluation and financial modelling of renewable energy projects [100]. HOMER was chosen over these software platforms because of its wide-use in research, ease of use and good presentation of results and analysis.

3.2.3 Simulation of protection of grid connected solar PV DGs on MATLAB

The study on protection of grid-connected solar PV DGs consisted of two subtasks. The first subtask was determining a suitable protection scheme for grid-connected PV DGs. The second subtask was investigating on the cost-effective, technically stable and reliable communication network that can support communication between protection devices: intelligent electronic devices (IEDs), PMUs and the central control stations as mentioned in subsection 2.10.1.

The protection scheme simulations were performed on Matlab 2011a Simulink. Matlab is a comprehensive integrated development environment used for data analysis, visualisations, and numerical computations. It is used in design and modelling of many scientific and engineering applications. It is used in simulating communication networks, signal and radar processing, electric power networks, computational biology and financial modelling [101]. A grid-connected solar PV microgrid was built on Simulink. Simulink is a feature-rich model-based simulation platform that is part of Matlab. It has a dynamic and interactive graphical design environment with customisable block libraries. These blocks can be used for design, implementation, analysis, testing of communication systems, control system, video processing etc [102].

An alternative approach to using Simulink was PowerFactory DIgSILENT. DIgSILENT also provides power systems modelling, analysis and simulation functionalities. Nevertheless, Matlab was chosen over DIgSILENT because of the extensive documentation and help that was available. Hence the objectives of the study could be achieved faster with Matlab.

3.2.4 Simulation of MAN for control and monitoring of the microgrid on OPNET

The second subtask of modelling MAN for monitoring, control and protection of the microgrid was performed on OPNET. OPNET was introduced in subsection 3.2.1. Its wireless network simulation modules were used for modelling of the protection and control communication network. This simulation is limited to Wi-Fi only.

In addition to the four studies described above, two case studies relating to projects in DSM were undertaken as part of this thesis. Their aim was to study real-life project management approaches of AMI and solar PV systems. The methods used in these case studies are explained in subsection 3.2.5 explained below.

3.2.5 Case Study 1: AMI Project Implementation

This case study reviews initial stages (project planning) of project management processes in implementation of AMI projects based on South African context. It was decided to perform research in planning of AMI projects as a case study instead of simple review of project management theories. Doing it as a case study has advantages of strengthening the findings by combining the known theories with real-life experiences in South African industry.

AMI projects are still very rare in South Africa. Hence there were not many options for sources of data. Project initiation has the most activities of all project management stages. It was therefore decided to focus more on this stage. The second reason for this choice was scarcity of data regarding these types of projects in South Africa. Thus information used came from projects that are only in their initial stages.

This task began with investigation on local companies that are involved in AMI projects. The method used to identify these companies was to first search for recently released tenders or request for proposals (RFP). It was found that the City of Tshwane was ahead with plans of deploying AMI. The project was confirmed in the city's budgeted speech in 2011 [103] [104]. The project is being implemented by Accenture which oversees project management tasks. Information used in this thesis was sourced from Eldo Energy which has working relationship with Accenture [105].

3.2.6 Case Study 2: Solar PV DG Project Design and Implementation using HOMER

The aim of this study was to apply solar PV system design approach using HOMER to a real-life project. The case study was approached in an almost similar manner of identifying companies

that are working on solar PV projects. In this case, a company called Consttec Construction based in Lesotho was approached. This company works on general building and also does work on installation of home-based small scale solar PV systems. Consttec was responding to a request for proposal (RFP) from the Africa Adaptation Program (AAP) home based solar project overseen by Lesotho Meteorological Services and Ministry of Natural Resources - Lesotho [106]. The results presented in this case study are from the project which was titled: "Supporting Integrated and Comprehensive Approaches to Climate Change Adaptation in Lesotho". The equipment prices used in the proposal were obtained from various suppliers. Project team remunerations were estimated from various enquiries to companies that have completed similar jobs. Hence they can be assumed to be market based. The project involved design and implementation of solar PV systems project for rural electrification in Lesotho. I introduced the design approach used in this thesis and described in 3.2.2 above to Consttec. This solar PV design approach, which uses HOMER, was adopted to produce a proposal on how the project can be realised.

Compared to simply requesting information as was done in the previous study, this hands-on approach gave more insight into design techniques and project management tasks that need to be performed to successfully deliver the project. More importantly, it put the HOMER based solar PV design to a real-life project test.

3.3 Analysis Methods

It was mentioned earlier that this dissertation is an empirical study that employs quantitative research methods. Thus a quantitative analysis of data was used. Numerical findings were recorded and interpreted in relation to theories learned. Graphical and statistical plots were used. Specific methods of analysis used in each of the tasks depend on the task and on the study methods used. That is, whether the study was case based or experimental simulation. For experimental studies, analysis method was determined by the simulation software platform used. Exact details of how each of the findings from the research tasks mentioned above is given below.

3.3.1 Analysis of AMI simulation on OPNET

The AMI simulation was built, compiled and run on OPNET. OPNET has a statistical analysis tool. This tool was used to obtain graphical simulation results that were comparatively analysed. It allows the network designer to choose from a set of statistics, a network statistic they want to monitor. The statistics are performance measures of the network. Examples of these

performance metrics available in OPNET are network latency, utilisation, throughput, packet loss, etc.

3.3.2 Analysis of solar PV systems feasibility study simulation on HOMER

The PV simulation on HOMER focused on feasibility of PV systems as an option for curbing impacts of peak demand on the main grid. HOMER computes sensitivity analysis of different configurations of PV systems that can most effectively meet the load and achieve the said aim. The analysis will calculate the levelised cost of energy of the solar PV system and net present cost as explained in subsection 3.2.2 above.

3.3.3 Analysis of solar PV protection simulation on MATLAB

A grid-connected solar PV system was built on MATLAB. The aim of this task was to simulate differential protection technique applied at the PCC of the grid and the PV microgrid. Therefore a three phase fault was injected in the grid and current was monitored on the three phases with a scope. The current changes were then plotted on a graph. Analysis of the differential current protection method was therefore based on the graphical plots obtained from current readings by the scope (current sensor). The data collected by the current sensors in relays would then be sent to a central database through communication networks in a complete system.

3.3.4 Analysis of MAN for protection of microgrids simulation on OPNET

Analysis of the MAN network was done on OPNET. Build-in network performance analysis features in OPNET were used to analyse suitability of the network. The analysis was based on the ability of the network to meet guidelines provided by SEMI F47 standards. Thus the analysis was both numerical and graphical.

3.3.5 Case study on AMI project management

This study is a qualitative review of project management approach used on a real-life project. Analysis of the information comments on the conformance of the project management practiced in the studied case to project management theories.

3.3.6 Case Study on Solar PV project management

The case study on solar PV focused on design of real-life solar PV system in response to a request for proposals. Hence data was sourced from this RFP. The analysis of this study was therefore a qualitative record of experiences and meanings of the findings.

4 *Design of Software Simulations*

This chapter presents design of the simulations covered in order to study the DSM programmes proposed in this thesis. The aim of the simulations is to model the proposed DSM technologies. The simulations were focused on finding solutions to the most critical issues related to each of the presented technologies. Therefore AMI integration discussion concentrates on supporting communication networks. Integration of domestic solar PV discusses grid security and protection issues. It presents a design of grid protection scheme that solves the identified issues. One of the important aspects to be covered is the viability of the proposed DSM methods. A feasible implementation of AMI in South African context is highlighted. A more detailed design of a viability study of domestic solar PV integration is presented in this chapter.

4.1 **Design of AMI network simulation**

This section entails a description of the design background, motivation, objectives of the simulation and the actual design of the AMI network. Furthermore, the actual design presents architecture of the proposed MPLS network. This section commences with a design background in subsection 4.1.1. Objectives of the design are expounded in subsection 4.1.2. Subsection 4.1.3 describes the network simulation design process. The architecture of the designed network is presented in 4.1.4. Subsection 4.1.5 concludes the AMI design discussion by considering a real-life implementation of AMI network in South Africa. This conclusion is based on the work I did in [107].

4.1.1 **Design Background**

As indicated in Section 2.4, smart grid applications have heterogeneous communication network requirements. The simulated network attempts cater for these specific requirements. Table 4-A below shows the applications that the AMI network should support. Wenpeng Luan et al (2010) defined three categories of AMI traffic. It is traffic from AMI meters, grid control and monitoring and advanced applications (such as load control) [16]. He further argued that the initial step in planning AMI communication network is understanding traffic profiles of AMI applications in order to decide on the capacity required [16]. The simulation described in this section is based on the work done by Kenneth C. Budka et al (2010) [18]. In his paper, Budka has done a

detailed quantitative comparison of network requirements of smart grid applications. This work motivated the focus of the simulations described in this section. Thus for clarity, the table below quotes the AMI communication network requirements stipulated in Budka's paper. Applications that are of greater interest for the purpose of this thesis are highlighted in bold in the table. The table also shows network scope required by the applications (that is, whether the network is peer to peer (P2P) or hub spoke (HS)), data rates/data volume (amount of data generated by the application), latency the application can allow, required reliability, and security requirements.

Table 4-A. Smart Grid Communication Network Properties [18].

Applications	Scope (HS or P2P)	Data Rate/Data Volume (At Endpoint)	(One Way) Latency Allowance	Reliability	Security
Smart metering	HS	Low/very low	High	Medium	High
Teleprotection	P2P	High/low	Very low	Very high	Very high
SCADA	P2P, HS	Medium/low	Low	High	High
Operations data	HS	Medium/low	Low	High	High
Distribution Automation	HS, P2P	Low/low	Low	High	High
DE management & control (ADR, Storage, PEV, PHEV)	HS, P2P	Medium/low	Low	High	High
Video surveillance	HS	High/medium	Medium	High	high
Microgrid management	HS, P2P	High/low	Low	High	High
Corporate data	HS	Medium/low	Medium	Medium	Medium
Corporate voice	P2P	Low/very low	Low	High	Medium
Mobile workforce (push-to-x)	HS	Low/low	Low	High	High

Legend:

ADR – Automated demand response
 DE – Distributed energy
 EMS – Energy management system
 HS – Hub-spoke
 P2P – Peer-to-peer
 P(H)EV – Plug-in (hybrid) electric vehicle
 SCADA – Supervisory control and data acquisition.

The column on “data rate/data volume” from the table above indicates that all smart grid applications are LOW on data volume with the exception of substation video surveillance.

Nevertheless, quality of service requirements especially latency, reliability and security are stringent. These factors reflect the heterogeneity expressed repeatedly in this dissertation. It was highlighted in subsection 2.7.3 that one of AMI implementation challenges is deciding on networking approach. The important decision to make is whether a utility should construct their own communication network infrastructure or whether they should connect their AMI via existing network service providers (NSPs). This question was answered by the work I did in [107]. Utilisation of a dedicated smart grid communication network was found to be very low. Based on the work reported on in this paper, this section investigates implementation of AMI on a NSP's infrastructure.

Furthermore, it was highlighted in subsection 2.7.4 that the motive is for utilities to reuse most of their existing communication networks infrastructure. In [107], it was established that cost of implementation of the chosen networking approach, network utilisation and AMI QoS requirements play an important role. It is for this reason that a converged network that supports applications with varying QoS requirements and multiple networking protocols was chosen for investigation in this thesis. The converged network to be investigated is MPLS. MPLS will allow NSPs to connect many customers that run diverse applications over one network.

4.1.2 Objectives of the AIM network simulation

The aim of the simulation was to compare the performance metrics of pure IP based network with that of MPLS to determine whether MPLS has an advantage of better performance than a pure IP network. Thus, the simulation was divided into two OPNET scenarios: the pure IP case and the MPLS case.

Performance metrics to be evaluated in this simulation are latency (end to end delay) and reliability (end to end delay variation, number of hops). Latency is a measure of time delay for a packet to travel from a source (smart meter) to a destination. It is therefore a measure of whether the AMI system based on the simulated network will be able to meet very low latency requirements of applications such as tele-protection. Reliability of the network was determined by monitoring congestion and throughput across the network. Congestion inhibits optimal flow of packets through the network. This lowers end-to-end throughput of the network. Hence the network becomes unreliable as some data packets are lost while others are delayed. Furthermore, MPLS's traffic engineering mechanisms will be simulated in an attempt to support edge-to-edge service levels. OPNET 14.5 network simulation platform was used to design the both the IP network and the MPLS networks. Two scenarios were created to represent the two

study cases: the pure IP network and the MPLS network. The main difference in the two simulated scenarios is that the pure IP scenario has no traffic engineering while the MPLS scenario includes traffic engineering. Hence the results and discussions in Chapter 5 will report on the effect of TE in bettering the performance of the network. Subsection 4.1.3 and 4.1.4 below describe the procedure followed in carrying-out the simulations.

4.1.3 IP Network architecture design on OPNET: Scenario 1

Scenario 1 is considered as the benchmarking scenario. The benchmark IP network was designed first. Figure 4-1 below illustrates the IP network built in OPNET. Smart meters and relays are the most important nodes in energy management applications hence DSM. For simplicity of the simulation, the network design is such that three utility DSM and grid control subnets (marked by the red circles) and a portion of head-office LAN responsible for energy management are shown. The assumption is that this network belongs to a NSP who has other clients' networks connected via their core network as indicated by the clouds labelled Net 1, Net 2, and Net 3. Net 1, Net 2, and Net 3 can be academic institution network, enterprise networks, etc. Another simplification of the design done for the purpose of the simulation is within the core network. The core network consists of five IP routers connecting the four utility subnets. In this dissertation, interest is on data flowing from nodes within the utility DSM, grid control and monitoring subnets to the MDMS.

Each of the utility subnets shown has three smart meters and a relay. This is a representation of the common network nodes in a smart grid. The number and the types of nodes may differ in real-life. As would be the case in a real network, the end nodes (smart meter and relays) are connected to network switches which also connect to the backhaul network through gateway routers (IPR_1, IPR_7, IPR_8 and IPR_9). The gateway router performs routing functions of the subnet. Among other features, they host network address translation (NAT) protocol which supports storage of addresses of the nodes within the subnets and broadcasts them to the neighbouring routers. This is the configuration used in each of the utility subnets in Figure 4-1. The other subnet (circled in yellow at the bottom of the figure) is the LAN at the utility office. It consists of a MDMS database, a workstation to be used by load management stuff, a workstation for grid protection and monitoring team, and the third workstation for billing stuff. Again, these are a subset of the AMI components shown in Figure 2-5.

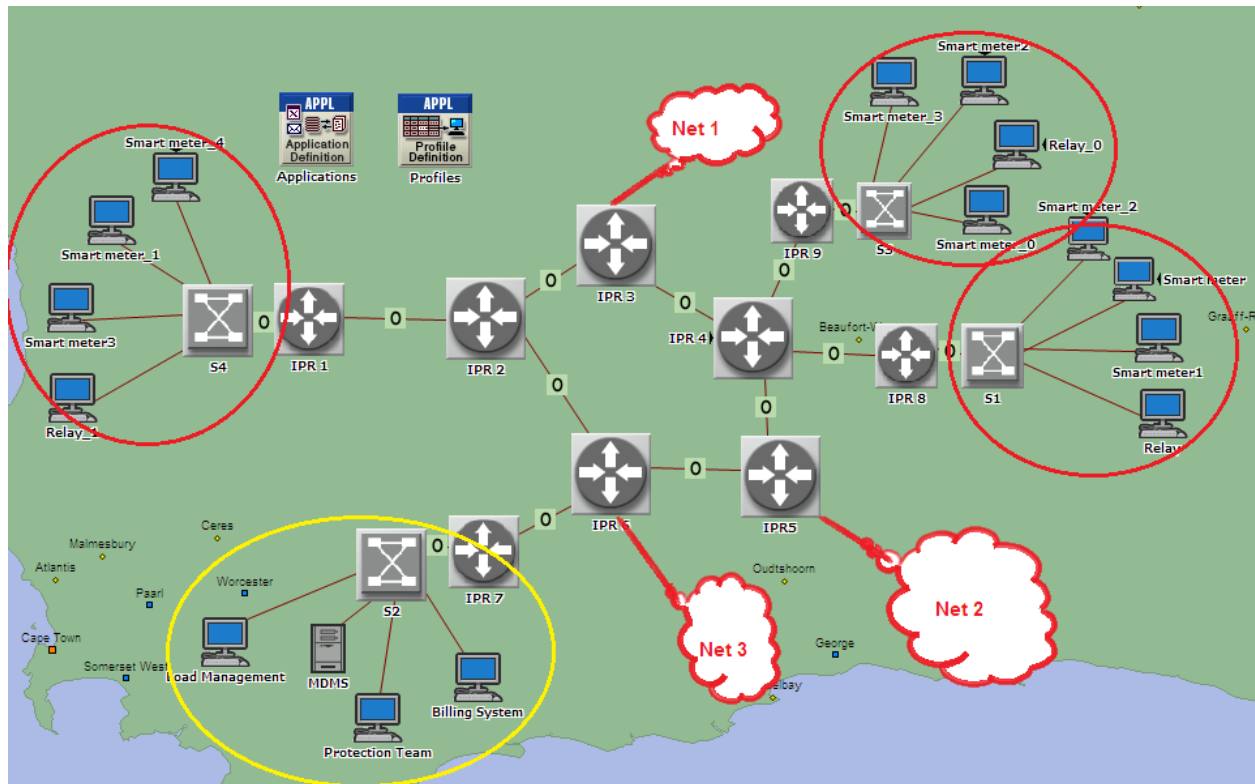


Figure 4-1. Structure of IP based AMI network.

As indicated, OPNET does not have build-in smart meter clients and MDMSs. These components were built from custom end nodes and servers respectively. Moreover, the clients in the utility head office LAN were configured to support the following applications: Hyper text transfer protocol (http), File transfer protocol (ftp), video and VoIP. These are common elements in any communication network. They were added to create background traffic to make the simulation closely model a real world situation. Including these nodes was necessary because as mentioned, the simulated network belongs to a NSP who has many other applications from various clients. Hence the outcome of this simulation will indicate whether NSP can support the proposed energy management systems.

The backhaul network was connected with 1000Base-X gigabit Ethernet optic fibre links. All the clients within the subnets were connected to the switches using a 100 Mbps Ethernet links. The switches were also connected to the gateway routers with 100 Mbps links. Also necessary to point out are the two modules at the top of Figure 4-1 shown above. The modules are applications, and profiles configuration. The applications configuration model defines the type of services that the network is to support. As highlighted above, the network was configured to support all network services that a normal communications network carries. These are http,

voice over IP, ftp, email, etc. In addition to these, the network was configured to support databases as this is an important application for AMI. The MDMS hosts a database of smart meters data. The profiles configuration module allows a network designer to choose the type of service profiles that the network is to support. There are many profiles that can be set: academic, engineering, enterprise, etc. In the case of the simulated NSP's network, it was assumed that the network should be able support all of these profiles as the NSP may have different customers connected over the same physical network. Hence the simulated network was configured to support all the profiles. The IP network simulation defined above is the first scenario of the simulation. The second scenario built was the MPLS network simulation. The design of this network is described in subsection 4.1.4 below.

4.1.4 MPLS network architecture design on OPNET: Scenarios 2

The MPLS network was structured in a manner that mimics the IP network described above. This is a design choice made so that there was a fair comparison between the IP network scenario and the MPLS network scenario. Hence the networks in both scenarios had the same number of nodes. The MPLS network shown in Figure 4-2 below also has four subnets: three DSM, control and monitoring subnets (highlighted by the red circles) and the head office LAN (circled in yellow).

The difference in the two networks is in the core. In the IP network, the core network consists of IP routers whereas the core of the MPLS network is made of label switch routers (LSRs). The other unique nodes in the MPLS network are the label edge routers (LERs). The LERs perform the functions of the gateway routers mentioned in the previous section. In addition to these functions, their main responsibility is to encapsulate IP packets from the sending nodes into MPLS frames. They also “push” these frames into respective label switched paths (LSPs) depending on their destination. The function of encapsulating packets into frames and pushing them into the MPLS network is done by a class of LERs called Ingress LERs. At the exit of the MPLS network, the LERs are called Egress LERs. Their responsibility is to “pop” the IP packets within the MPLS frames by removing the labels and sending the packets to the appropriate destination nodes using their IP addresses. In Figure 4-2 below, the LER connected to the switches with the subnets are LER 1, LER 2, LER 3 and LER 4. On the other hand, LSRs forming the core network determine the FECs which to associated incoming MPLS frames and forward the frames to the appropriate LSPs depending on these FECs.

The configuration modules have also increased to three as shown in the figure below. In addition to the applications and profiles configuration modules, there is a MPLS configuration module. In both scenarios, the networks were configured to support open shortest path first (OSPF) routing algorithm.

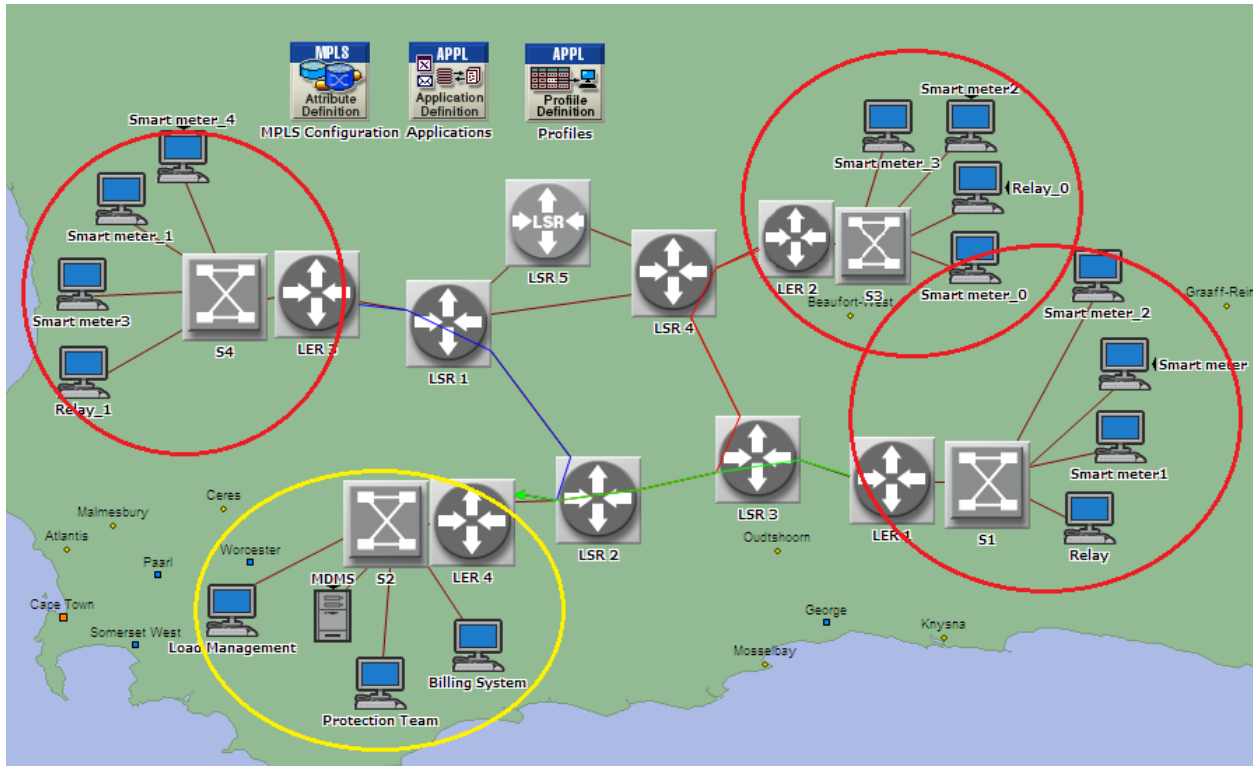


Figure 4-2. Structure of MPLS based AMI network.

Section 4.1 above described the design of the backhaul network for the proposed AMI system. It established how the IP and MPLS network was configured. This network will be used for metering, monitoring and control of the proposed smart grid. One of the grid smartening interventions proposed by this thesis report is integration of solar PV DGs. Section 4.2 below describes design of the simulation of the proposed integration.

4.2 Design of solar PV DG simulation

Simulations on solar PV DG were done to determine feasibility of using home based solar PV DGs for curbing peak demand by supplementing power needs for new urban residential area households with solar power. The urban houses were assumed to be connected to the main grid. They were also assumed to be of similar income and hence their energy consumption is relatively equal. Subsection 4.2.1 discusses the objectives of the simulations. Background to the

simulation design is presented in subsection 4.2.2. These subsections are followed by detailed description of the actual design of the simulation.

4.2.1 Objectives of the PV DG simulation

Two simulations were performed regarding the proposed solar PV DSM solution. The models determined economic and technical feasibility of the solar PV DSM. These simulations were a viability study of grid connected PV DG systems and protection of grid connected PV DGs. Both simulations were set to address questions on economic and technical feasibility of solar PV as a DSM programme, especially for grid connected households. Therefore the general objectives of the simulations were to answer the question of economic feasibility of the proposed solution and to find a solution dealing with the known disturbances (concerning protection) that PV DGs have on the power network.

The aim of the economic feasibility study was to answer the following questions:

- What is the energy potential of solar irradiance data in the region identified for the simulated installation?
- Are grid-connected solar PV systems viable and
- what is the feasible design option?

On the other hand, the technical feasibility study endeavoured to determine applicability of differential current protection technique for grid connected PV DG. The following aspects form the core of this discussion: microgrid differential current protection, adaptive control and fault location identification. In grid-connected mode, power flow in microgrids is bi-directional. This characteristic rules out many of the traditional protection schemes based on current direction. Thus differential current protection scheme was the sole focus of the simulations.

Before discussing these two tasks separately, it is important to clarify general concepts that were considered during the design of the proposed solar PV system. Subsection 4.2.2 below presents this background information that accounts for design choices that were made.

4.2.2 Solar PV system design

There are two ways of configuring a solar system installation to give different power output suitable for differing user needs. The configuration can either be serial or parallel. Solar panels differ in solar to electrical energy conversion output. Hence they have varying voltage and current ratings. For example, a typical solar panel produces a peak voltage output of 17 volts.

Two of such panels can be connected in series to produce an effective voltage of 24V. This configuration may also be parallel. A parallel configuration of solar panels results in more power at the load (the battery bank) [108]. However, the parallel connection produces high current in larger systems. The problem of large current values produced becomes need for thicker and therefore costlier wires. Figure 4-3 below shows a configuration of a household size solar PV system. It demonstrates how the system components are wired for a domestic installation.

A home-based solar system consists of seven main components. These are solar panels, charge controller, AC breaker panel, a meter, a circuit breaker, battery bank and a power inverter. Some advanced power inverters provide an option of integrating the solar PV DG to an AC generator or to the grid. These inverters act as points of common coupling (PCC) linking the solar system to the utility grid via the AC breaker panel as shown in the figure. The charge controller's main function is to regulate battery charging to ensure that the batteries do not get over-charged. The inverter converts DC voltage from the batteries to AC voltage. E.g. it can convert 12V from the batteries to 120V AC. In grid-connected mode the inverter acts as a charge controller which charges the battery bank with power from the utility grid. This is where the bi-directional nature of power flow in microgrids is encountered. Having described the configuration of a single DG system above, the details of the system will be omitted and the system will from here be referred to as a single domestic solar system.

There were a couple of assumptions that were made in the design for the sake of the simulation. The first was that the households were taken to be of similar income group hence their energy requirements relatively equal. Each household was taken to have one of these solar systems. An ideal setup where each household would have its own PV array source supplying its own load of batteries was assumed. Thus, this would make each household system an independent and autonomous gridlet. Having each household gridlet stand on its own translates into complex wiring. It also complicates the system protection issues.

An alternative approach was then used to reduce wiring and need for complicated protection system. The chosen approach also makes the system more reliable by introducing redundancy.

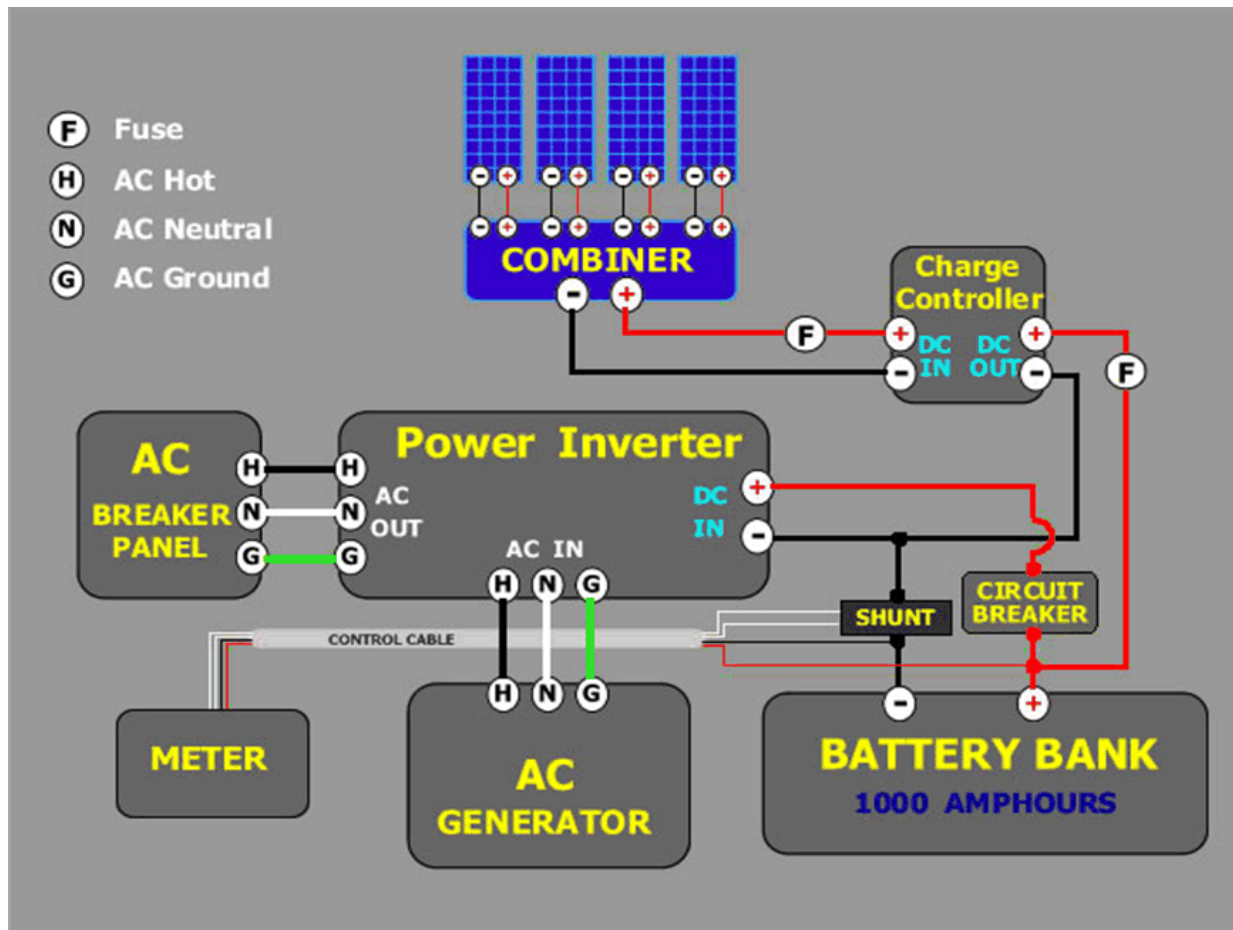


Figure 4-3. Overview of a domestic solar system [92], et al.

With this design, two to three households are combined to form one load. Moreover, this superfluous design guarantees that failure of one DG unit will be complemented by others which will share its load [83]. Figure 4-4 below demonstrates the structure of the envisaged meshed microgrid design formed out of home-based “gridlets”. The schematic diagram focuses on demonstrating the proposed meshed microgrid design and does not go deep into accurate details on connectivity. As mentioned each household will have their own solar system (SS) installed. Three of the solar systems from neighbouring houses are combined into a single system; forming a microgrid. This microgrid is then connected to the main grid.

The system shown in Figure 4-4 consists of abstracted solar systems on households, IEDs, bus bars and sections of the main utility grid. The solar panels are configured to act as a single source charging one battery bank and feeding or being fed from a single bus bar. This retains autonomy of the system and simplifies the network, unlike in a situation where each household is regarded as a separate source.

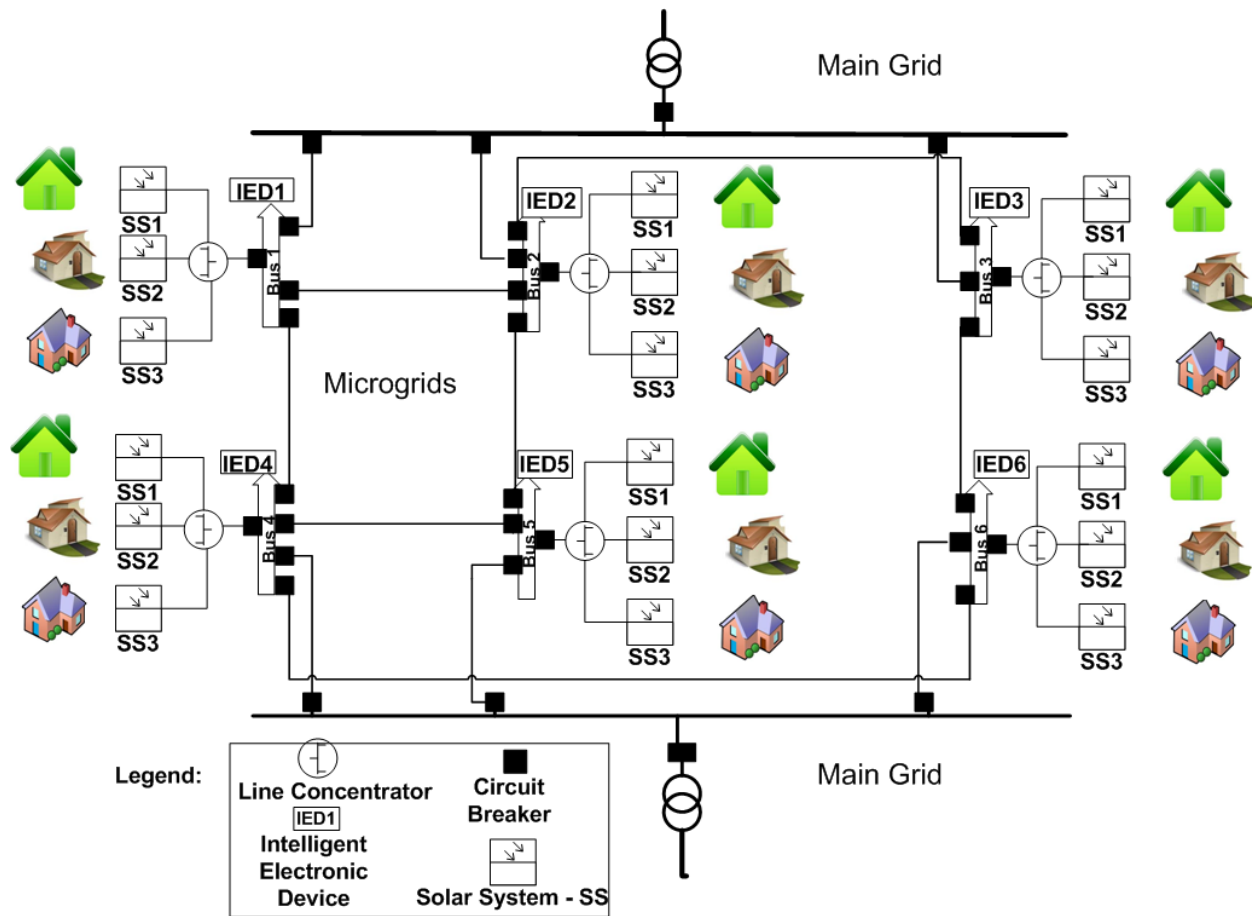


Figure 4-4. A schematic of the proposed meshed grid-connected microgrid [96].

The subsection above presented an overview of the design of the proposed grid smartening programme through integration with solar PV DGs. The following subsections delve into the core of the research questions addressed by this thesis: feasibility study and protection of grid connected solar PV systems. The two studies give an insight into the practicality of the proposed DSM programme.

4.2.3 Design of feasibility study of a grid connected solar PV DG simulation on HOMER

The capital investment required for the proposed grid connected system depends on the cost of the components and the size of the system. Thus, these costs and size are cornerstone factors of the design. Size of the system is controlled by the load that it is to serve. It can also be determined by the system developer's target renewable to conventional energy ratio. This subsection presents these design factors. It also discusses the configuration of the simulated grid connected microgrid.

The HOMER simulation discussed in this subsection considers viability of installing a solar system for a household. Thus the simulation attempts to determine if it makes economic sense to deploy home-based solar systems as a DSM alternative. To determine this viability, HOMER takes in the following main input variables: prices of the system components, solar irradiance at the proposed location where the system is to be implemented and expected load that the system is to serve. Therefore the design presented here considered these factors.

Table 4-B through to Table 4-D below presents inventory and cost prices of the components which were used as inputs to HOMER. The tables include all the main components that are needed to build a home-based solar system. A household size solar system requires the following components: solar panels, batteries, a solar regulator, an inverter, and a battery charger. However, for the simulation, the important components are solar panels, batteries, and the inverter. The component prices used in the design were sort from South Africa's online eco store, *Sustainable.co.za* [109]. For each of the components, HOMER requires that the designer provide it with component sizes in kilowatts, cost price of the component, replacement cost, and operation and maintenance cost per year.

HOMER uses US\$ currency. Hence all the prices shown in the tables are US\$ equivalents of the prices that were found from the online eco store. The US\$ to ZAR conversion exchange rate used was ZAR8.00 to US\$1.00. This was assumed to be the closest estimation of the exchange rate as it has been swinging between ZAR7.50 and ZAR8.50 in the past six months. Replacement costs of the equipment were also estimated using the current South African targeted consumer price index (CPI) of 6% [110]. Under the economic settings, HOMER was also set to use the 6% as annual interest rate for the envisaged 20 year life of the project. Thus the replacement cost was calculated as follows:

Replacement Cost = 1.06 x Current Cost Price.

Table 4-B below tabulates solar PV panel sizes, cost price of the panels, replacement cost taking CPI into consideration, and operation and maintenance (O & M) costs per year. It was assumed that maintenance requirements of the panels will be minimal hence the low budget allocated per year. The PV panels specification used in the design was not particular on PV models to be used; only the sizes mattered.

Table 4-B. Solar PV inventory and cost prices

PV Size (kW)	Cost Price (\$)	Replacement cost(\$)	O&M (\$)/yr
0.050	116	122.96	2
0.085	186	197.16	4
0.135	295	312.70	6
0.180	394	417.64	8
0.200	463	490.78	9
0.250	578	612.68	11
1.000	2312	2450.72	41
2.000	4624	4901.44	81
3.000	6936	7352.16	121
4.000	9248	9802.88	161
6.000	13872	14704.32	241
8.000	18496	19605.76	321
10.000	23120	24507.20	401
11.000	25432	26957.92	441
12.000	27744	29408.64	481
13.000	30056	31859.36	521
14.000	32368	34310.08	561

Table 4-C lists battery sizes and costs used in the simulation. The battery model used is a Trojan T-105. Specifications of the battery model are described below.

Nominal capacity = 225 Ah, Nominal voltage = 6V, Round trip efficiency = 85%, Minimum state of charge = 30%, Float life time = 10 years, Maximum charge rate = 1 A/Ah, Maximum charge current = 11 A, Lifetime throughput = 845 kWh.

Table 4-C. Battery bank inventory.

Number of Batteries	Cost Price (\$)	Replacement Cost (\$)	O & M (\$)
1	230	243.80	2
2	460	487.60	4
3	690	731.40	6
4	920	975.20	8
5	1150	1219.00	10
6	1380	1462.80	12
7	1610	1706.60	14
8	1840	1950.40	16
9	2070	2194.20	18
10	2300	2438.00	20

Table 4-D presents the converter inventory used as input to HOMER. In addition to the prices, the table also shows models that were chosen in the design. An attempt was made to include as much as possible in the design, a converter that has a build-in battery charger and AC transfer relay features. These features would allow the converter to act as a PCC for the PV system and main grid. In addition, it would charge the battery bank with power from the main grid whenever necessary.

Table 4-D. Converter inventory and cost prices.

Model	Size (kW)	Cost Price (\$)	Replacement Cost (\$)	O & M (\$/yr)
Cotek: 700W, SK700 - Pure Sine Wave	0.7	522	553.32	50
Cotek 1000W: ST1000 Sine Wave Inverter with AC transfer Relay	1.0	1053	1116.18	52
Omnipower : HT-S-1200 Sine Wave Inverter	1.2	631	668.86	53
Cotek 1500W: ST1500 Sine Wave Inverter with AC transfer Relay	1.5	1393	1476.58	56
Cotek 2000W: ST2000 Sine Wave Inverter with AC transfer Relay	2.0	1936	2052.16	60
Victron: Multiplus 3000W Pure Sinewave Inverter/Charger	3.0	2605	2761.30	70

Having presented specifications of the system components that were considered in the design, configuration of these components by HOMER is given in the figures below. Figure 4-5 and Figure 4-6 below show snapshots of schematic diagrams from HOMER. Looking at the configurations shown in the figures from right to left, they consist of a solar PVs connected to a battery bank via a DC bus. There is a converter which rectifies power from the national grid, converting it to DC power that charges the battery bank in the absence of sunshine. The converter also serves as an inverter which converts the DC power from the PV supply to AC to feed the residential AC load. The AC power from the converter is connected to an AC bus which connects the residential load and the main grid. The configurations in both individualised system and the integrated system are similar. The only difference is in the load served. Hence sizes of the components. As can be seen in Figure 4-5 below, the primary load of a single house is 26kWh/day with a pick demand of 2.4kW. On the hand, the integrated system serves a primary

load of 77kWh/day with peak demand of 7.3kW where load of the three households is integrated as shown by Figure 4-6 below.

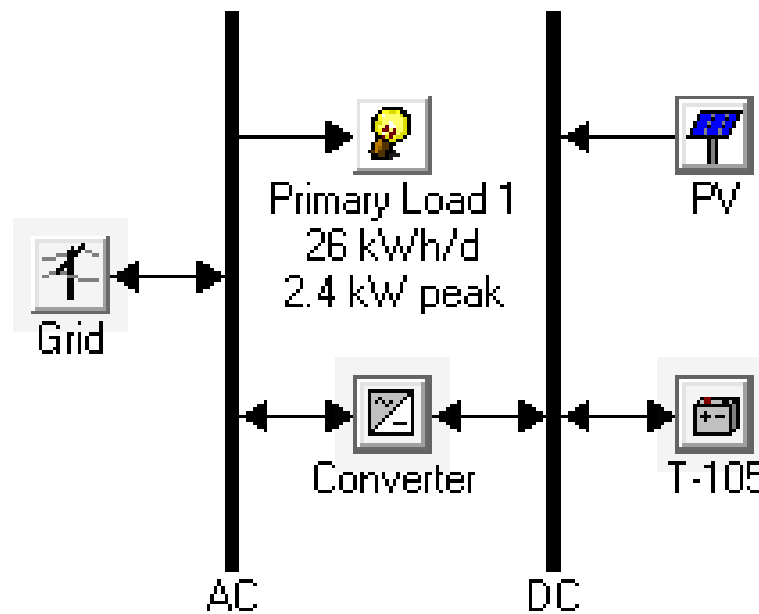


Figure 4-5. A HOMER configuration of the home-based solar system simulation.

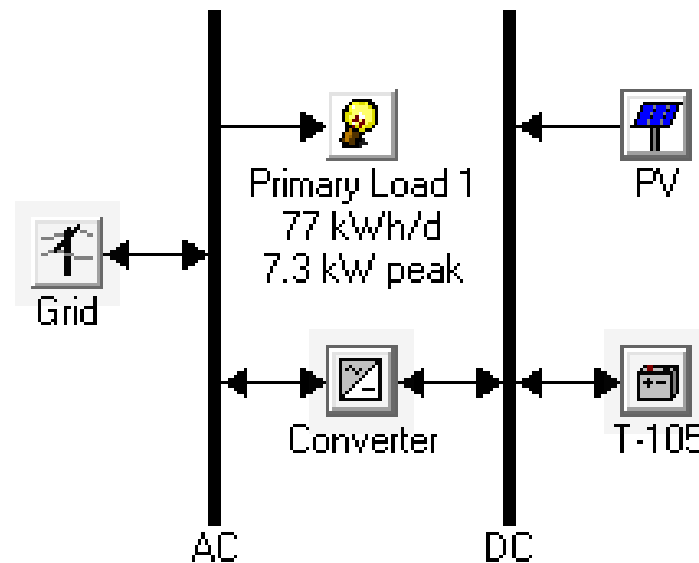


Figure 4-6. Configuration of a 3-house integrated system.

As highlighted above, solar irradiance is a crucial input for HOMER to perform sensitivity analysis of the system. Table 4-E below lists monthly averages of clearness index and available solar irradiation used in the design for the proposed location. Solar irradiance is an integral

measure of solar irradiation that can be converted to electrical energy per square meter of a collector (PV cell) in a day. It consists of direct beam component and diffuse beam component of the global irradiation that falls on a horizontal surface of the earth. Clearness index is the ratio of average global irradiation to extraterrestrial daily irradiation [111]. Thus the higher the clearness index and solar irradiation values, the greater the energy generation potential. The work presented by Kryza et. al in [112] explains how solar irradiance is calculated.

Table 4-E. Average monthly clearness index and solar irradiation.

Month	Clearness Index	Solar Irradiation(kWh/m ² /d)
January	0.626	7.505
February	0.610	6.648
March	0.589	5.370
April	0.559	3.929
May	0.543	2.902
June	0.532	2.429
July	0.513	2.514
August	0.536	3.372
September	0.526	4.352
October	0.569	5.832
November	0.613	7.143
December	0.612	7.513

Figure 4-7 below is a graphical plot of the data in Table 4-E above. The red line represents clearness indices throughout the year. The bar graph plots average daily radiation on a monthly basis throughout the year. Clearly indicated by the plots is the radiation pattern in the site used for the design. There is high energy potential in November, December, January and February. June and July experience the lowest radiation hence low solar energy generation potential.

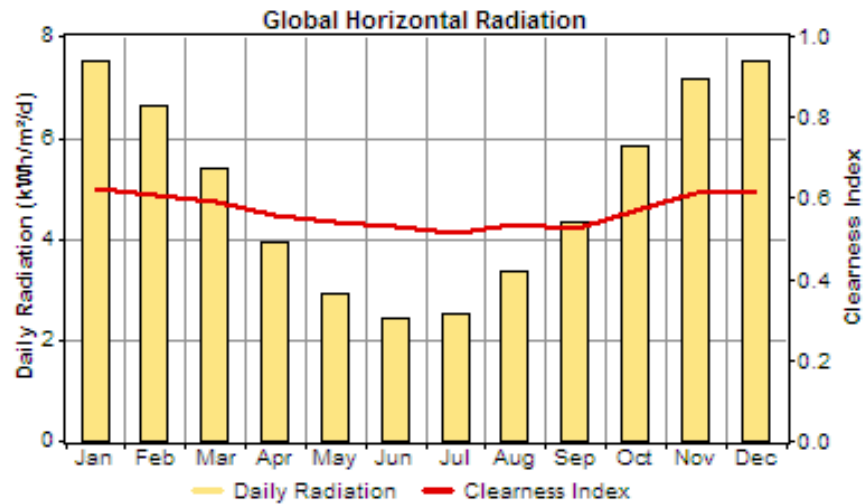


Figure 4-7. Global horizontal radiation for the site used.

In [96], an economic sector breakdown of energy consumption is given. The paper shows that 36.8% of South Africa's energy production is consumed by residential segment.

Table 4-F below lists City of Cape Town's hourly energy consumption. Therefore residential load for the city was estimated as 36% of the total city's consumption. As shown in [96], the residential load was estimated as thus:

Residential load = City Cape Town Load x 36.8%.

Average consumption of a mid-income household is 774kWh per month [113]. Hourly energy demand of each house was calculated based on this value as thus:

Estimated average load per day for each household is $774/30 = 25.8$ kWh. The number of days in a month was taken to be 30 in the calculation.

Nevertheless, to calculate the hourly consumption using the data sort from the City of Cape Town required the number of households in the city be estimated. This estimation was calculated as follows:

No. of households = Total Residential load per day (kWh)/Average load of a household per day (kWh).

$(5713.2 \times 10^3) / 25.8 = 221441.86 = 221442$ households.

The number of households was used to estimate amount of energy consumed by one household in an hour. These are the values that HOMER takes as its input for sensitivity analysis calculations. Hourly demand for a household was calculated using the following formula.

Hourly load per household = Hourly residential load (kWh)/No. of households [96].

As explained above, the study discussed here focuses on determining viability of the proposed meshed microgrid system. As shown in Figure 4-4, the system consists of PV systems installed on three households being integrated to service one battery bank load which then serves the three houses. Advantages of this structure were discussed in [96], and further in highlighted subsection 4.2.2 above. The number of integrated households can be anything more than two. However, this study investigates integration of systems on three houses and compares the results to a system consisting of individualised grid-connected systems.

The first column in the table below is the hour of the day, the second column lists average load of Cape Town at the said hour of the day, and the third column is the portion of the load which is residential, measured in mega-watt hours (MWh). Load per household in kilowatt hours (kWh) is shown in column three while the last column shows load for the three households whose PV systems were integrated into a microgrid.

Table 4-F. Load profile of a typical household for the proposed area.

Time of Day	Cape Town's Load (MWh)	Residential Load (MWh)	Load Per Household (kWh)	Load for 3 Households (kWh)
01:00	400	147.20	0.664734	1.994202
02:00	375	138.00	0.623188	1.869564
03:00	350	128.80	0.581642	1.744926
04:00	360	132.48	0.598260	1.794780
05:00	375	138.00	0.623188	1.869564
06:00	650	239.20	1.080193	3.240579
07:00	775	285.20	1.287922	3.863766
08:00	800	294.40	1.329468	3.988404
09:00	810	298.08	1.346086	4.038258
10:00	800	294.40	1.329468	3.988404
11:00	775	285.20	1.287922	3.863766
12:00	750	276.00	1.246376	3.739128
13:00	730	268.64	1.213139	3.639417
14:00	725	266.80	1.204830	3.614490
15:00	720	264.96	1.196521	3.589563
16:00	705	259.44	1.171593	3.514779
17:00	700	257.60	1.163284	3.489852
18:00	825	303.60	1.371014	4.113042
19:00	800	294.40	1.329468	3.988404
20:00	750	276.00	1.246376	3.739128
21:00	700	257.60	1.163284	3.489852
22:00	650	239.20	1.080193	3.240579
23:00	550	202.40	0.914009	2.742027
00:00	450	165.60	0.747826	2.243478
Total	15525	5713.20	25.79998	77.39994

The hourly load profile for the three households whose PV systems were integrated is shown in the bar graph below. The profile of a single house is similar; however it is 1/3 of the load shown in the figure below.

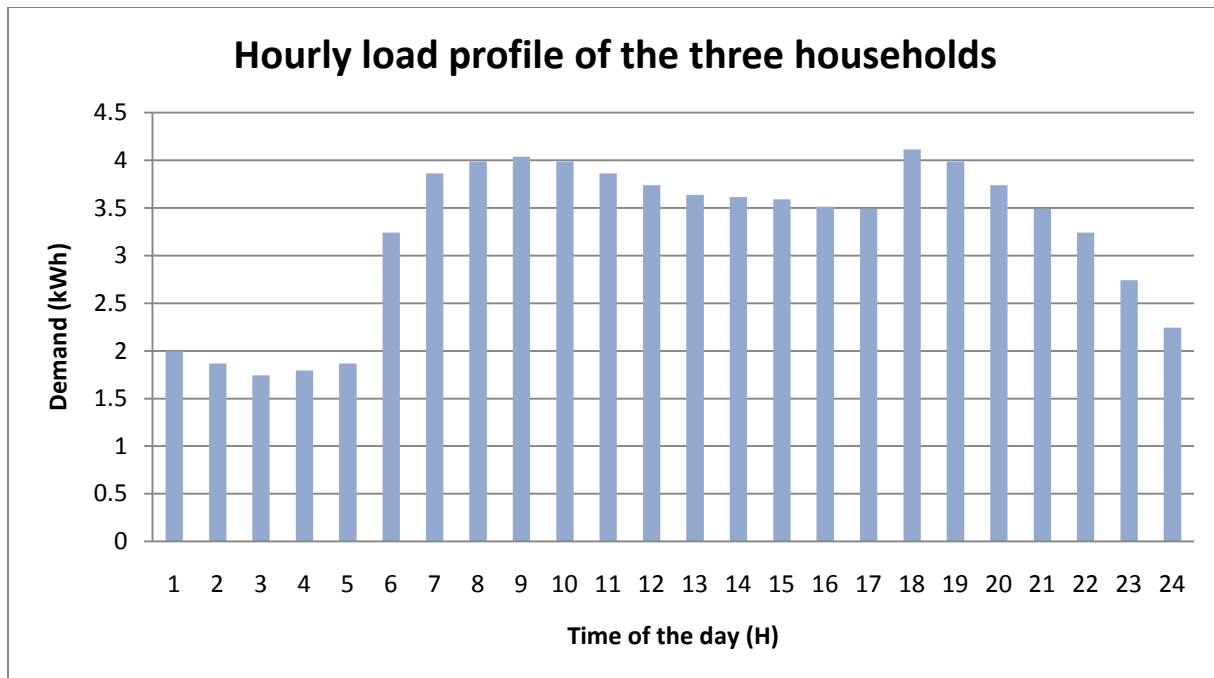


Figure 4-8. Hourly load profile of the three households.

It is important to mention some of the assumptions that the above design choices made. As was highlighted, it was assumed that CPI is 6%. A further assumption is that this CPI will sustain for a period of 20 years which is the presupposed lifetime of the systems. This assumption affects the prices of the components, hence replacement and O & M costs. Secondly, the design takes solar resources to be consistent every month of the twenty years of the project life. The third assumption made was that all the three households will have similar load profile. It was further assumed that the sell back price (REFIT) of energy for the PV systems of magnitude 100 kWh and less will be the \$0.291 defined for systems of 1MW magnitude. Finally, the load profiles of the households are assumed not to grow in the 20 year lifespan of the project.

Design of the feasibility study of solar PV systems is set. The discussion on the design of the simulations on solar PV explores protection of the proposed grid-connected PV system in subsection 4.2.4 below. Protection and control of the PV system was identified as one of the crucial issues of concern in the proposed DSM of household solutions.

4.2.4 Design of protection of a grid connected solar PV DG simulation on MATLAB

It was highlighted in subsection 2.10.1 that many researchers established that grid connected microgrids suffer a variety of contingencies which compromise quality of power produced. A range of protection schemes that have been proposed by many researchers were discussed in

subsection 2.10.3. Evolution and improvements in protection technology has brought changes that incorporate new capabilities in these protection schemes. As was mentioned, the current era of protection schemes is the one that uses IEDs to monitor conditions of the power grid and transmit measured readings of the conditions via a speedy communication network to central control server. This configuration creates a self-healing and adaptive protection and control system. The adaptive protection and control system consists of measurement of network variables and communication of those to the central Control Centre. Thus the focus of this section is measurement of differential current and its ability to help determine contingencies in the power grid. This scheme was chosen because of its simplicity and versatility. Thus the setup of the model grid used to simulate the scheme is described below.

Figure 4-9 illustrates a grid connected solar PV system built on Matlab Simulink. The model was used for the demonstration of different components of a grid connected solar PV system. The simulation described here focused on protecting a single PCC to demonstrate concepts involved in differential protection. The PCC is represented by bus bar B1 shown in the illustration below. The proposed meshed microgrid in Figure 4-5 shows that there will be many of these PCCs. The differential protection principle can be combined with new protection concepts such as wide area monitoring, protection and control through the support of communication networks described in 4.2.5 below. The combination supports a seamless protection of the entire grid through coordination and communication between the PCCs.

The illustration in Figure 4-9 was used to assess differential current protection of the grid connected solar PV system. The system consists of the irradiance model, PV cell model, inverter model with maximum power point tracking (MPPT), voltage solar charge (VSC) controller and a bus/substation model which is the protected PCC. The modelled grid has two sections: the microgrid section and the main grid section. Each section has current sensors monitoring current changes on either sides of the PCC. The irradiance model represents randomised solar energy reaching the solar PVs to be converted into electricity. The PV model mimics properties of a solar panel. A solar panel produces a direct current, the inverter is incorporated to convert the DC power to AC so that it can be synchronised with the AC in the main grid. The system also has the MPPT mechanism which attempts to increase efficiency of conversion of solar energy to electrical energy. The microgrid and the main grid are separated by a bus (substation) which serves as the PCC.

The simulation modelled two scenarios which were compared: 1) no-fault scenario and 2) a three-phase fault scenario. Normal operation of the grid was modelled with the no-fault scenario. Figure 4-10 below shows two three-phase V-I (voltage - current) measurement units around the bus bar. These represent functions of IEDs. The IEDs were simply used to monitor the PCC by measuring current flowing across B1. Thus measurements of the state of current between the solar PV microgrid and the PCC (bus bar B1) and between the PCC and the main grid were read at regular intervals. The currents on the three phases were monitored by PV-B1 and B1-Grid scopes as illustrated in the figures below.

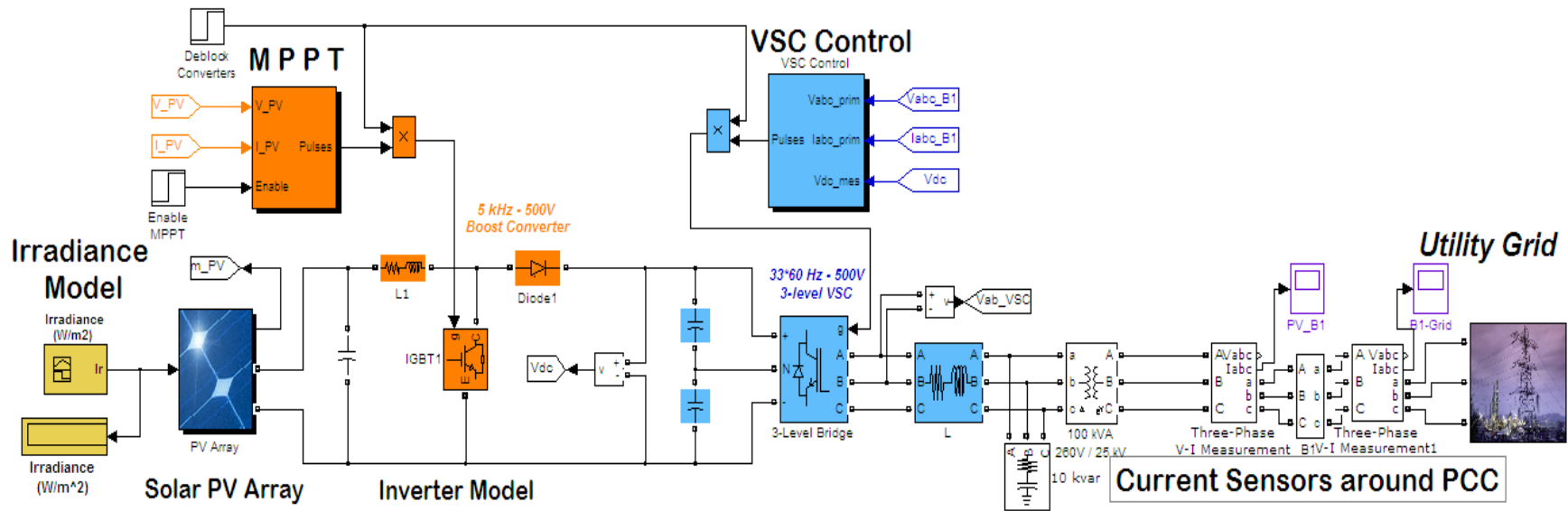


Figure 4-9. The schematic of a grid connected solar PV system.

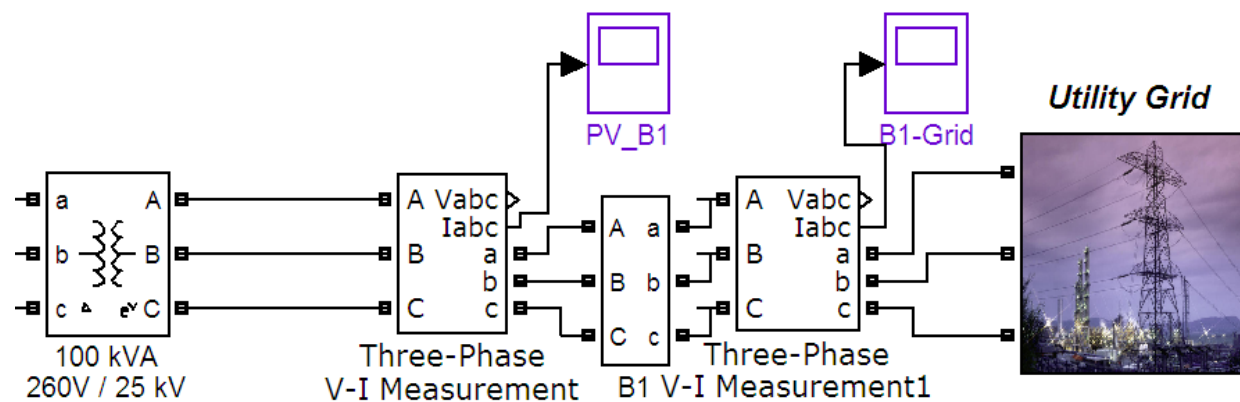


Figure 4-10. Benchmarking scenario where there is no fault in the network.

The second scenario (illustrated in Figure 4-11 below) represented a situation where there is a fault in the PV system side of the grid. This situation was modelled by injecting a three-phase fault in the PV side of the integrated grid so that it is detected by the IEDs on the microgrid side. Figure 4-11 shows a snapshot of the second scenario.

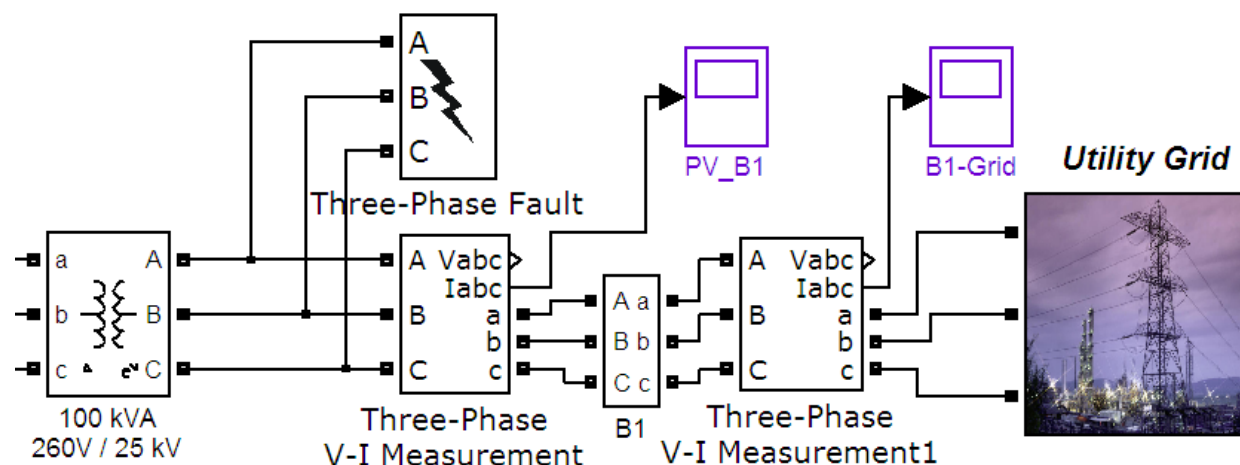


Figure 4-11. Fault scenario with 3-phase fault injected.

The V-I measurements data read by the IEDs is then communicated with the central control station or between relays monitoring different PCCs and other protected grid elements. The communication modules supporting this function are **not** shown in Figure 4-9 through to Figure 4-11 above. The figures demonstrated voltage and current sensing models. Data from the

models is sent to intelligent digital relays that have communication support. Subsection 4.2.5 below introduces and discusses design of a wireless communication network supporting protection of grid integrated PV systems.

4.2.5 Design of MAN for protection of microgrids simulation on OPNET

As indicated in Figure 2-11, the backbone of new control and protection schemes based on new digital relays is a communication network. This section therefore discusses a design used to investigate feasibility of using wireless fidelity (Wi-Fi) for a metropolitan area network of intelligent digital relays used in meshed network architecture of a microgrid. Supervisory control and data acquisition applications were traditionally based on power-line carrier (PLC) networks. Nevertheless, the meshed structure of the proposed microgrid makes this approach complicate the power network. It involves installation of many devices such as signal traps and PLC modules on the many buses of the network. Thus a wireless network such as Wi-Fi is a flexible and simpler solution. Moreover, an added advantage is that Wi-Fi will allow fault location identification through use of triangulation methods.

The MAN simulation involved building a Wi-Fi network on OPNET as shown in Figure 4-12. This network consists of one microgrid controller node and several IEDs connected to the controller station. The IEDs usually monitor frequency, current and voltage state in the microgrid and send the information to the controller station in real-time. Figure 4-12 below illustrates the proposed wireless network built (NB. The network is wireless, the lines demonstrate the formation of triangles which are the basis of triangulation method of locating the area of a fault). The design has a microgrid control agent station (MCAS) placed at the centre of the IEDs to make the triangles apparent. In a real-life application, the structure would be irregular yet the triangles can still be deduced. Thus, this simple design of the structure of the model illustrates how triangulation can be applied as shown by a layer of triangles in the figure.

The modelled network consists of a local MCAS representing a centre node. This node was also configured to serve as an access point that would connect the MAN subnets to the wired core network that transmits data to the central control station located at utility's head office. The core network proposed is based on MPLS VPN protocols as described under AMI above. The other nodes surrounding the MCAS represent the IEDs on different buses of point of common contact (PCC) and other protected grid units. The IEDs are collecting information about the state of the power network at PCCs. This information is continuously transmitted to the MCAS which decides actions to be taken by relays at these PCCs depending on the conditions determined

from the data received. The other two nodes at the bottom-right of Figure 4-12 are profile configuration and application configuration nodes. These are used in the modeller to configure network profile characteristics and features of the application to run on the modelled network.

The network was designed to support an Engineering profile as protection and control activities match best with this profile. OPNET does not have a default definition of protection and control application as it does with HTTP, FTP, email, VoIP etc. Thus for the purpose of this demonstration, light video application was used as it resembles most of the characteristics of control data such as being real-time and requiring strict level of quality of service. The aim of the design described here was to determine the effects of bandwidth, number of nodes connected to a single MCAS and distance of the IED from the MCAS. These design factors were identified as having notable effect on data transmission delay. Thus, two Wi-Fi scenarios were simulated: 11Mbps and 36Mbps networks. Wi-Fi technologies have bandwidth ranging from 1 Mbps to 56 Mbps. The other factor that was varied is the transmission power of the IED nodes. The first case used 0.001 watts while the second case used 0.03 watts.

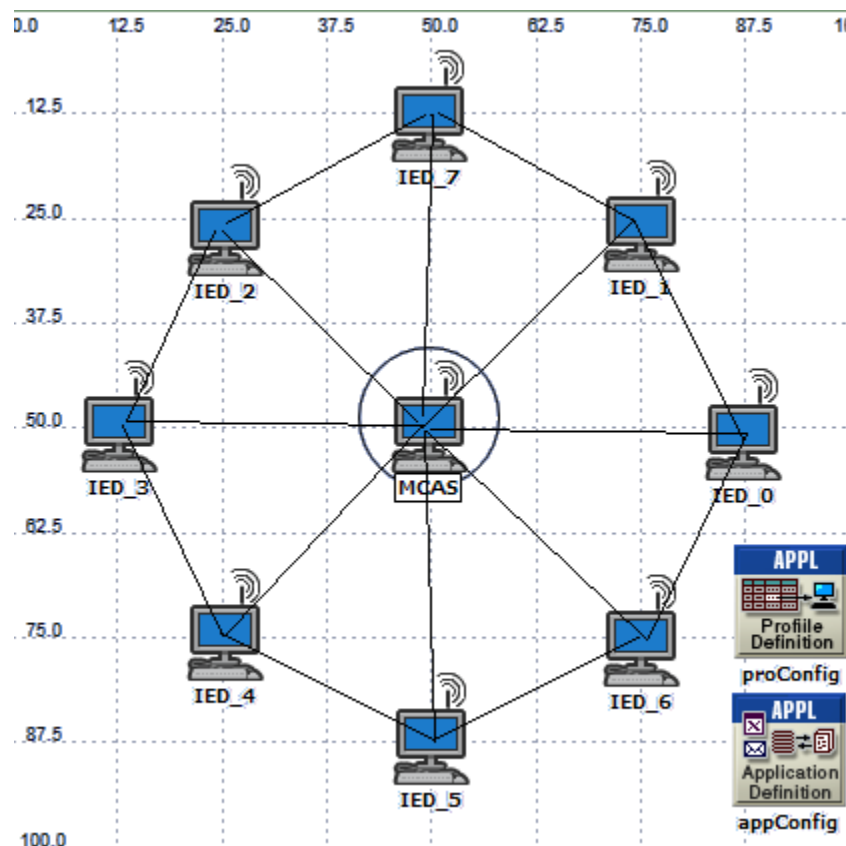


Figure 4-12. A network of IEDs communicating via Wi-Fi.

This chapter presented design rationale and procedures pertaining all the studies and simulations of the proposed AMI and grid-connected solar PV microgrid DSM systems. The chapter presented design of the proposed MPLS based AMI WAN and compared its performance to IP based network. The chapter also looked at design of a viable design configuration for household based solar PV microgrids. Furthermore, a MAN for control, protection and monitoring of the proposed microgrids was also designed and presented in this chapter. Chapter 5 below presents and discusses results from the simulations designed in this chapter.

5 Results and Discussions

This chapter discusses the results from the simulations of the two proposed demand side management programmes. The thesis looked at various aspects concerning implementation of these DSM programmes. The programmes simulated are; 1) AMI and 2) grid-connected solar PV. Critical aspects of the programmes were turned into research questions which led to the simulations whose results are presented in this chapter. The chapter follows the similar structure that the other chapters took. The first question addressed is on implementation of AMI; focusing more connectivity. Chapter 3 discussed methods used to answer the question of connectivity of AMI in subsection 3.2.1. Chapter 4 followed with a discussion of the design of the simulations performed Section 4.1. Having answered the question of connectivity of AMI, the second question was whether the proposed grid-connected PV system is a feasible solution; both economically and technically. Methods used to answer these questions and the designs of the simulation that validate the propositions were described in Chapter 3, subsection 3.2.2 and Chapter 4, subsection 4.2.4 respectively. The culmination of the said discussions is this chapter which presents the results obtained from the simulations.

The rest of this chapter is organised as follows. Section 5.1 presents results from AMI network implementation simulations. It is followed by a discussion of the results on feasibility of the grid-connected PV DGs. The feasibility study simulated two facets of the system: economic feasibility and technical feasibility (looking at protection issues). Results from the first facet on economic feasibility are presented and discussed in Section 5.2. The technical feasibility looked at implementation of differential protection scheme and a metropolitan area network for control, monitoring and protection. Results from these simulations are given in Section 5.3 and Section 5.4 respectively.

5.1 AMI network implementation on OPNET

The objectives of the simulations whose results are presented here were described in detail in subsection 4.1.2. The main objective was to compare performance of IP and MPLS based AMI networks. Thus, performance statistics of these network protocols were compared. This section presents three sets of performance metrics statistics that were collected for comparison of the

two protocols. The statistics sets are: end to end delay, end to end delay variation and number of hops. These statistics were chosen because they test the network's conformance with the smart grid network requirements in Table 4-A. End to end delay is a measure of latency requirements. End to end delay variation serves as a measure for reliability of the network. Number of hops are the number of network portions/sections (caused by intermediate routers/devices) that a packet of data passes through as it traverses from source to destination node. Latency increases with increasing number of hops. The results chosen for presentation here represent what was observed in all the nodes of the network. Thus sample statistics shown monitored flow of data from two smart meters selected from different subnets. The first meter's IP address was 192.0.0.3. The second meter was allocated the following IP address: 192.0.1.3. These meters are referred to as smart meter_1 and smart meter_2 respectively. The IP address of the MDMS was 192.0.1.1.

The first set of statistics presented is the end to end delay. Figure 5-1 and Figure 5-2 below plot average end to end delays for IP and MPLS networks. The results plotted in the graphs indicate that MPLS based network has lower latency than IP based network. In Figure 5-1 below, the blue line represents average end to end delay (in transmitting data from smart meter_1 to the MDMS) within IP network. The red line plots average end to end delay within the MPLS network. Within the IP network, it took the smart meter_1 node an average of 0.0035 sec to send one packet of data to the MDMS. It took the same node approximately 0.0031 sec to send one packet of data to the MDMS in a MPLS configured network.

On the other hand, Figure 5-2 below shows an extreme case where end to end delay for data sent from the smart meter_2 node with IP address 192.0.1.3 to the MDMS is almost equal for IP and MPLS networks. Latency shown in the figure below is approximately 0.0008 sec. This happens when the IP route followed by the data packets is similar to the LSP followed in the MPLS network. The slight difference is caused by differences in data processing at source and intermediate routers (IP routers and LSRs). MPLS processes data more at the source node while creating IP packets, creating LSPs, associating those packets to LSPs, and then pushing them into the network. In contradistinction, IP network just creates at the source node and then pushes them into the network. However, the intermediate routers have to decapsulate and encapsulate the packet checking for destination IP address to determine the next hop.

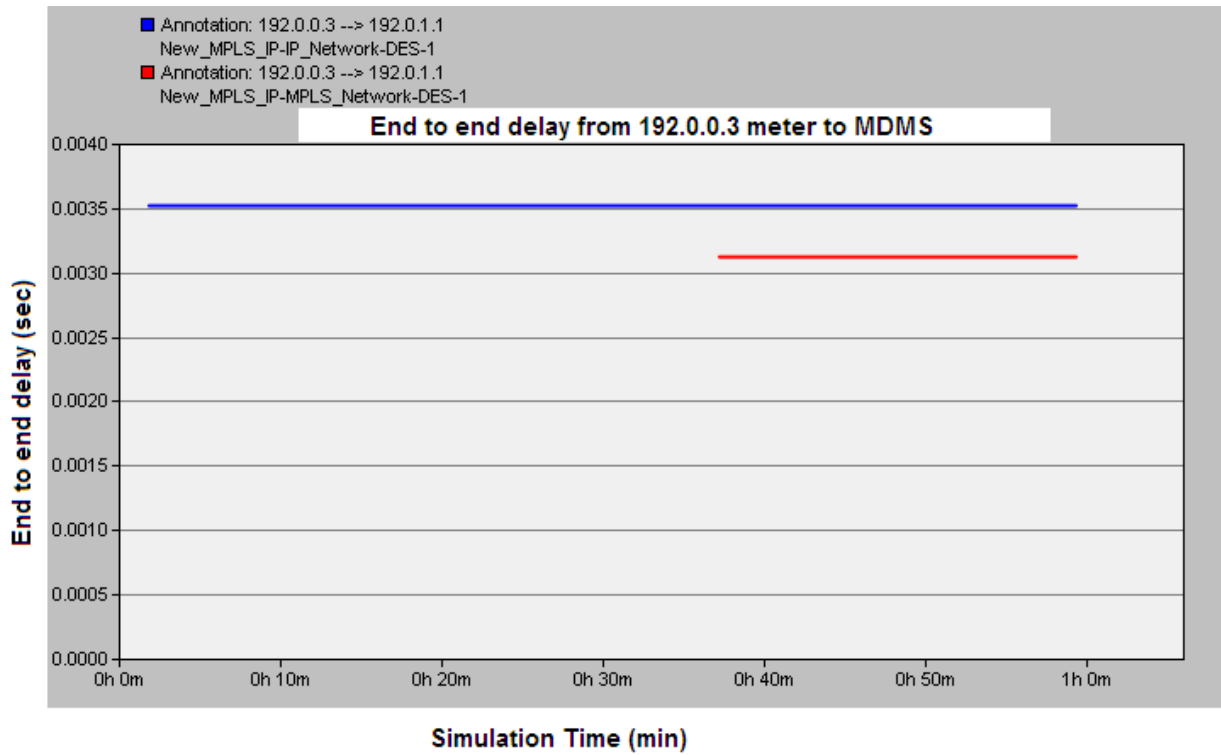


Figure 5-1. End to end delay (latency) between a smart meter_1 with IP address 192.0.0.3 and the MDMS.

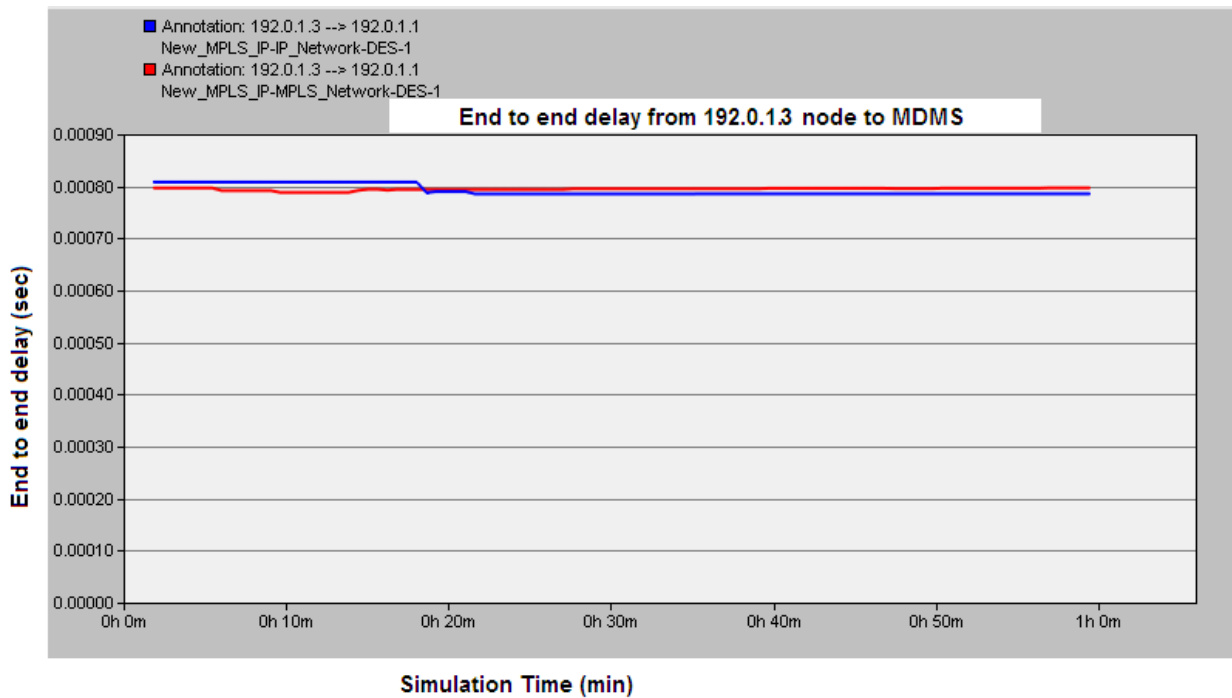


Figure 5-2. End to end delay between smart meter_2 with IP address 192.0.1.3 and MDMS.

In addition to latency requirements, the simulations investigated and compared reliability of IP and MPLS based AMI network. Variation in end to end delay was investigated and used as a metric for judging reliability of the protocols. A large variation in delay is an indication of an unreliable network. On the other hand, a smaller value of variation in end to end delay shows that the network can be trusted to transmit data from source smart meter/relay to the MDMS or to the MCAS within the expected time. It shows a small margin of error through which data may fail to reach the designated node within the expected time.

In Figure 5-3 below, the blue line represents end to end delay variation in the IP route between smart meter_1 and the MDMS. The red line in the graph plots end to end delay variation experienced by data flowing from smart meter_1 to MDMS through MPLS' LSP. In the IP network, latency varied by values between 0.000036 to 0.000046 seconds. On the other hand, variation in delay within the chosen LSP in the MPLS network was between 0.000033 and 0.000025 seconds. Again the larger values of end to end delay variation experienced in the IP network are an indication of unreliability of the IP network compared to the MPLS network.

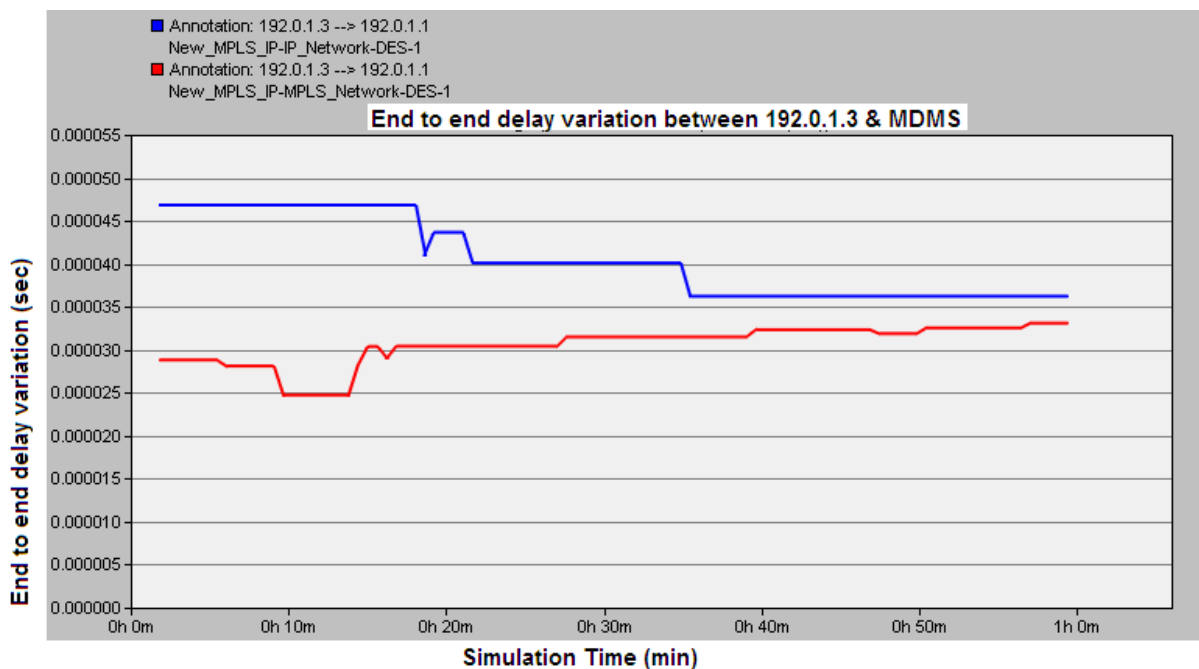


Figure 5-3. End to end delay variation between a meter with IP address 192.0.1.3 and MDMS.

Figure 5-4 below plots end to end delay variation mapping to the latency shown in Figure 5-2. As was observed in the end to end delay in this route, the variations in IP and MPLS networks

are almost similar even though that of MPLS shown by the red line in the figure below is slightly less.

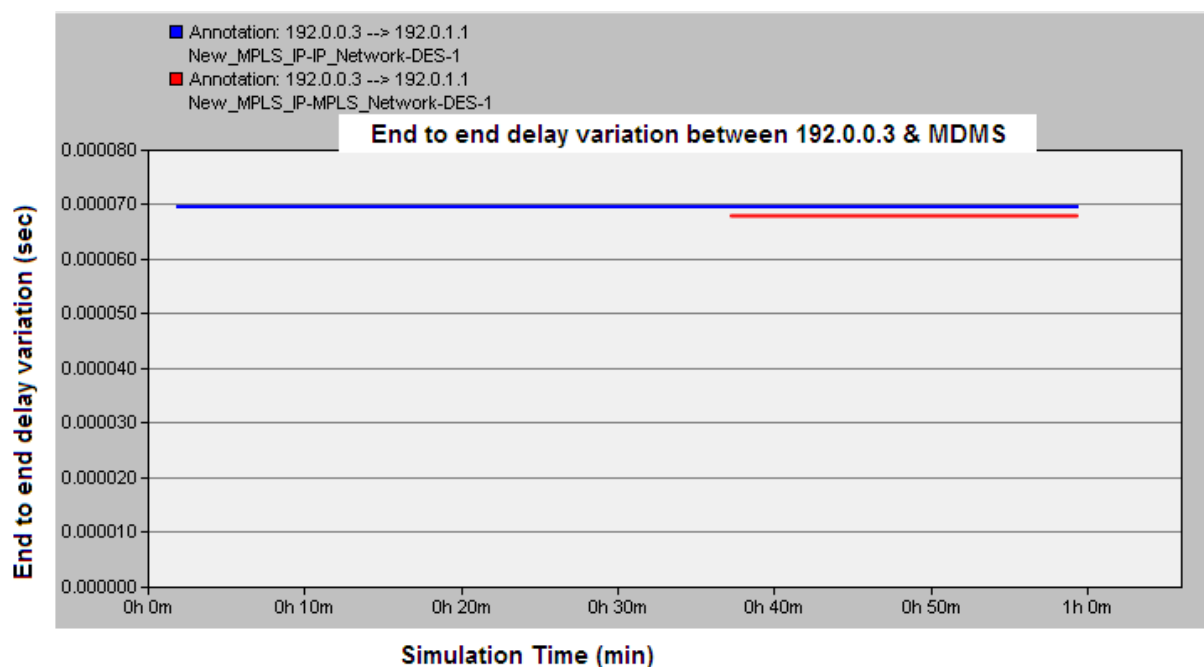


Figure 5-4. End to end delay variation between smartmeter1 and MDMS.

This observation further confirms that data flowing in the IP network took the similar route as the LSP in the MPLS network. It is not surprising that this was observed as both of the networks used similar OSPF routing protocol. MPLS has an advantage of traffic engineering mechanisms which make it more efficient in many cases.

A further investigation to validate efficiency of MPLS in comparison to pure IP networks involved monitoring number of hops traversed by data from smart meter_1 to the MDMS. It was observed that traffic engineering features in MPLS protocol reduce the number of hops that data goes through from source to destination. This observation explains shorter latencies experienced by data sent through an MPLS network compared to latency of data sent by a pure IP network. Reducing the number of hops by defining a fixed LSP has effectively decreased latency. Figure 5-5 below plots the average number of hops traversed by data flowing from smart meter_1 to the MDMS. The blue line in the graph shows average number of hops in the IP based AMI network while the red line is the number of hops between the same nodes in the MPLS AMI network. On average, the number of hops in the IP network was 5 while in MPLS, the average number of hops was 4. In larger networks, the difference can be huge.

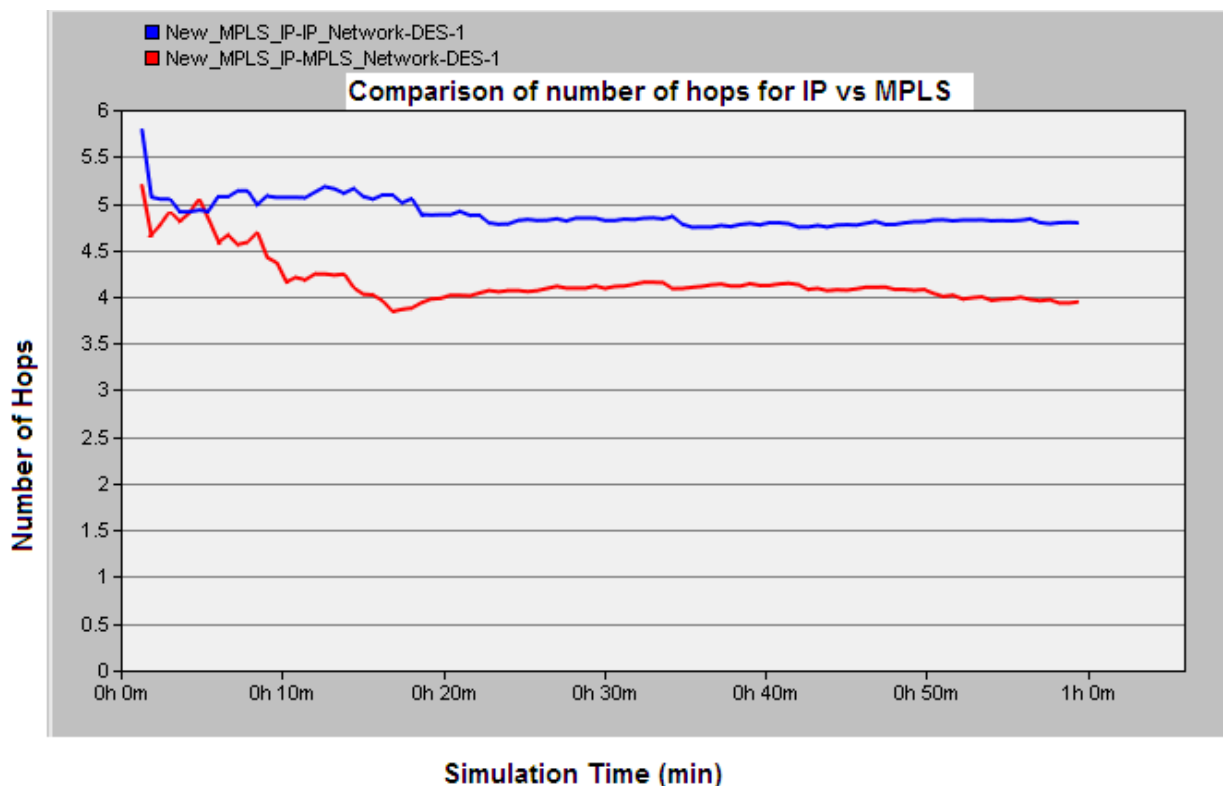


Figure 5-5. Number of hops for IP vs number of hops for MPLS.

This section presented observation on effectiveness of MPLS based AMI backhaul network. In addition to adding a layer of communication networks to smarten energy demand management systems, solar PV microgrids integration was also proposed. Section 5.2 below discusses the results obtained from the investigations conducted to test feasibility of this proposition.

5.2 Feasibility of grid integrated solar PV microgrid: studied on HOMER

This section presents results from the study undertaken to determine the most feasible configuration of the household based solar PV system. The first scenario simulated a PV system installed on one household and independently connected to the national grid. The second scenario simulated an integrated system where PV systems installed on three households are combined into a single microgrid and then connected to the national grid. In both scenarios, the renewable percentage was varied.

Table 5-A presents results from the grid-connected PV system gridlet installed on a household. Table 5-B presents results from the three integrated PV systems on three households. Each of the tables has three columns. The columns from left to right list as thus: renewable percentage, initial capital, net present cost (NPC), battery autonomy, levelised cost of energy (COE), energy

production by the PV system in kWh/year, energy purchased from the grid in kWh/year, and energy sold to the grid in kWh/year. The first five of these variables are defined in detail as thus:

- Renewable percentage is the proportion of total energy production of the system that was generated by the PV system.
- Initial capital is the total cost of installing the PV system.
- Net present cost is the total cost of the system (capital cost, operations and maintenance, replacements, etc.) during its life time (20 years in this case), minus total revenue from electricity sold to the grid, salvage value of the system, etc.
- Battery autonomy measures capacity of battery bank compared to the total load served. The greater the autonomy value the bigger the storage capacity, hence the longer the battery can service the load.
- Cost of energy (COE) is the per kWh cost of energy of the entire system.

Table 5-A. Single house based system - gridlet.

Renewable %	Initial Capital (\$)	NPC (\$)	Battery Autonomy	COE (\$)	PV Production (kWh/yr)	Grid Purchases (kWh/yr)	Grid Sales (kWh/yr)
16	3,825	17,653	1.77	0.165	1,549	7,955	5
31	6,137	18,983	2.66	0.177	3,078	6,889	62
42	8,679	20,895	2.66	0.195	4,647	6,303	93
50	10,991	23,180	2.66	0.216	6,196	6,008	110

Table 5-B. Three households integrated system.

Renewable %	Initial Capital (\$)	NPC (\$)	Battery Autonomy	COE (\$)	PV Production (kWh/yr)	Grid Purchases (kWh/yr)	Grid Sales (kWh/yr)
11	8,437	33,210	3.55	0.161	3,126	25,468	1
21	12,564	33,917	1.77	0.165	6,252	22,956	18
32	19,216	36,101	2.66	0.175	9,378	20,212	479
40	24,178	36,874	2.66	0.179	12,504	16,813	1,768
50	29,724	37,898	2.66	0.184	17,193	14,674	2,423

Important general observations that were made from the data presented in the two tables above are that:

1. Initial capital costs of solar PV systems are high. Example from Table 5-A above shows that a 50% renewable resources powered solar PV system capital cost is \$10,991.00 (\$10,991 x 8 = R87,928.00).
2. COE increased slightly as a percentage of renewable resources powering the system increases. Example from Table 5-B shows that when renewable portion was 11%, COE was \$0.161(R1.29). This value ramped to \$0.184 (R1.47) when the renewable percentage was increased to 50%.
3. Initial capital is directly proportional to the renewable percentage. That is, initial capital required increases as renewable percentage increases and bigger PV system components are required for the renewable percentage to increase.
4. Analysis show that over a period of 20 years, a household without one of the PV system discussed above would pay more for energy as compared to the household with one of these systems. Assuming that the energy demand of the household stays constant over the project lifespan, using the CPI of 6% per year for 20 years, COE bought from the utility will be as thus:

$$\begin{aligned} \text{COE in 20 years} &= \text{Current tariff} \times (1 + \text{CPI}). \\ &= 1.072 \times (1 + 6\%) = \text{R}3.438 \text{ per kWh} \end{aligned}$$

On the other hand, a house hold with the system installed will enjoy COE of either R1.728 (\$0.216) or R1.47 (\$0.184), assuming the exchange rate will stay constant at R8.00 per US\$.

Perhaps, more important observations made were in comparison of the data in these two tables as this was the essence of this thesis.

- 1) In terms of required capital investment, the initial capital of the three-household integrated system is three times that of the gridlet system as expected. Comparing the 50% renewable systems on the two tables, the three-household system's initial capital is \$29,724.00 which is approximately three times of the three gridlet systems (\$10,991 x 3 = \$32,973.00).
- 2) The scenario where PV systems on three households were integrated together was able to achieve lower COE for the same renewable percentage. Example, the tables above show that when renewable percentage is 31 % on a gridlet system, COE = \$0.177 (R1.42) while it was \$0.175 (R1.40) for the three-household integrated system of 32 % renewable. Again, with 50 % renewable, the COE for the single household system was \$0.216 (R1.73), while the three-household integrated system achieved a COE of \$0.184 (R1.47).

- 3) The three-household integrated system sold more power to the national grid than 3 times of the single household system. Looking at the 50 % renewable system in Table 5-A, 110 kWh/year of energy was sold to the grid by each household. Therefore three gridlets would sell three times of these, which comes to only 330 kWh/yr whereas the three-household system of the same 50 % capacity sold 2,423 kWh/yr.
- 4) The most important observation made is on the comparison of the NPCs in the two scenarios. An obvious expectation was that the NPC of the three-household integrated system would be three times that of a single household based system just as initial capital was as shown in point 1) above. However, the converse was true. Looking at Table 5-A, at the end of the twenty year lifetime of the project, the NPC of the gridlet system with 50 % renewable was \$23,180.00. Threefold of this is therefore \$69,540.00. On the contrary, NPC of the three-household integrated system is \$37,898.00! This is 46 % less than the NPC which three of the single household based system have:

$$\frac{\$69,540 - \$37,898}{\$69,540} \times 100 = 46\%$$

To further elaborate more on this, Table 5-C below lists the NPCs for the three scenarios (column 1 through to column 3). The second and third scenarios show a case where each household has the grid-connected systems that are independently installed. For comparison with the first scenario which also serves three households, the third scenario (whose values are in column three of the table) was determined by multiplying the second scenario by three.

Table 5-C. Net present values at different renewable percentages.

Renewable %	NPC for the Integrated system (\$)	NPC for the single household system (\$)	3x NPC for the single household system (\$)
11	33,210		
16		17,653	52,959
21	33,917		
31		18,983	56,949
32	36,101		
40	36,874		
42		20,895	62,685
50	37,898	23,180	69,540

A graphical representation of the NPCs data in the table above is shown in the figure below. The graph plots NPCs against renewable percentage of the systems. The brown line at the

bottom of the graph is a plot of NPCs for various renewable percentages in the grid-connected solar PV gridlet system. The blue trend line plots NPCs for the three-household integrated system. The third green-coloured line indicates three times of the NPCs represented by the brown trend line.

As was shown, initial capital of the integrated system is three times that of the single household based (gridlet) system, suggesting that this system is three times bigger than the single household based system. Clearly, the graph on Figure 5-6 illustrates that the integrated system has lower NPC than three of the single household based systems. Since initial capital was shown to be threefold of that of the single household system, the apparent efficiencies in the integrated system can be attributed to operation and maintenance, wiring and energy sharing.

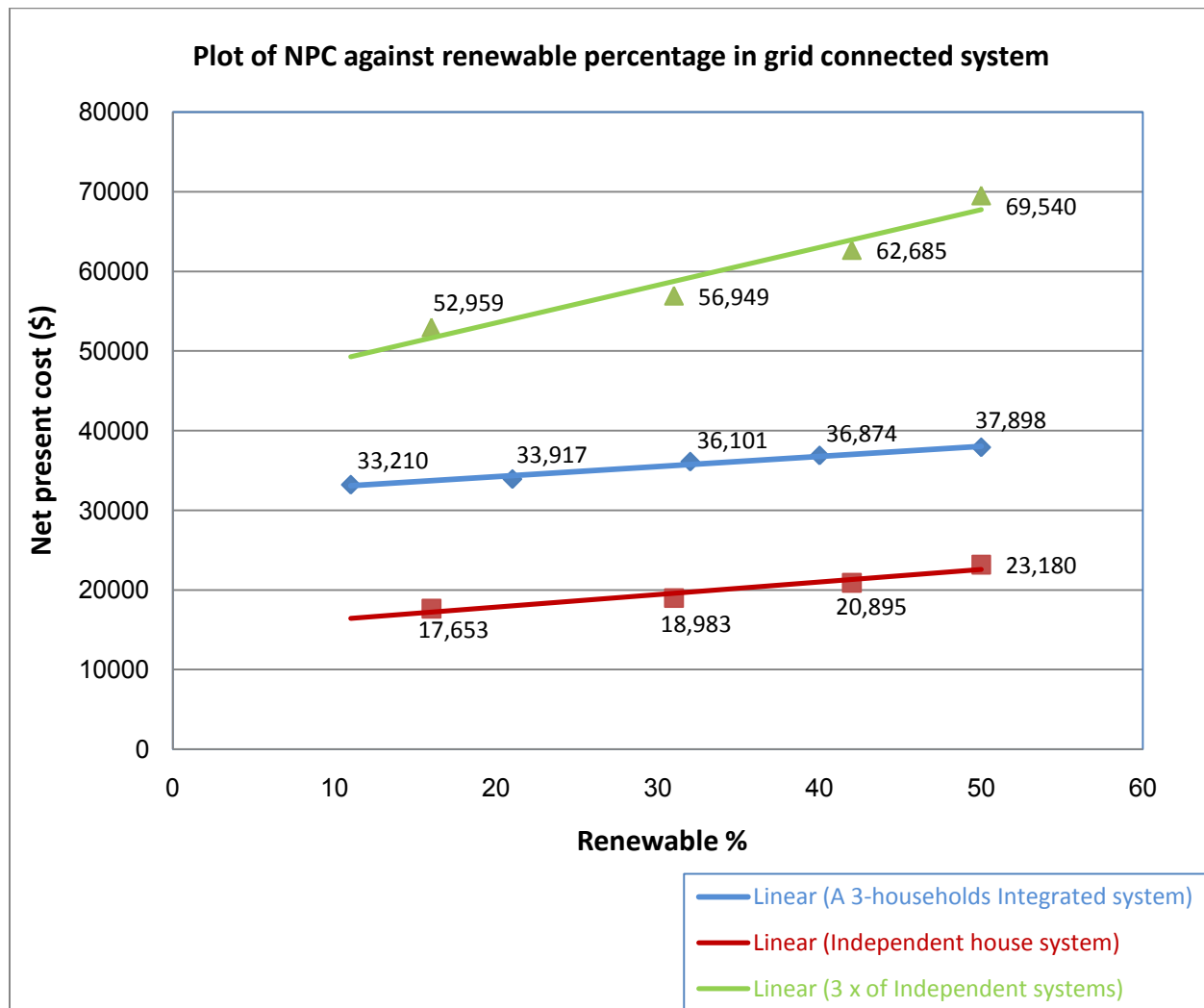


Figure 5-6. Plot of NPCs against renewable percentage.

Clearly, as proved by the discussions above, the proposed integrated system is efficient and hence economical than the counterpart gridlet system.

Having determined the most viable configuration, the question that needs to be dealt with on PV is feasible protection techniques. Section 5.3 presents results from studies carried out in search for the optimal technique to solve protection issues.

5.3 PV-DG Protection Scheme Results: studied on MATLAB

An important function of a protection scheme is its ability to detect contingencies in the power grid. The aim of the microgrid integrated power system model described was to demonstrate monitoring of the PCC. The simulation focused on observing the flow of current across the PCC (B1 in this case). Analysis of flow of current is the basis of the proposed differential current based WAMPAC. This section describes the results captured from the no-fault and the three-phase fault scenarios introduced in subsection 4.2.4.

Figure 4-11 illustrated that current between the microgrid and the bus B1 was measured by PV_B1 current sensor while B1-Grid current sensor monitored current between the bus and the main utility grid. The two scenarios modelled translate into two sets of results. The first set of results show a plot of phase currents between the PV microgrid and B1 and between B1; and the main grid. The phase currents are plotted against simulation time. The first set is a “no fault in the network” used as a benchmarking scenario.

The following graphs indicate the similarity in the phase-to-phase current measured before the bus bar in the microgrid side of the network and after the bus bar in the main grid side of the network. Figure 5-7 and Figure 5-8 show plots of current on one phase (red phase) on the two respective sides of the integrated grid.

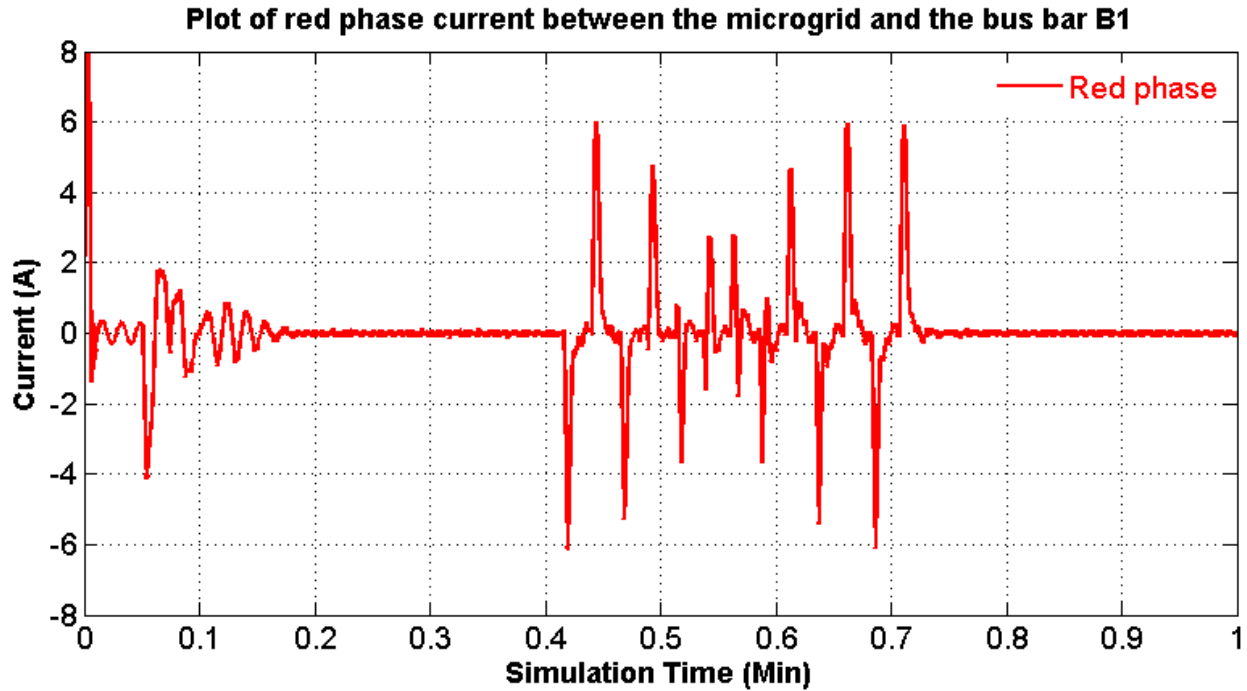


Figure 5-7. Red phase current measured between the microgrid and bus bar (B1).

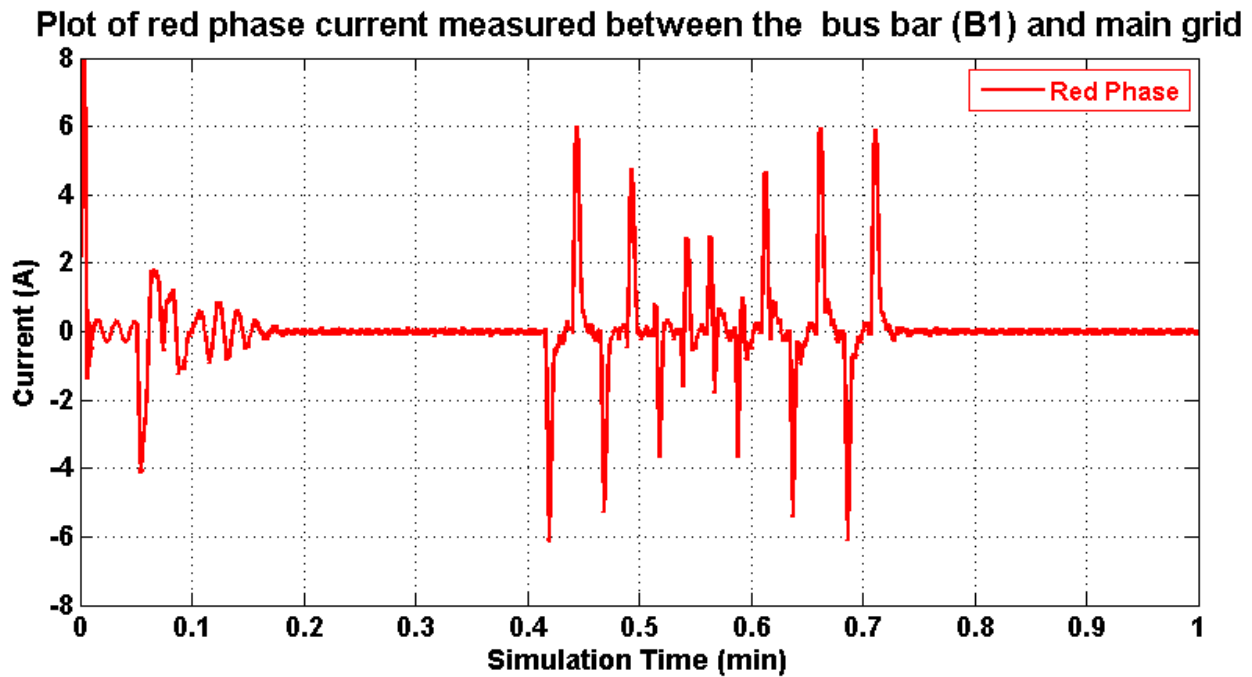


Figure 5-8. Red phase current measured between the bus bar (B1) and main utility grid.

Figure 5-9 and Figure 5-10 further illustrate the first set showing current in all the three phases. Similarity in Figure 5-9 and Figure 5-10 below demonstrate that when there is no fault in the network, phase currents across the PCC are equal in magnitude. This result is based on

Kirchhoff's law and is the basis of fault detection made by differential current protection scheme. This result illustrates a required condition in the network.

When the simulation starts, there is a current surge indicating instability in the system as shown in Figure 5-9 and Figure 5-10 below. The instability continues until about the 0.17th minute of the simulation when the phase currents die to zero. At around 0.41th minute, clear oscillating currents are observed until the 0.71th minute.

Plot of 3-phase current between the microgrid and bus bar (B1) when there is no fault

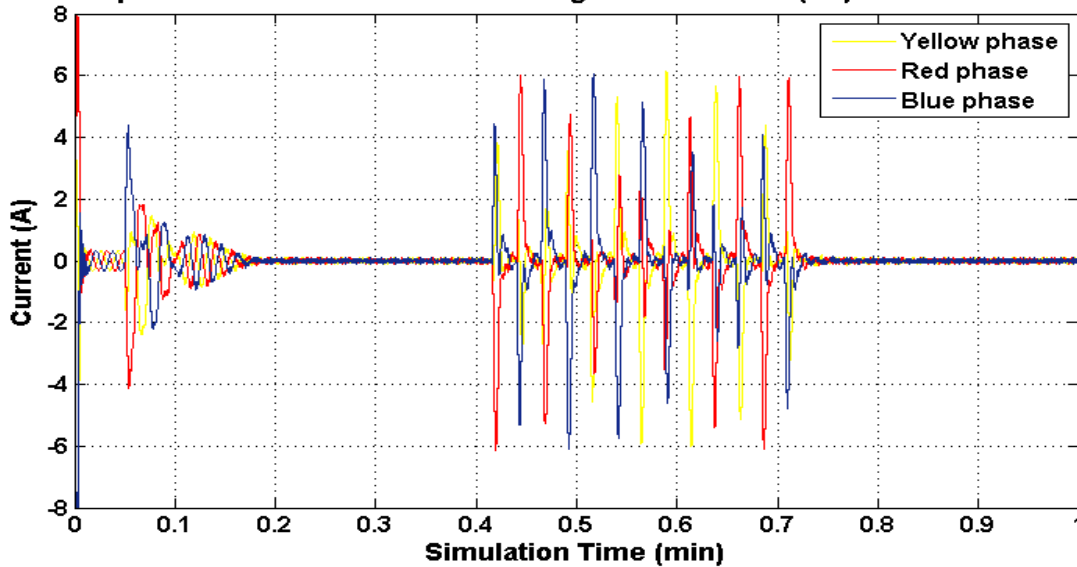


Figure 5-9. Phase currents between the microgrid and the bus bar before injection of a 3-Phase fault.

Plot of 3-phase current between the bus bar (B1) and main grid when there is no fault

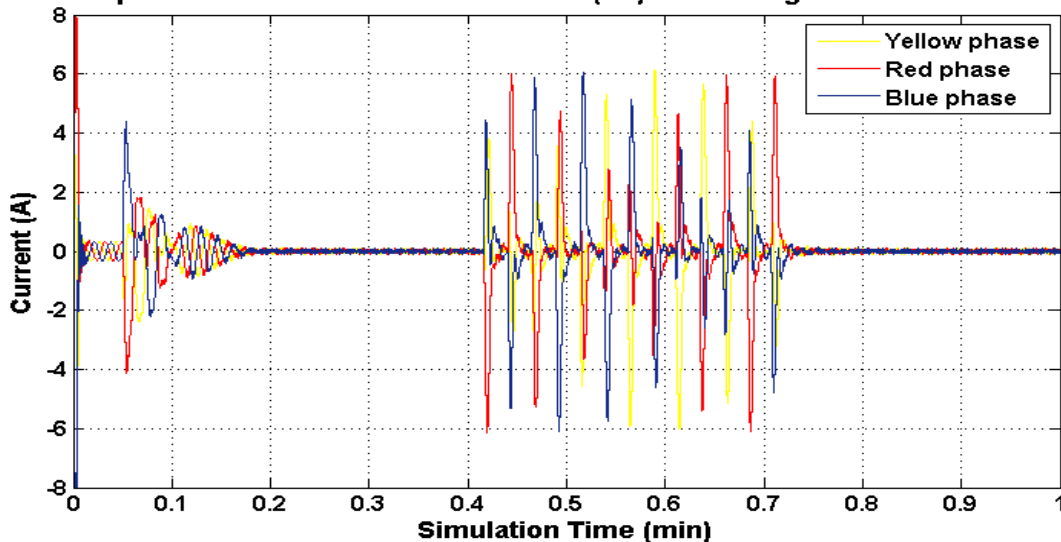


Figure 5-10. Phase currents between the bus bar and the main grid before injection of a 3-Phase fault.

The second set of the results illustrate plots of phase currents when a three-phase fault was injected in the network. Figure 5-11 and Figure 5-12 show plots of the red phase current in the two sections of the grid. Figure 5-11 is a plot of phase currents in the microgrid section while Figure 5-12 shows the phase currents in the main grid section of the power network.

In Figure 5-11 below, there is no current detected by the current sensor placed on the microgrid side of the bus bar until the 0.5th min of the simulation. This is an indication of a short circuit caused by the 3-Phase fault injected in the network. It has translated into a current surge (current magnitude of about 2900 Amperes) as shown in the beginning of the graphs in Figure 5-12. The current spike continued until about the 0.17th minute of the simulation when the phase currents die to zero. At around 0.41th minute, clear oscillating currents are observed until the 0.71th minute; but the current magnitude is still abnormally high at around 490 A on both sides of the PCC.

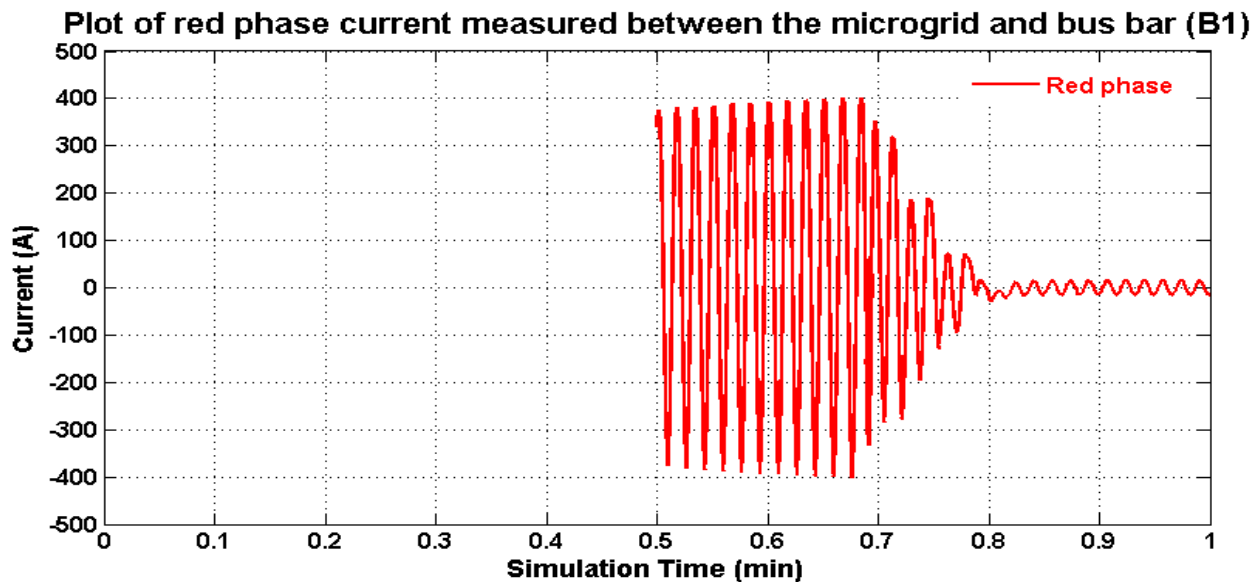


Figure 5-11. Red phase current between the microgrid and the bus bar when there is a 3-Phase fault

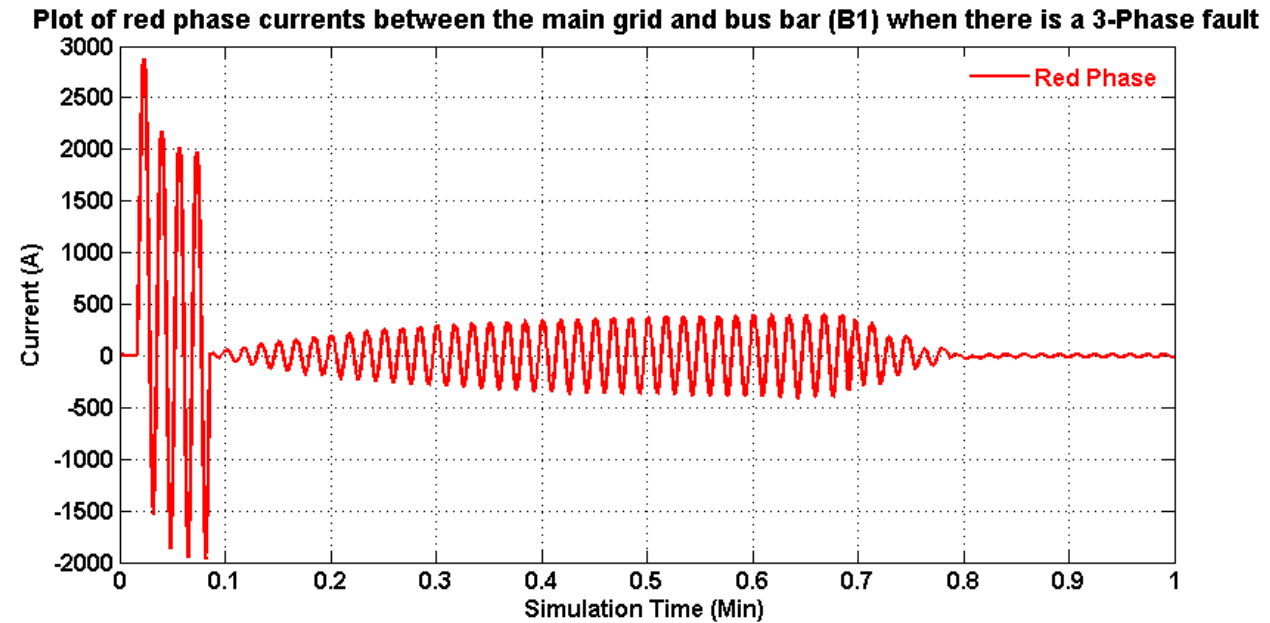


Figure 5-12. Graph of current between the main grid and bus bar (B1) when a 3-Phase fault is injected.

Comparison of Figure 5-13 and Figure 5-14 indicates an abnormal condition in the grid where phase currents across the PCC are not equal in magnitude. This disobedience of Kirchhoff's law is an indication of a fault in the grid.

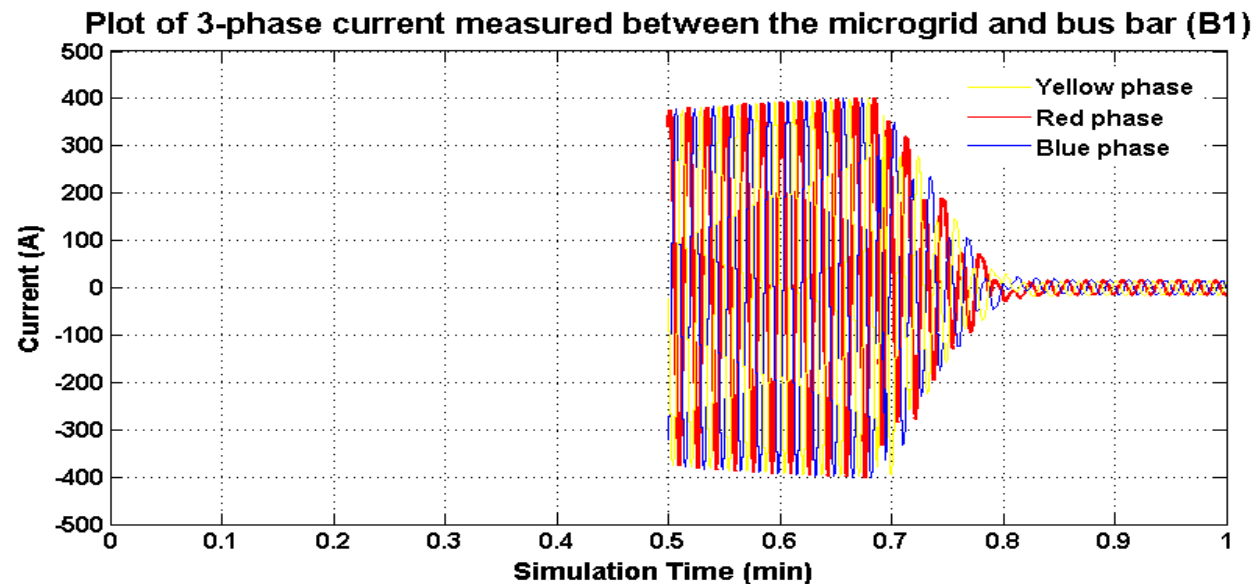


Figure 5-13. Phase currents between the PCC and the microgrid when there is a fault.

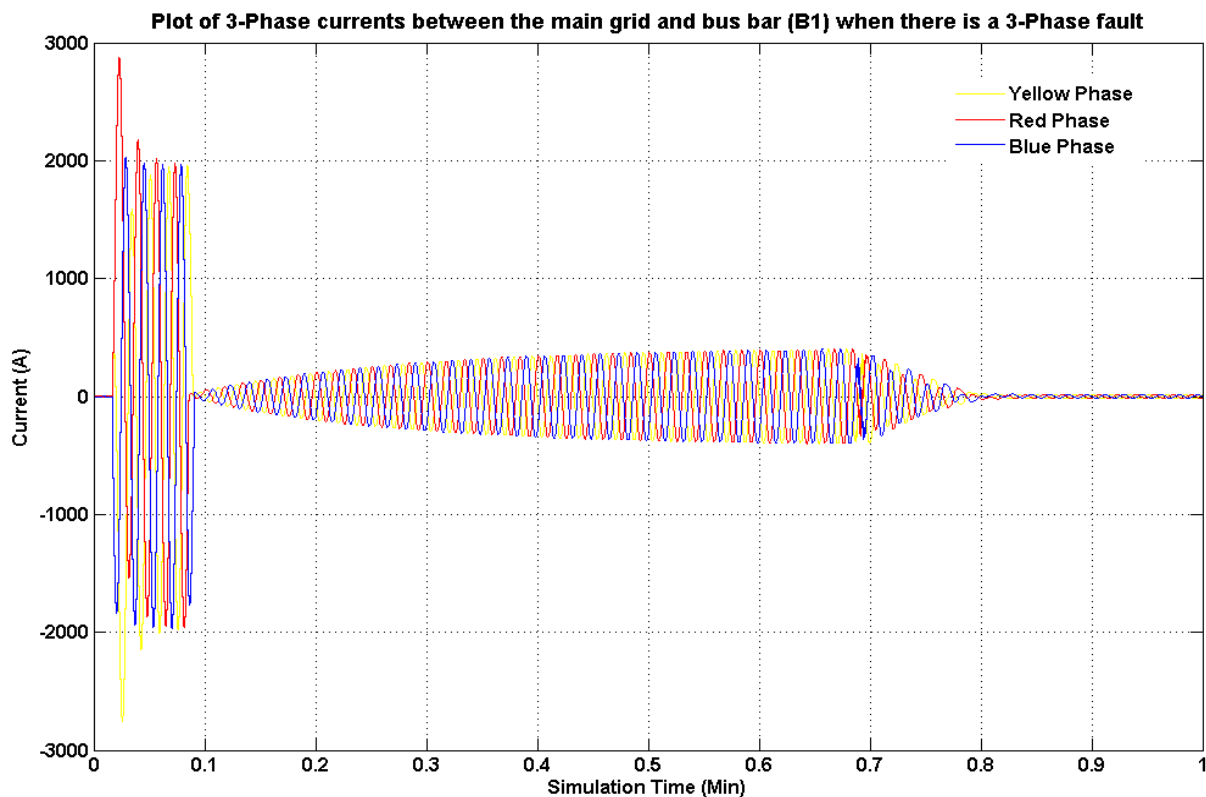


Figure 5-14. Phase currents between the PCC and the main grid when there is a fault.

The similarity in Figure 5-7 through to Figure 5-10 showed that the phase currents across B1 are equal in magnitude and have similar direction across the PCC when there is no fault in the network. The result is in harmony with Kirchhoff's current law. However, Figure 5-11 through to Figure 5-14 gave a different picture. There is no correlation in the graphs for the first 30 seconds of running the simulation. This shows that the IED on the microgrid side and the IED on main grid section read different current values. Thus the difference between the magnitudes of the phase currents across the PCC will not be zero. Therefore this condition is inconsistent with Kirchhoff's current law. The current sensor on the main grid side only detects current after 30 seconds of the simulation time. This irregularity in the phase currents detected across the PCC suggests an abnormality in the power grid. Having detected the fault, appropriate protection and fault control instructions must be sent to the relay affected. Hence there is a need for robust communication networks.

Speed of the communication networks determines responsiveness of the protection system. Central microgrid control computer system sends commands to relays. Attempting to apply automatic reclosers is usually the first line of protection. If this attempt to fault correction fails, protection algorithms will then locate and identify the fault using information from the

neighbouring current sensors combined with time-stamped GPS coordinates. The faulty line/phase will finally be isolated. Thus importance of communication networks is upheld. This promulgated further research into the best communication networking technology that can be combined with the differential current protection scheme discussed above. Section 5.4 below presents the results from a simulation of MAN for microgrid protection.

5.4 MAN for microgrid protection: studied on OPNET

A suitable communication network that can be implemented for protection of microgrids is guided by SEMI F47 standards. The SEMI F47 standards highlight the importance of targeting a short microgrid from main grid separation time during contingencies. These guidelines advise equipment manufacturers on designing secure grid equipment. The standard quotes a rapid separation of less than 50 ms [88]. This threshold therefore serves as a guideline for the design of the Wi-Fi network used in this simulation. A suitable network must transmit protection data between the relays and the MCAS in time less than 50ms to meet the requirements of the SEMI F47 standard. The results for the MAN simulation that tested the proposed network against this standard are presented below.

Graphs in Figure 5-15 through to Figure 5-17 illustrate delay/latency in the network plotted against time. Network delay is the measure of how long it takes for a packet created by node A to reach the destination node B. Thus, it is important that for the protection of a microgrid, overall delay is less than the 50ms as said above. In all the three figures, the bottom most line plots the time taken by MCAS to generate traffic. It serves as the reference line.

There were two scenarios simulated. The scenarios compared performance of the proposed network for the 11Mbps (Mega bits per second) and 36 Mbps bandwidths. The plot on Figure 5-15 shows average delay over the duration of the simulation. Data rates of the transmitting and the receiving nodes were set to 11 Mbps. It illustrates network delay where there are two nodes in the network: the transmitting node (MCAS) and the receiving node (IED). The figure shows that the MCAS takes an average of 0.0195 seconds to generate traffic for one IED. The target IED receives the data in approximately 0.0225 seconds after the simulation starts. This results in an average delay of $(0.0225 - 0.0195) = 0.003$ seconds between sending and receiving of data. This time represents approximately the same time that it would take the IED to generate data and send it to the MCAS.

Bandwidth of the MCAS and the IED was increased to 36 Mbps. The network configuration was as described above. As expected, increasing the transmission bandwidth saw the average delay

between sending and receiving of data drop to $(0.0064 - 0.0056) = 0.0008$ seconds. Figure 5-16 plots the delay after the bandwidth upgrade. Furthermore, the number of IEDs served by one MCAS was also increased. Figure 5-17 shows plots of delays when there are eight nodes connected to the MCAS. Average delays in data received by the three of the eight IED nodes were plotted. Bandwidth and transmission power were set to 36 Mbps and 0.03 watts respectively in all the nodes.

Effect of distance of the IEDs from the MCAS on delay was also simulated. This was done by increasing radius of the network coverage. Again, in Figure 5-17, the bottom most line is the delay by the node that generates traffic (MCAS). The other three lines represent time taken by the IEDs to receive the data.

Thus the delays experienced by the three IEDs are in this order:

$$\text{IED_3: } 0.0139 - 0.0108 = 0.0031 \text{ seconds}$$

$$\text{IED_5: } 0.0180 - 0.0108 = 0.0072 \text{ seconds}$$

$$\text{IED_0: } 0.0190 - 0.0108 = 0.0082 \text{ seconds.}$$

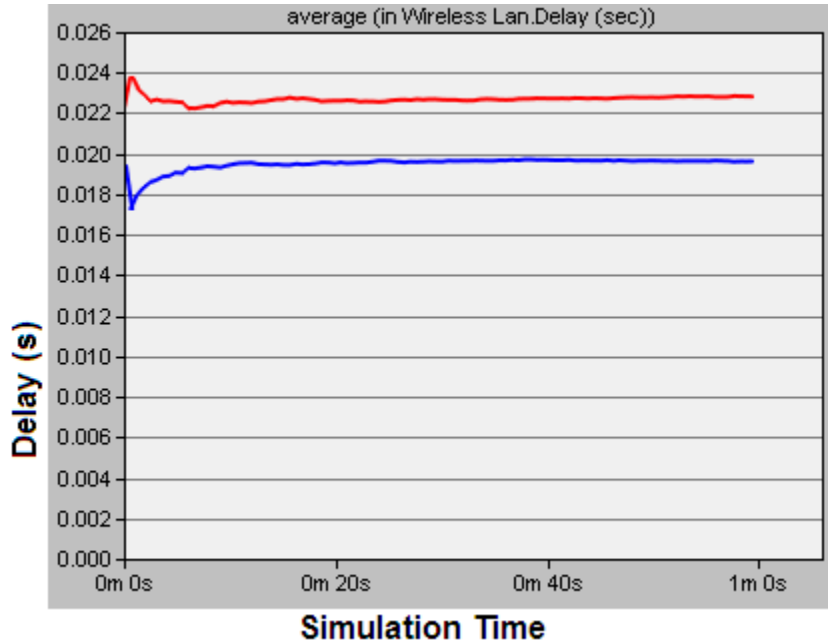


Figure 5-15. Average delay experienced by data sent by the IEDs to the MCAS.

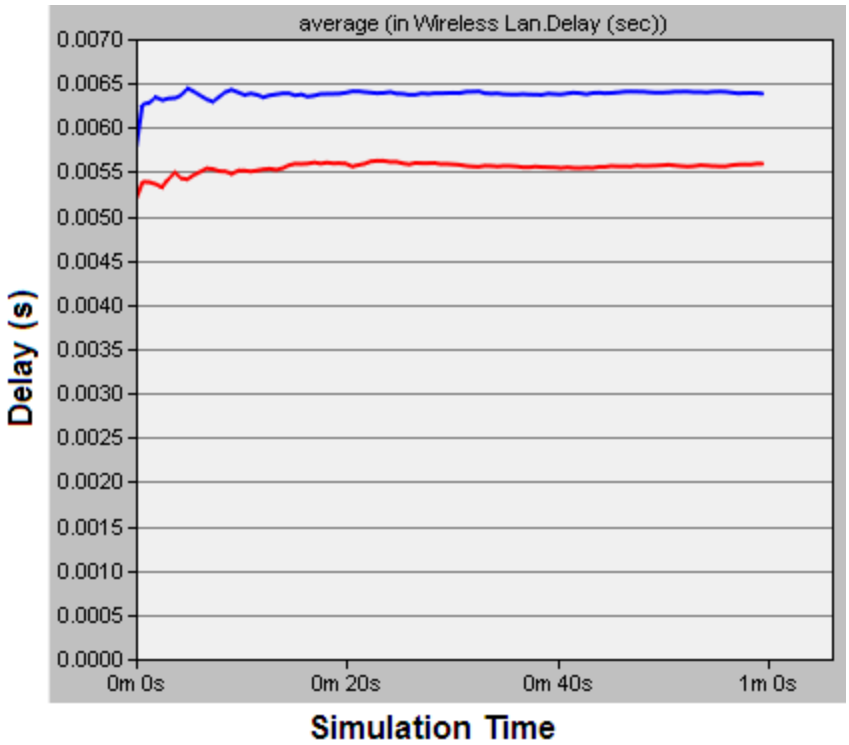


Figure 5-16. Average delay when bandwidth is increased.

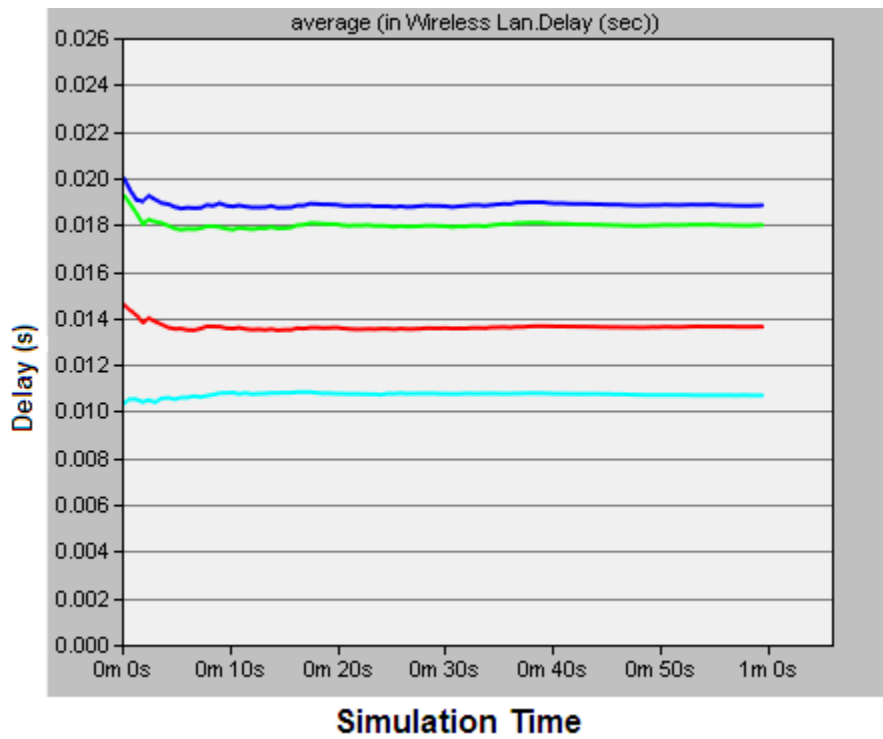


Figure 5-17. Average end-to-end delay with three IEDs.

This chapter presented results from the simulations performed in this dissertation. Results from the simulation of AMI backhaul network were presented and discussed. The results compared MPLS network with pure IP network. The chapter also presented results from the simulation of grid-connected solar PV feasibility study as well as protection solar PV microgrid. Protection of solar PV simulation presented results from the differential protection scheme and the Wi-Fi MAN supporting the protection system. Chapter 6 and Chapter 7 below discuss case studies carried out for this dissertation. The study in chapter 6 below looks at implementation of real-life AMI project.

6 Case Study 1: AMI Project Implementation

In the previous chapters, AMI was introduced. Its role in DSM was discussed. Up to this far, the thesis discussed AMI functions and its components. Communication networks were the main focus. It also reviewed challenges involved in implementing the infrastructure. Most of this information was sort from literature more of which discusses academic research findings. The dissertation presented design and simulations of AMI communication networks.

This chapter takes the discussions a step further by looking at a real-life implementation of AMI. The case study is based on the proposed City of Tshwane AMI project. As was highlighted in Chapter 3, this chapter focuses on planning phase of the project. Section 6.1 is a brief background of the project. Inception of AMI projects is presented in Section 6.2. The section discusses inception of the City of Tshwane AMI project. Resource planning is presented in Section 6.3. The chapter is concluded with pertinent regulations that the implementer must abide by.

6.1 Background of the project

The project studied and discussed here is the proposed AMI Implementation Programme by the City of Tshwane (CoT). This project was initiated in 2007 with issuance of tenders for suppliers and installers of the AMI technology. Four vendors who are going to act as service providers for supplying and installing the smart meters were appointed in 2010 [114]. A total of 160 smart meters (40 from each vendor) have already been procured for the pilot project.

The proposed project is to be done in three phases: phase 1 involves 16 201 High Tension and Low Tension Maximum Demand Meters for large power users, phase 2 consists of 192 000 conventional meters consuming in excess of 999kWh per month, phase 3 has 292 000 conventional and pre-paid meters. These numbers are indicative of the complexity and magnitude of this programme. Hence the amount of planning that has to go into this project to make it a success. Thus as mentioned, the gist of this chapter is to look at resource planning for an AMI project of this magnitude. The chapter discusses and analyses contents of the tender document from the CoT to determine the requirements of an AMI project.

6.2 Project inception requirements

Project inception requires careful identification of all stakeholders. With the AMI project in question, the stakeholders are the CoT, the households, and the service providers. Each of these stakeholders has a unique role which they must fulfil for the success of the proposed project. The CoT is the client who initiated the project. The households where the meters are to be installed are beneficiaries of the programme from the perspective of the chosen implementer. Service providers are suppliers and installers of the smart meter infrastructure. Implementers are also a team of service providers who handle the organisational tasks of the project. The implementer is appointed by the client to provide project management services. They are appointed through a tender process. This implementer becomes responsible for running the programme management office (PMO).

The PMO's task is to coordinate necessary project management, resources, system integration and implementation of all the components required. The responsibilities of the PMO are to plan the general approach of the project, producing detailed plans, project schedule and schedule management, and management of contracts. The office governs the project and manages coordination and communication amongst all stakeholders. It also monitors performance and legal abidance based on the guidelines provided by regulations and standards as outlined in Section 6.5 below. The PMO devices strategy and business case for the project based on the specifications and terms of reference provided by the client.

6.3 Project stages

The following table of project deliverables and stakeholders was compiled from a study of the scope of work in CoT's tender document. The table depicts the AMI PMO tasks by name and describes the content of each deliverable. It also determines stakeholders for each of the deliverable tasks. The tasks are performed one after another in the order in which they are tabulated below. For the CoT's project studied, each task was allocated a week to complete.

Table 6-A. AMI PMO project deliverables, designed in response to Part C of scope of work in contract no. CB107/2011 [115].

Task No.	Tasks Name	Task Description	Stakeholders	Completion Date
1	Project Initiation	Consist of information gathering and analysis workshop. Aims to: Define project scope, Identify risks and constraints, and Agree on assumptions.	Service Provider and team of managers involved in the project, Client (CoT).	2 nd Jan. 2012
2	Project Charter	Product of the initiation workshop which documents constraints, assumptions and high level budget. It is a document that authorises the project.	Client Representative meets with the Service Provider to review the Project Charter.	29 th Feb. 2012
3	Scope Document	Establishes mutual expectation between the client and Service Provider.	Client Representative and Service Provider.	14 th Mar. 2012
5	Risk and Issue Assessment	Logs maintained and communicated continuously during the project's life cycle.	All Service Provider's staff identify, log and communicate risks to Client's Representative.	Continuous
6	Project Plan	Serves as a framework documenting the agreed scope of work deliverables.	Client and Service Provider Representatives have to agree on the plan.	31 st Mar. 2012
7	Functional Specification of the project	Stipulates the expectations from each of the deliverables.	Service Provider and the Client must agree on these specifications.	30 th Apr. 2012
8	Solution Architecture	Gives physical and logical design of the AMI system. It documents software and hardware requirements for the AMI solution.	Must be send to the Client's Representative before project implementation begins.	21 st May 2012
9	Solution Build Guide Document	Documents details of how the AMI system is to be build throughout the lifecycle of the project.	Submitted to the Client's Representative before project closeout.	29 th Jun. 2012
10	Testing	AMI system testing	Conducted by all PMO officials in different portfolios in conjunction with Client's representatives.	After each installation
11	Quality Assurances/ Control	Quality assurance plan is made before commencement of implementation of the project. It details how control and monitoring of quality is to be ensured.	ISO Quality Assurance System applied by certified and listed Service Providers.	20 th Jul. 2012
12	Operations Document	Documents operations and configuration of the system for support by the clients' team.	Submitted to the Client's Representatives before project closeout.	29 th Nov. 2012
13	Skills Transfer	Engaging with and Educating the Client's support team on lessons learned during the project. Done before/during project handover.	Client's support team.	At the end of the installations completion.

This table can serve as guideline for AMI projects. It is however flexible and can be twisted to fit specific requirements of a client and those of a Service Provider. The following section discusses resources required to setup a PMO.

6.4 Human resource requirements

The meatier issue that the planning phase of the project addresses is resource procurement. This is true for AMI projects because of their complex nature. Implementation of AMI requires skills from Power Engineers, Communication networks Engineers, Software Engineers, System Architects, Accountants and Project Managers. Professionals from these areas are required for formation of the AMI PMO introduced above. Experience of the team of people that form a PMO is very crucial to the success of the project. This section summarises the key skills requirements that the appointed Service Provider must have in his/her team. These skills were prescribed for implementation of the CoT's proposed AMI programme. However, they can be applied for any AMI implementation.

General Programme/Project Manager – is responsible for coordinating overall management of the programme. This manager ensures that the client's requirements are met with the prescribed standards and within the planned time schedule. Key skills and experience required of the person to fill this role are project management, management of business cases, financial, quality and risk management. The person should be computer literate and have a background in working within and managing technology projects. They are required to be able to manage teams. Most importantly they should understand power utilities, municipalities, meter to case process and AMI/AMR. This manager reports directly to the client or client's representative.

Project Administrator – provides support of the administrative tasks to the project manager. They are responsible for generating reports, facilitating payments of contracts, document filing etc. The person to fill this position will therefore be involved in organisation and administration of the project. Hence these are key skills they must possess.

AMI projects also require specialised skills. These are also summarised below.

Project Finance Administrator – manages project finances, purchase orders and invoices from vendors. Key required skills for this role are financial and accounting management.

Project Manager: Strategy, Design and Processes – the main tasks of this role is to manage teams that deal with strategic planning, design of system architecture, organisational design, user acceptance tests, business case development and updating etc.

Project Manager: Meter Deployment and Engineering – manages and drives project teams responsible for field installations of meters. They ensure delivery of field installations, meter validations, compliance with standards and specifications, storage and logistics of equipment. They create and manage a plan for field installations. They are responsible for procurement of human resources. Therefore skills and experience needed for this role are project management, logistics management and AMR/AMI project experience.

There are many other skills resources required as highlighted in the section introduction above. The skills mentioned above are key to every AMI project.

6.5 Standards, Regulations and Acts guiding AMI projects in South Africa

The other important factors that implementers of AMI in South Africa should consider are the legal and good practices guidelines set by South African legislation. Standards and regulations are meant to protect end users and ensure good service delivery. This section summarises some of these standards and regulations. The CoT tender quotes the following guidelines and regulations that are relevant to implementation of AMI.

Occupational Health and Safety Act, 1993 (Act No. 85 of 1993) – this regulation binds the implementer with liability to ensure that he abides by the health and safety requirements set out in this law. The equipment used for the project is also required have been approved by at least one of the following: South African Bureau of Standards (SABS), National Regulatory Services (NRS), British Standards (BS), International Electro-technical Commission (IEC), and International Standards Organisation (ISO). The following ISO standards are specifically quoted: ISO9001, ISO19011, and ISO1401. ISO9001:2008 gives quality management system requirements [116]. ISO19011:2011 specifies requirements for auditing management systems. Furthermore, ISO1401:1999 sets guidelines for protection of the environment [117]. Because of AMI's heavy reliance on communication networks, implementation of the programme must be compliant with Independent Communications Authority of South Africa (ICASA). The implementer is also expected comply with CoT's by-laws and regulations.

If the CoT's project is executed successfully, the methods applied in it are going to inform the approach that other municipalities will adopt when they roll-out AMI. In addition to AMI, this thesis discussed grid integrated solar PV DGs. The chapter below focuses on project management activities of implementation of off-grid solar PV DGs for electrification of rural households.

7 Case Study 2: Solar PV Project Implementation

This dissertation has looked at two critical issues that need to be considered when using solar PV system integration as a DSM tool. The two questions addressed are protection of these solar systems and then viability of their implementation. This chapter describes how the design techniques proposed and simulated in the thesis were applied to a real-life project of designing and planning a home based solar PV system for a rural electrification project. The chapter presents a short background to the project, project inception, and detailed technical and financial proposals.

Many of the renewable energy projects currently rising are initiated from the public sector. This is because high cost of these projects calls for government subsidies. Thus, the approach followed in this chapter discusses conceptualisation and implementation methods suitable mostly for public sector born projects.

7.1 Background of the Project

The project studied here is part of the Africa Adaptation Programme (AAP) initiatives to develop African Governments, institutions and communities to boost climate change strategies. The Government of Japan is providing financial support, through the United Nations Development Programme (UNDP) in New York, for the implementation of the Africa Adaptation Programme, titled “*Supporting Integrated and Comprehensive Approaches to Climate Change Adaptation in Africa*”. The programme is running in twenty countries in Africa, including Lesotho [106]. The Ministry of Natural Resources, through Lesotho Meteorological Services and UNDP Lesotho are jointly implementing the project with focus on Health and Energy sectors. The expected main outcome of AAP is that Governments, local institutions and communities are able to develop and implement climate change adaptation strategies. It is in response to this that the RFP discussed here was issued. This particular project was proposed for design and supply of home solar systems to 100 rural houses located at Poriking in Mohale’s Hoek district, Lesotho.

7.2 Project Inception

This project began with issuance of RFP by AAP Lesotho. AAP is the client and Consttec and its partner (responding to the RFP) are referred to as a Consultant/Bidder in the RFP. The discussion in this chapter is based on a response to RFPs for design and implementation of the home based solar systems. The RFP is accompanied by a terms of reference (ToR) document. The ToR is the most important document which describes the proposed project to companies that want to respond to the RFP. It standardises the format of the responses and proposals from these companies. It is important that before a project sets-off, all stakeholders are clear of the requirements of the project. This is achieved through descriptions of the project background, objectives and goals, project scope and expectations, stakeholders and their roles, standards to be used, and project control strategies [118]. This information is provided in the ToR.

The ToR described the proposed system by its components as thus: a solar PV panel, a battery, three direct current (DC) lights (two lights are for internal house lighting and one is for security lighting outside the house), multi-cell phone adapter, a socket for cell phone charging, a socket for radio and a socket for a fan of a portable energy saving stove with charging voltage of 7.5V. The system was required to provide electricity to the household for 8 hours per day. The lights were specified as light emitting diodes (LEDs) or compact fluorescent lights (CFLs). Other requirements specified are that the equipment proposed should bear a logo and address of its manufacturer. Proof of accreditation of this equipment would also indicate authenticity and thus advantage to the proposal. Another extra requirement was that samples of the proposed components should be readily available for demonstration to the client if need be.

The expected deliverables from the bidders were as thus:

1. Design of the appropriate solar home system (SHS)
2. Demonstration of assembly of the components of the system and
3. Proposal of delivery and payment schedule.

The RFP advert and the ToR are provided in Appendix A to give this information in detail as it was from the client. Sections 7.3 and 7.4 below discuss the technical and the financial proposals that were compiled for this RFP. They are presented in a tone that explains to the client how the project team would approach the work if they were to be awarded the contract.

7.3 Technical proposal: Applying HOMER based design in the dissertation

A standard technical proposal has six main sections. The sections listed below are in the order of their appearance in the proposal document.

1. Technical proposal submission form
2. Consultant's references
3. Comments and suggestions of the consultant on the Terms of Reference
4. Description of the proposed system including component specifications
5. Curriculum Vitae for the Consultant's team
6. Proposed Activity Schedule

My main responsibility in the project was design. Hence the first task was analysing the RFP, commenting and suggesting points which have been omitted from the RFP document and yet important for the design (point 3 above). The second point which was my sole responsibility was component four above; describing the proposed system and specifying the components. Lastly, I produced a work schedule for the project. The following subsections describe how each of these components of the proposal was handled.

7.3.1 *Comments and suggestions addressing deficiencies in the ToR*

After a careful study of the RFP document and the given ToR, the following limitations and omissions in the ToR were identified.

1. **Clearness Index and Solar Radiance Data Omission:** This data indicates solar energy generation potential for a certain location where a solar PV system project is intended to be deployed. The sizing of an off-grid solar energy system does indeed require a sensitivity analysis of input data used; of particular importance are the variation of solar irradiation, clearness index and the load profiles to be met by the system. Clearance index and solar radiance are an important input which enables accurate determination of the size of solar PV system that can efficiently and effectively service the given load profile.

The likely negative effects of missing this fundamental data and leaving it to bidders to source the information out for themselves are as thus:

- Some bidders will not take this important information into consideration.
- They are therefore going to either come-up with designs that over-estimate or under-estimate the size of the required solar home systems (SHS).

2. Load Profile: The structure of the given load profile data is incomplete and likely to cause discrepancies in the design of the appropriate system. A helpful structure of the load profile states specifications of devices to be used and the time for which they will be consuming electricity. The given information implies that the three (3) DC lights, cell phone, and fan for portable energy saving stove are plugged-in for 8 hours. An alternative structure would attempt to answer the following questions:

- How long is the multi cell phone charger expected to be plugged on? How many cell phones should the system be able to charge per day if we assume a charge period of 3 hours per cell phone? Can multiple chargers be plugged-in at the same time?
- The electricity ratings for the fan for the energy saving stove is trickier to estimate from the given information of 7.5 V.

The essence of this format is to ensure that the load profile used in the design models the expected household energy consumption behaviour as closely as possible. This will ensure correct and more accurate optimisation of the SHS solution.

3. Mounting of solar panels and housing of battery bank: The ToR does not indicate whether the SHS will be mounted on roof tops or what form of mounting will be made. The battery bank also requires separate secure housing that cannot be easily accessible to infants. The housing must also protect the batteries against excessive dust and extreme weather conditions.

4. Electrical wiring of the houses: Provisions for electrical wiring of the houses have not been catered for in this proposal. Electrical installation and provision of a solar system to power a house are separate tasks. A normal practice even in grid-connected houses is that electrical installations take place between the client and their chosen contractor. The utility then tests and certifies the wiring for compliance with the utility standards and then supplies/connects the house with power from the grid. In the case of the project at hand, it is likely that the houses have not been wired. However, the ToR has not explicitly specified whether the consultant should cater for this task.

Having looked at the loopholes that were identified in the ToR, the proposal described the team's proposed project approach and design methodology as follows.

7.3.2 Description of the proposed system including component specifications

The consolidated approach to this project is described in the sections below. The sections will cover description of proposed approach, methodology and work plan. Before sinking into the details of the project management approach, technical description of the proposed SHS is given below. Section A covers system requirements; Section B presents solar energy potential for Poriking, load profile is in Section C. Sections D and E present description of the system architecture and components specifications respectively.

A. Requirements of the system

The proposed design of the system will meet the following requirements:

1. Provide electrical energy for eight (8) hours per day to power three (3) DC lights, cell phone charging, and fan for potable energy saving stove. The charging voltage for the fan is 7.5 Volts.
2. Two (2) lights are for internal house lighting while one (1) will provide security lighting outside a house.
3. The lights will be the Light Emitting Diode (LED) and or Compact Fluorescent Lights (CFL) types.

B. Solar energy potential at Poriking

Solar energy potential for the proposed Poriking site in Mohale's Hoek (GPS coordinates 30.2 South, 27.5 East) is shown below. This data dictates the size of the SHS that will service the given load profile. November, December, January and February have the highest energy generation potential due to abundant sunshine during these months. June has the lowest potential. Therefore June becomes the benchmarking period in the design as the system must meet the supply requirements particularly during these scarce sunshine days.

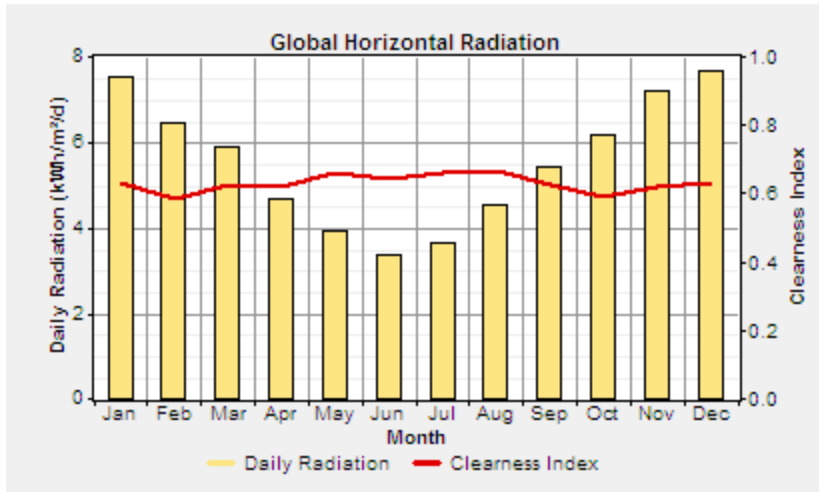


Figure 7-1. Poriking solar energy generation potential.

The system must service the load described below.

C. Load Profile

The proposal made assumptions regarding the load profile because of the missing information as described in point 2 of subsection 7.3.1 above. The load power ratings used to determine the load profiles graphed in Figure 7-2 below are as thus:

1. The fan of a portable energy saving stove rating was taken to be 1000W (this is for a P&H energy saving electric stove [119]).
2. 2 x 14W C.F Philips Energy saver bulbs for internal lighting.
3. 1 x 15W E27 LED light for security lighting.
4. 1 x 5W radio.
5. 6V, 500mA Multi cell phone adapter.

As shown in Figure 7-2 below, the stove was assumed to be on for 3 hours in the morning and for 5 hours in the evening. The radio is also on at the same time. The cell phones can be charged anytime during the day. Lights are on from 17:00 to 22:00 daily. These assumptions were made because this are times when households are more likely to be in the house. The important point to note about this typical household load profile is that energy is required more during periods of no sunshine. Hence this influences a great need for storage so that energy generated during the day is stored for use in the evening and in the morning.

The house uses 8.3 kWh per day. It has a peak demand of 1.9 kW as shown on Figure 7-3 below.

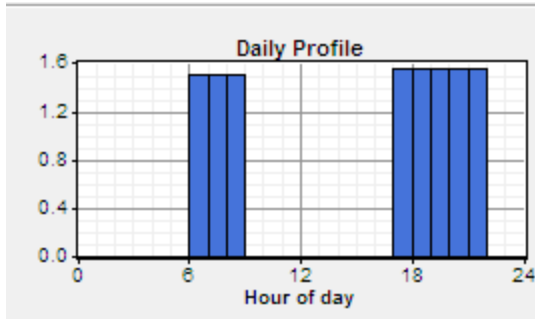


Figure 7-2. Daily load profile that the SHS should service.

D. System architecture

Figure 7-3 below illustrates a simplified schematic architecture of the proposed DC SHS. The system consists of a PV array, a battery bank and the load.

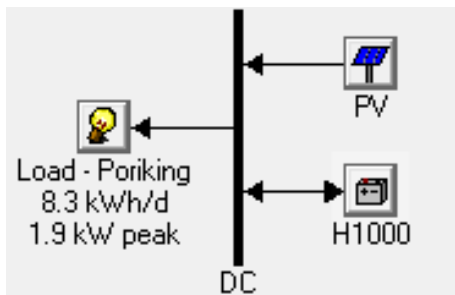


Figure 7-3. The Schematic view of the SHS.

Sensitivity analysis performed using the load profile data graphed in Figure 7-2 above showed that the optimised SHS which would meet the requirements specified in the ToR should consist of:

1. 2 solar PV panels
2. 5 batteries and
3. 1 solar boost charge controller.

Figure 7-4 below shows how the components of the proposed system are to be interconnected. Specifications of these components and other items required to realise the system are shown in Section E below.

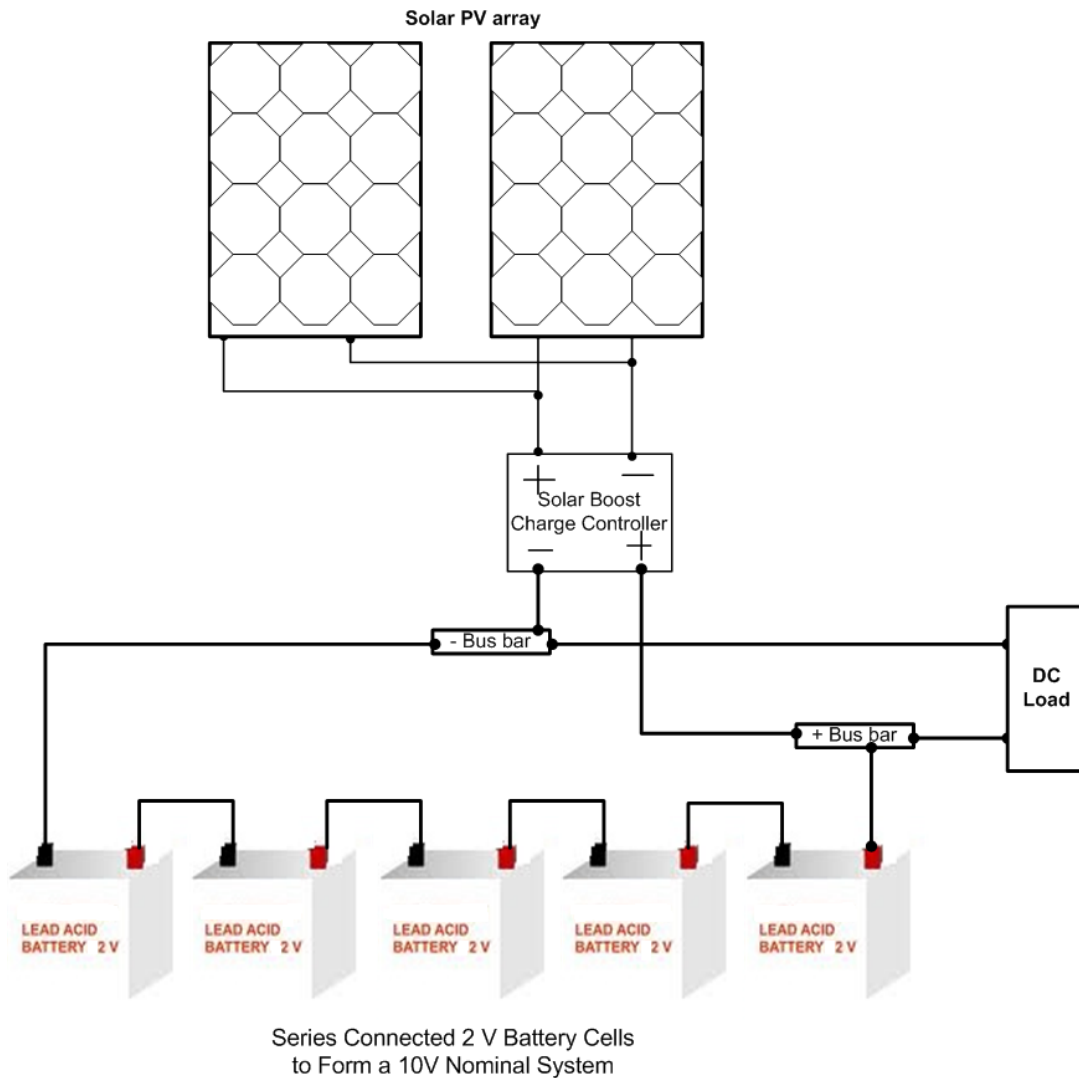


Figure 7-4. Off-grid solar PV system setup.

E. Components specifications and cost of supply

Table 7-A below presents specifications of the components needed for installation of the SHS on one house. The table shows that cost of required components of the SHS per household is **M35, 907.25** (1.00 Maluti (Lesotho currency) is equivalent to ZAR 1.00). Thus for the proposed 100 units, the total estimated cost of the components is **M359, 072.50**.

Table 7-A. Specifications and costs of components for one household.

Item	Description	Quantity	Total Cost
54V 180W HIP	Sanyo HIP 180B2 Solar Module 180W Max Volt. 54V; Max Current 3.33A (HIT Crystalline) Size: 1319x894x35mm.	2	14,715.00
12/24V 60A	Solar boost 12/24V 60A MPPT charge controller (Incl. Temp. sensor)	1	5,670.00
1050Ah Tubular	2V 1050 (810) Ah. MTL25F Tubular battery; incl. Log book, Hydrometer, interconnecting plates	5	8,714.25
	Distribution Board	1	1,350.00
	Armoured Cable	10	378.00
	Lightening Protection	1	1,200.00
Mini 04	Sinetech's Omni Combiner Box	1	R800.00
	Mounting Frame	1	R1080.00
	Transport	1	2000.00
	Total		35,907.25

This section described the technical design of the SHS. The following section presents how the proposal explained the project management methodology and work plan.

7.3.3 Work Approach, Methodology, Project Team

The proposed approach and method described here is based on the ToR given with the RFP. The approach is therefore limited by the system requirements briefing as per the RFP. Some of the limitations that were highlighted are that:

- Daily irradiance and
- Clearance index for the proposed Poriking site were not given.

Further comments on the given RFP were given in Section 7.3.1 above. The following section describes the work approach proposed.

A. Work Approach

The following work plan was produced in accordance with the proposed design presented in the section above.

1. Preliminary design stage

Based on the load profile data given in the ToR and solar irradiation data of the Poriking site available on NASA satellite database, the preliminary design of the SHS was made. The design which includes sketches of the proposed system was presented in subsection 7.3.2 above. Therefore activities performed at this stage were:

- Initial design
- Costing
- Design reporting

2. Award of the contract and site handover to the design team

Following an award of the contract to our team, the project leader arranges consultative meetings between Lead Consultant, Electrical Engineers/Mechanical Engineers, the Constructor, and the following project stakeholders:

- The client (AAP, UNDP, Lesotho Meteorological Services, Government of Japan Representative, etc.),
- Benefiting Poriking households, and
- Any other relevant departments of the Ministry of Natural Resources.

The purpose of these meetings will be to seek further understanding and agreement on the project brief (requirements and specifications) in order to confirm that the design team is on the same page with all the stakeholders.

The following activities will be performed during this stage:

- Consultations with the beneficiaries by the Project Leader.
- Refinement of the requirements and specifications.
- Topographic and topological surveys of the sites by Engineers and technicians.
- Measurements of the buildings for wiring purposes by Technicians.
- Establishment of site office.

Upon receipt of the client's approval and comments, when consultations with relevant authorities are over and agreements on the preliminary designs have been reached, Stages 3 and 4 below will follow.

3. End user needs analysis

Consultations with the beneficiaries of the project will further inform the system requirements and further the understanding of their needs hence the requirements the solution must meet. This stage is necessary for the design team to further reconsider and refine the system to reduce error margin and costs associated to apparent misunderstandings.

Specific task under this stage is:

- The design team meets to analyse additional data collected from Stage 2 above.

The outcome of this stage is input to Stage 4 below.

4. Detailed design and optimization of the SHS

Once user specific data has been analysed, the design team works on the detailed design of the SHS. At this stage the design team addresses the client's comments on the preliminary design report. They further optimise the design to ensure that it meets the user requirements. A final decision on the component specifications and architecture is made.

A review of the project implementation programme is made by the Project Leader so that it takes into consideration the changes instigated to account for additional user/client comments.

Main activities undertaken in this stage are:

- System design review and finalisation of component choices by the Consultant.
- Review of the implementation schedule
- Revision of the system cost estimates based on more detailed information from the design team.
- Detailed design report consisting of the detailed design, revised programme, and cost estimates is compiled for approval by the client

5. Installation site preparation

Once the client has approved the detailed design, the sites are prepared for installation. This involves the following activities performed in close consultation with project beneficiaries:

- Agreeing with households where the panels will be mounted.
- Identifying the location where the battery bank and the solar boost charge controller will be housed.
- Identifying spots for placement of lamps.

6. Procurement of system components

Having reached an agreement on placement of the equipment, procurement of equipment including special fixtures and fittings is made.

The following activities are performed by the Project Leader under procurement:

- Quotations are sort from the identified supplier/manufacturer.
- Orders are placed.
- Orders are expedited.
- Transport arrangements are made for delivery of the equipment to site.
- Arranging for insurance to cover the equipment against any risk of damage.
- Receiving the components at the site office.
- Arranging for warehousing of the SHS components and accounting for handling of fragile equipment such as solar panels etc.
- Accounting: checking the budget, purchase order, invoice and delivery note for discrepancies before making payments. Keeping and updating all the necessary records and communicating any deviations to the relevant parties.

7. Installation of the SHS

At this stage the Project Leader assisted by his team of Engineers carryout the administration of the project. They oversee the installation process which is implemented by the Construction Manager and his team of technicians.

One Engineer from the design team will act as a resident site representative to work with the Construction Manager and lead the installation team. This Engineer will perform the following activities:

- Attend regular site progress meetings. The meetings are arranged to be at fortnightly interval. Weekly check-ins will be done during the first month of the installation process and during the last month of the project completion.
- Inspect the installation works for conformity with the contract documentation.
- Certify work for processing of payments.

8. End user training and acceptance

The Lead Consultant or representatives from his team of Engineers will prepare user training material written in English and Sesotho.

The team will facilitate a training presentation targeted to the benefiting households. The aim of the material will be to educate the households on how to use the SHS. Particular attention will be given on how to care for the system especially the batteries. That is, checking for water levels using the hydrometer, and filling the battery log book. The training material will also cover health and safety factors.

The main activities in this stage are as thus:

- Preparation of training material,
- Conducting the training of the end users in groups, and
- Performing acceptance tests to ensure that the system works as required.

9. Project close out

Following the successful completion of the installation works, the design team will facilitate the project close-out. This includes preparation of necessary project completion documentation according to the contract. The project will then be handed over to the client.

B. Design Methodology

It is the intension of the design to ensure that the system meets the requirements of the beneficiaries much as possible. This is achieved by careful analysis and modelling of the load profile. Renewable energy analysis software tools are applied to determine the best optimal SHS solution that satisfies the requirements of the user under various weather conditions, especially when sunlight is minimal like in winter seasons.

Furthermore, wherever possible locally available components such as panel mounting rails, cables and switches will be used. Use of locally available components is adapted to support local businesses. Aesthetical design considerations will be taken into account to ensure that the system is pleasurable to use.

C. Project team and roles

The project team formed for this project consisted of the design team, construction and installation, and support teams. The roles in the team are illustrated in the organogram below.

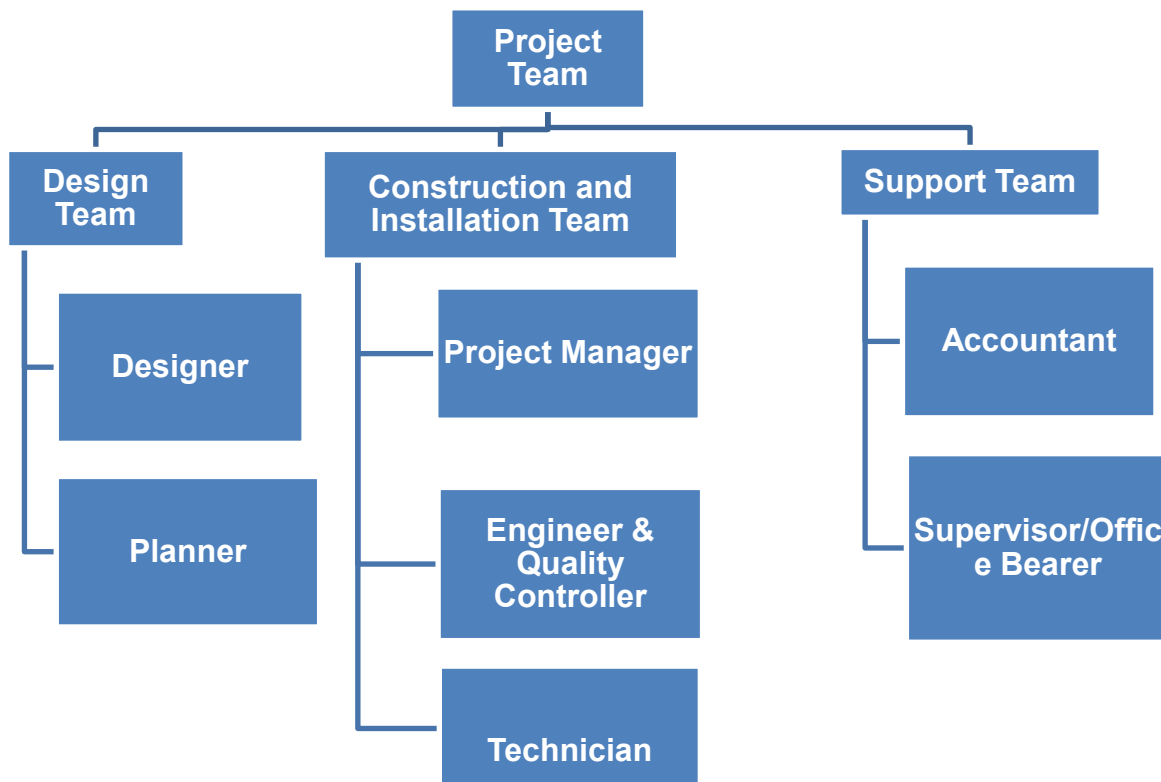


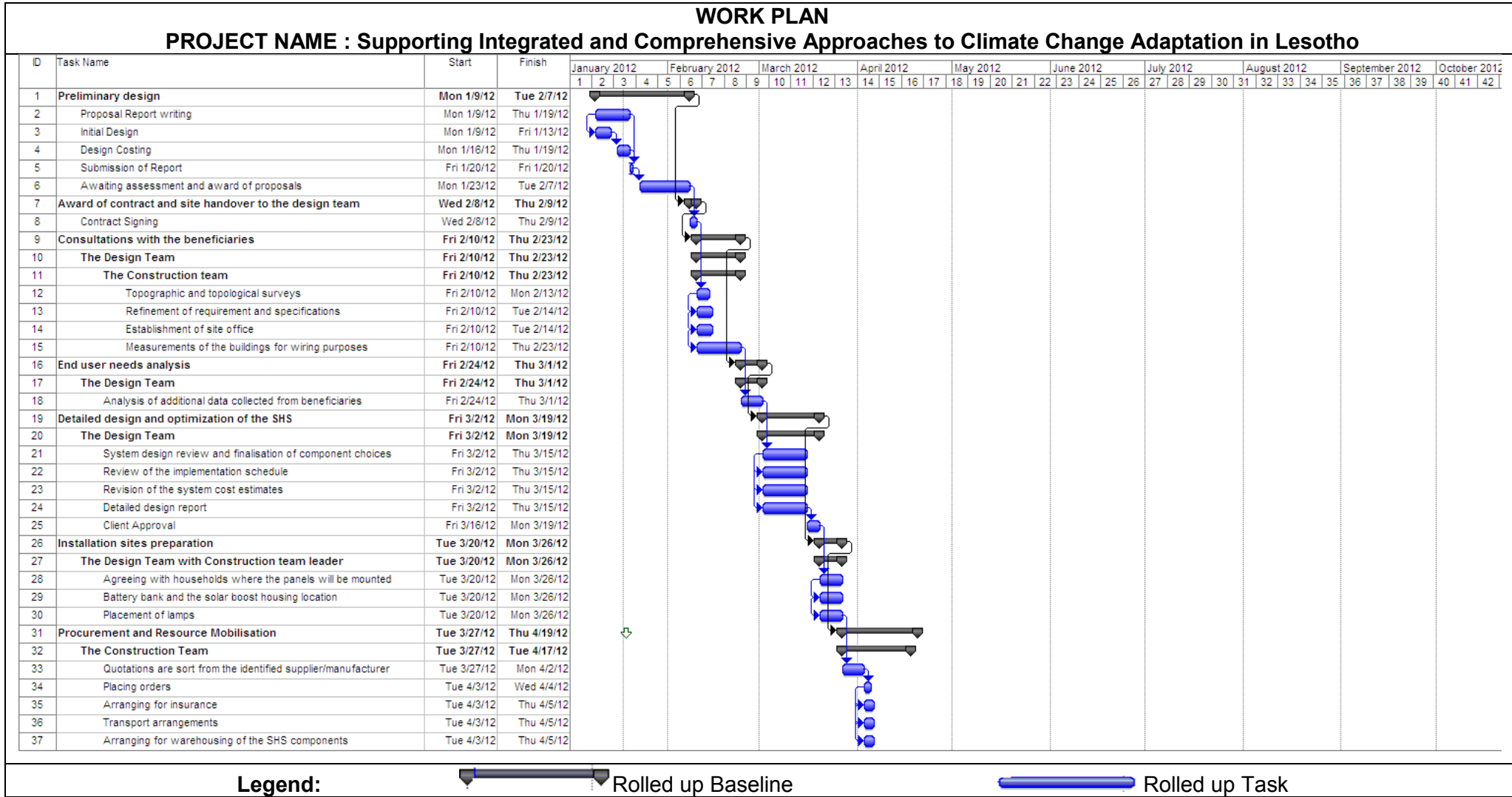
Figure 7-5. Organogram showing roles in the project team.

The technical description of the proposal consisted of work approach, design methodology, and project team as discussed above. Subsection 7.3.6 below presents the schedule that was proposed for this project.

7.3.4 Activity (work) schedule

The proposed work plan is closely related and influenced by the technical approach and methodology described above.

Table 7-B. Detailed activity schedule produced from Microsoft Project.



After describing the technical details of the proposed project, the question that had to be answered was the cost of the proposed design. The following section describes the financial proposal that was tendered for this project.

7.4 Proposed Budget for the technical proposal

The budget proposal details costs of implementing the project. The proposal covered costs for consultancy services to be rendered plus installation costs. It consists of the following sections: financial proposal submission form, breakdown of summary price, summary of remuneration per activity, daily subsistence allowance (DSA), and miscellaneous expenses.

Proposals and tendering process requires remuneration for the basic services to be done on a per activity basis by issuing claims (completion certificates) to the client after completion of a certain activity/phase of the project. Section 7.4.1 below describes the summary of the per activity remuneration schedule that was presented to the client.

7.4.1 Summary of remuneration per activity

Table 7-C through to Table 7-J below tabulate a breakdown of costs for each of the eight activities (deduced from Table 7-B above). The rates are based on Consttec's charges for jobs of this nature.

Table 7-C. Preliminary design.

Activity	Description of Activity	No. of Days	Daily Rate (M)	Total Amount (M)
1	Preliminary design	22		
	Initial Design	5	2 300.00	11 500.00
	Design Costing	4	1 600.00	6 400.00
	Proposal Report writing	9	1 600.00	14 400.00
	Submission of Report/Proposal admin	1	1 900.00	1 900.00
	Sub-total			34 200.00

Table 7-D. Award of contract and site handover to the design team.

Activity	Description of Activity	No. of days	Daily Rate (M)	Total Amount (M)
2	Award of contract and site handover to the design team	12		
	Contract Signing/contract meetings	2	1 900.00	3 800.00
	Consultations with the beneficiaries	10	2 300.00	23 000.00
	Measurements of the buildings for wiring purposes	10	1 100.00	11 000.00
	Refinement of requirement and specifications	3	2 300.00	6 900.00
	Establishment of site office	3	1 900.00	5 700.00
	Topographic and topological surveys	2	1 100.00	2 200.00
	Sub-total			52 600.00

Table 7-E. End user needs analysis.

Activity	Description of Activity	No. of days	Daily Rate (M)	Total Amount (M)
3	End user needs analysis	17		
	Analysis of additional data collected from beneficiaries	5	2 300.00	11 500.00
	Detailed design and optimization of the SHS	12	2 300.00	27 600.00
	System design review and finalisation of component choices	10	1 600.00	16 000.00
	Review of the implementation schedule	10	1 600.00	16 000.00
	Revision of the system cost estimates	10	1 600.00	16 000.00
	Detailed design report	10	1 600.00	16 000.00
	Client Approval/contract meetings	2	1 900.00	3 800.00
Sub-total			106 900.00	

Table 7-F. Installation sites preparation.

Activity	Description of Activity	Number of days	Daily Rate (M)	Total Amount (M)
4	Installation sites preparation	5		
	Agreeing with households where the panels will be mounted	5	1 400.00	7 000.00
	Battery bank and the solar boost housing location	5	1 400.00	7 000.00
	Placement of lamps	5	1 400.00	7 000.00
	Sub-total			21 000.00

Table 7-G. Procurement and resource mobilisation.

Activity	Description of Activity	No. of days	Daily Rate (M)	Total Amount (M)
5	Procurement and Resource Mobilisation	18		
	Quotations are sort from the identified supplier/manufacturer	5	550.00	2 750.00
	Placing orders	2	550.00	1 100.00
	Arranging for insurance	3	550.00	1 650.00
	Transport arrangements	3	550.00	1 650.00
	Arranging for warehousing of the SHS components	3	550.00	1 650.00
	Expediting orders	7	550.00	3 850.00
	Receiving the deliveries	1	550.00	550.00
	Accounting: checking the budget, purchase order, invoice etc.	2	800.00	1 600.00
	Sub-total			14 800.00

Table 7-H. Installation of SHS.

Activity	Description of Activity	No. of days	Daily Rate (M)	Total Amount (M)
6	Installation of the SHS	92		
	Installation process	90	1 400.00	126 000.00
	Attend regular site progress meetings	90	1 900.00	171 000.00
	Inspect the installation works	90	1 400.00	126 000.00
	Certify work for processing of payment	2	2 300.00	4 600.00
	Sub-total			427 600.00

Table 7-I. End user training and acceptance.

Activity	Description of Activity	No. of days	Daily Rate (M)	Total Amount (M)
7	End user training and acceptance	6		
	Preparation of training material	3	1 600.00	4 800.00
	Conducting the training	3	550.00	1 650.00
	Performing acceptance tests	3	1 400.00	4 200.00
	Sub-total			10 650.00

Table 7-J. Project closeout .

Activity	Description of Activity	No. of days	Daily Rate (M)	Total Amount (M)
8	Project closeout	20		
	Final completion certificate	20	2 300.00	46 000.00
	Final accounting	10	800.00	8 000.00
	Final drawings	1	1 600.00	1 600.00
	Sub-total			55 600.00

7.4.2 Daily subsistence allowance (DSA) at UNDP applicable rates

This is money that the consultants are entitled to when they have to go out of their way to perform duties beyond normal working hours at the project site. These prices were given by the UNDP office Lesotho [120].

Table 7-K. Subsistence Allowance.

Activity	Days	Daily Rate (M)	Amount (M)
1. Preliminary design	12	0.00	0.00
2. Award of contract and site handover to the design team	5	400.00	2 000.00
3. End user needs analysis	17	0.00	0.00
4. Installation sites preparation	5	400.00	2 000.00
5. Procurement and Resource Mobilisation	10	400.00	4 000.00
6. Installation of the SHS	8	400.00	3 200.00
7. End user training and acceptance	6	400.00	2 400.00
8. Close out	0	0.00	0.00
Sub-total			M 13 600.00

Having looked at the individual cost of the project activities above, the costs were summed together as summarized in the section below.

7.4.3 Summary of total costs of the proposed system

The summary is broken into consultancy services costs and components costs. These form the total costs of the proposal. Summary of consultancy services are presented in the table below.

Table 7-L. Cost of consultancy services.

Price Component	Currency(ies)	Amount(s)
Remuneration for Basic Services	Maloti/ZAR	723, 350.00
Out of Pocket Expenses (DSA)	Maloti/ZAR	13, 600.00
Miscellaneous Expenses	Maloti/ZAR	40, 370.00
Sub – Total	Maloti/ZAR	777, 320.00

The table below captures the system components costs whose breakdown was presented in the technical proposal.

Table 7-M. Estimated cost of system components for 100 houses.

Price Component	Currency(ies)	Amount(s)
System Components	Maloti/ZAR	359, 072.50.

The amalgamated costs of the proposed project are presented in the table below.

Table 7-N. Total estimated cost of implementing the project.

Costs	Currency(ies)	Amount(s)
Estimated System Components	Maloti/ZAR	359, 072.50
Consultancy Costs	Maloti/ZAR	777, 320.00
Total amount of Financial Proposal	Maloti/ZAR	1, 136,392.00

This report thus far has presented all the studies undertaken to achieve the objectives of the dissertation. It looked at two DSM programmes modelling and project management case studies of the same programmes. Chapter 8 below presents conclusions and recommendations drawn from studying the models and the case studies.

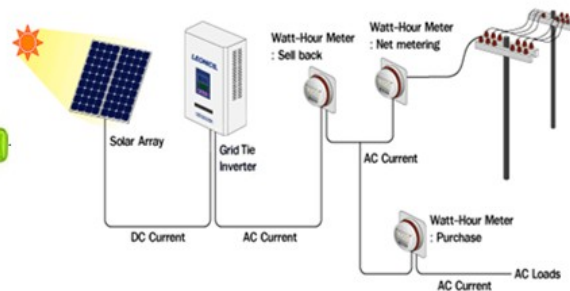
8 Conclusions, Recommendations and Future Work

This chapter presents conclusions and recommendations drawn from the studies as well as proposed future work. The thesis looked into different ways which can be employed for demand side management of households. The first of the propositions made in this report was adding a layer of technology called advanced metering infrastructure. The second solution discussed is integration of household based solar PV systems. Within each of these DSM interventions the thesis focussed on solving key issues concerning implementation of the proposed solutions. These issues are: 1) WAN connectivity for the AMI, 2) economic feasibility and 3) protection of grid connected home-based solar PV systems. Figure 8-1 below summarises the essence of achievements of this dissertation. The thesis proposed and studied MPLS based AMI WAN and grid connected solar PV systems to achieve an energy efficient household. Conclusions reached from each of the studies performed are detailed in the subsections below.

1. MPLS Based Energy Management System WAN



2. Grid-connected Home-based Solar System



Energy Efficient Household

Figure 8-1. Conclusion for the work done in this thesis

8.1 Conclusions

8.1.1 AMI networks investigations.

The AMI simulations focused on connectivity of smart meters. The core support of the advanced metering infrastructure is communication networks. Literature has shown that there are several alternative methods of approaching communication networks for energy industry. The thesis focused on two areas of the network: the WAN and the MAN. Most of the networking technology currently used in both areas was found to be proprietary. Lack of standardisation of the protocols used in these communication networks inhibits interworking of heterogeneous technologies from different manufacturers. This makes it difficult to rollout AMI projects.

Cost of implementation of most of the prevailing communication network approaches is high. Most of the currently proposed technologies such as optic fibre, and PLC require utilities to invest in costly private network infrastructure. This is exacerbated by low data volumes of metering and other smart grid applications. The private networks become under-utilised and

hence low return on capital investment. This makes implementation of AMI for DSM of households seems infeasible.

Using public networks for the WAN by connecting with network service providers is a technically feasible option. MPLS configured networks of the service providers are a viable solution of connecting energy smart meters. With MPLS data can be transmitted over a combination of heterogeneous layer two technologies (ATM, Ethernet, Frame Relay, etc.). It supports all layer three protocols such as IP. The simulations have shown that the proposed MPLS network outperforms pure IP network. MPLS network has lower end to end delay than that of pure IP network. Thus it carries data from the smart meters to the MDMS faster than a pure IP network. The lower latencies are also attributable to the lower number of hops experienced in MPLS configured networks as shown by Figure 5-5. MPLS networks have also proven to be more reliable than IP networks. This is shown by the lower variation in end to end delay.

Wi-Fi network was found to be suitable for MAN of IEDs in a control, protection and monitoring network. The protection network has more stringent QoS requirements than energy metering network as has been detailed; thus since the Wi-Fi network suits this network, it is also suitable for MAN of smart meters. In addition to energy management through provision of energy usage information provided by AMI, energy shortage can also be curbed by integrating solar PV systems into households. The subsection below presents conclusions reached on the feasibility of this option.

8.1.2 Solar PV DGs investigations

Solar PV integration investigations looked at economical and technical feasibility. Viability of a meshed microgrid system (with three households interconnected) was investigated and compared with that of a single household system. The meshed microgrid system with three households interconnected into a single load is more economically feasible than the single household system. As discussed in the analysis of the results, COE for the three-household system was found to be always lower than that of the single-household system. The 31% renewable energy system gave R1.40 for the meshed system and R1.42 for the single-household system. Moreover, for the 50% renewable energy system, the COE for the meshed system was R1.47, whereas it was R1.73 for the single-household system. While the difference in the levelised COE may not be considerable, the NPC show that the meshed microgrid system is far cheaper than its counterpart.

The technical feasibility investigated protection schemes suitable for the proposed household based grid integrated solar PV DGs. Differential current protection scheme was simulated. The differential current protection scheme detects three phase faults. It is therefore a technically feasible scheme for protection of the proposed meshed microgrids.

8.2 Recommendations

Subsections 8.2.1 and 8.2.1 below describe recommendations informed by the studies carried out in this dissertation. The recommendations are limited to the studies and literature presented in this dissertation.

8.2.1 AMI implementation in South Africa

Based on the above conclusions and the results in Chapter 5, the following recommendations on implementation of AMI are made. The backhaul network of the AMI should be based on NSP's network. NSP should configure MPLS on their networks to meet the varying and strict QoS requirements of utility applications. Furthermore, wireless networks should be used for the MAN. These networks offer flexibility and are easy to install. Moreover, in the South African context, Eskom and the Municipalities should liaise with state-owned NSP such as Telkom, Swiftnet, and Broadband Infracore to subcontract AMI network. This is likely to be a viable option as the networks will not be dedicated to AMI only. It is also a technically feasible option as it allows the utilities to focus on their core business.

8.2.2 Implementation of solar PV DGs

Meshed household based solar PV DGs must be used as opposed to having individual systems (gridlets) on each household connected to the main utility grid. The studies have shown that meshed microgrids are more economical. Furthermore, communication network supported differential protection scheme must also be implemented to protect the PCC of the meshed microgrids to form a WAMPAC system.

The proposed concepts on demand side management of households by integration of advanced metering infrastructure and solar PV distributed generators have been validated. The thesis focused on specific areas within these brought concepts. Refined objectives were set, pursued and have been achieved. The refinement left room for further areas of research within the DSM concept. Section 8.3 below briefly summarises further research that can be carried out to attain more insight into the proposed DSM programmes.

8.3 Future Work

This section describes future directions which research on the concepts of DSM using AMI and solar PV DGs may take. It describes future work that may be pursued on AMI. This is followed by recommended future research which can be done on grid-connected solar PV DGs. It also presents suggestions on important work that can be done on demand management and demand response.

8.3.1 *AMI Communication networks research*

New research areas which can be explored in field of AMI communication networks are Machine to machine (M2M) communication protocols, IP Multimedia Subsystem (IMS) and Evolved Packet Core (EPC). These areas are going to dominate research in communication networks in the near future. M2M protocols are part of new developments considered for bringing an “Internet of things”. Further developments being done are in the spectrum of convergence in the form of IP Multimedia Subsystem (IMS) as opposed to IP/MPLS discussed above. Another interesting development which can be seen as the future enabling technology for energy management infrastructure is the Evolved Packet Core (EPC). M2M, IMS, EPC are new communication network concepts which are likely to transform the internet as we know it today.

8.3.2 *Design of Demand Response Algorithms*

One of the cornerstone propositions in achieving demand side management (DSM) is the ability to control appliances. An interesting project which can be done as an extension to the DSM concepts in this thesis is the design and implementation of appliance controller devices (ACDs). The importance of ACDs is load management through demand response algorithms. They become useful tools in DSM programmes as they provide ability to utilities and homeowners to control appliances. The various questions which research in this area must answer are:

1. Which appliances must be switched-off?
2. When should they be switched off without inconveniencing end-users?
3. How long should they be off in order to achieve the desired shift of peak demand?

It is about learning consumer behaviour and designing algorithms that best achieve DSM without impacting the end user drastically.

8.3.3 Measurement and Verification of DSM Programmes

Eskom is currently employing universities to carry out measurement and verification of their DSM programmes. Perhaps an important project that may be done in future is to determine mechanisms of validating that the DSM programmes are actually achieving their claimed energy savings. The project in this area would design benchmarks for validating effectiveness of various DSM programmes such as the LED/CFL (light emitting diode/compact fluorescent light) bulbs drive, energy efficient shower heads drive, energy efficient motors, etc.

8.3.4 Wide Area Monitoring, Protection and Control (WAMPAC) Demo Tool

A future project work in the field of control and monitoring of meshed solar PV microgrids can be on WAMPAC. WAMPAC refers to use of system-wide distributed intelligent devices that collect information from the grid. The information is communicated to a central location and shared between the devices. This information is used to coordinate the power system to ensure wide-area stability. The devices used are phasor measurement units (PMUs), and other IEDs. The devices are expected to reduce number of occurrences of blackouts. They will improve reliability of power systems and ensure security of energy supply. WAMPAC is a new concept. Future research in this area may develop a demonstration tool for teaching purposes to educate power engineering students about WAMPAC concepts.

References

- [1] Anup Shah. (2004, October) Global Issues. [Online]. <http://www.globalissues.org/>
- [2] Anup Shah. (2012, March) Global Issues. [Online]. <http://www.globalissues.org/issue/178/climate-change-and-global-warming>
- [3] Eskom. (2011, March) Eskom Content. [Online]. <http://www.eskom.co.za/content/20110318QandA49m.pdf>
- [4] USA's Department of Energy. (2012, January) Weatherization and Intergovernmental Program. [Online]. <http://www1.eere.energy.gov/wip/wap.html>
- [5] K.F. Katiraei and J.R. Agüero, "Solar PV Integration Challenges," *IEEE Power & Energy Magazine*, vol. 9, no. 3, pp. 62 -71, May - June 2011.
- [6] Hanzheng Duo and F. Bucca, "Demand Side Management Programs in the Western Sydney Areas," in *CIREC Seminar: SmartGrids for Distribution*, Frankfurt, 2008, pp. 1-4.
- [7] Xiao-min Bai, Jun-xia Meng, and Ning-hui Zhu, "Functional analysis of advanced metering infrastructure in smart grid," in *Power System Technology (POWERCON)*, Beijing, 2010, pp. 1-4.
- [8] Kah -H. Ng and G.B. Sheblé, "Direct load control-A profit-based load management using linear programming," *IEEE Transactions on Power Systems*, vol. 13, no. 2, pp. 688-694, May 1998.
- [9] N A Siweya, "INNOVATIVE ENERGY EFFICIENCY COMMUNICATION AND AWARENESS CAMPAIGN," in *Industrial and Commercial Use of Energy (ICUE)*, Cape Town, 2011, pp. 181-183.
- [10] M Senatla, "FAST TRACKING THE IMPLEMENTATION OF MINIMUM ENERGY PERFORMANCE STANDARDS (MEPS) AND MANDATORY APPLIANCE LABELLING IN SOUTH AFRICA: LESSONS LEARNT FROM THE VOLUNTARY APPLIANCE LABELLING," in *Domestic use of Energy (DUE) Conference*, Cape Town, 2012, pp. 39-42.
- [11] ABB. (2009, February) A layman's guide to power networks. [Online]. <http://www.abb.com/cawp/db0003db002698/37130d5f9a0b0ae4c12572c80034021c.aspx>
- [12] ABB. (2006) Three phase power resource site. [Online]. <http://3phasepower.org/3phasesgenerators.htm>
- [13] Virtual Museum. (2010) The history of hydroelectric in Quebec. [Online]. <http://www.hydroelectricite.ca/en/from-the-switching-station-at-home.php>
- [14] Parliament Office of Science and Technology, "UK Electricity Networks," Parliament Office of

References

- Science and Technology, London, POSTNOTE 163, 2001.
- [15] Math H.J. Bollen, *The Smart Grid. Adapting the Power System to New Challenges*, 1st ed., Jerry Haddings, Ed. Lincoln, Nebraska, USA: Morgan & Claypool, 2011.
- [16] Wenpeng Luan, Duncan Sharp, and Sol Lancashire, "Smart grid communication network capacity planning for power utilities," in *IEEE PES Transmission and Distribution Conference and Exposition*, Burnaby, 2010, pp. 1-4.
- [17] Motive Industries Inc. (2010, December) Motive. [Online]. <http://autodesign-blog.com/tag/smart-grid-2/>
- [18] Kenneth C Budka, Jayant G Deshpande, and Tewfik L. Doumi, "Communication Network Architecture and Design Principles for Smart Grids," *Bell Labs Technical Journal*, vol. 15, no. 2, pp. 205-227, September 2010.
- [19] John Caskey, "Are Smart Meters Really Smart?," *Metering International*, no. 4, pp. 28-29, 2010.
- [20] C.L King. (2012, February) Microchip.com. [Online]. <http://ww1.microchip.com/downloads/en/AppNotes/00994b.pdf>
- [21] EDF Energy. (2012, February) Edfenergy. [Online]. http://www.edfenergy.com/products-services/large-business/PDF/B2B_ePublications/B2B-MBC-040.pdf
- [22] Microchip. (2005) Introduction to Utility Metering Tutorial. Tutorial.
- [23] Kes Tam, "A Low-Cost Single-Phase Electricity Meter Using the MSP430C11x," Texas Instruments, Dallas, Application Report 2002.
- [24] Atmel, "AVR465: Single-Phase Power/Energy Meter with Tamper Detection," Atmel Corporation, San Jose, Application Note 2004.
- [25] NEMA. (2012, February) Nema. [Online]. <http://www.nema.org/stds/complimentary-docs/upload/ANSI%20C12.10-2011%20Contents%20and%20Scope.pdf>
- [26] Alexander.E Emanuel, "Summary of IEEE Standard 1459: Definitions for the Measurement of Electric Power Quantities Under Sinusoidal, Nonsinusoidal, Balanced, or Unbalanced Conditions," *IEEE Transactions on Industry Applications*, vol. 40, no. 3, pp. 869-876, May/June 2004.
- [27] NMI. (2012, February) Metrology. [Online]. http://www.nmi.nl/metrology/type_examination/energy/watt-hour_meter
- [28] Efficiency Valuation Organisation. (2012, February) Evo-world. [Online]. <http://www.evo-world.org/>
- [29] John Schinter. (2012, February) Today's Facility Manager. [Online]. <http://www.todaysfacilitymanager.com/articles/services-and-maintenance-energy-measurement-and-verification1.php>
- [30] Efficiency Valuation Organisation. (2012, February) IEA. [Online].

References

- http://www.iea.org/work/2011/iip/evo_ipmvp.pdf
- [31] Energy Valuation Organisation. (2012, February) Evo-world. [Online]. http://www.evo-world.org/index.php?option=com_docman&task=doc_view&gid=641&lang=en
- [32] Eskom. (2011, April) Eskom Web site. [Online]. <http://www.eskom.co.za/content/Tariff%20brochure%202011.pdf>
- [33] City of Cape Town. (2011, December) Cape Town Government. [Online]. <http://www.capetown.gov.za/en/electricity/Pages/ElectricityTariffs.aspx>
- [34] Brand South Africa. (2011, May) SouthAfrica.info. [Online]. www.southafrica.info/business/economy/infrastructure/energy.htm
- [35] A Van Deventer, S Chowdhury, S.P Chowdhury, and C.T Gaunt, "Management of Emergency Reserves Dispatching in Electricity Networks," in *Power System Technology (POWERCON)*, Hangzhou, 2010, pp. 1-5.
- [36] Richard P Lewis, P Igic, and Z Zhou, "Assessment of Communication Methods for Smart Electricity Metering in the U.K.," in *IEEE PES/IAS Conference on Sustainable Alternative Energy (SAE)*, Swansea, 2009, pp. 1-4.
- [37] NRS. (2011, May) NRS online. [Online]. www.nrs.eskom.co.za
- [38] National Energy Technology Laboratory, "The Modern Grid Initiative," Office of Electricity Delivery and Energy Reliability, Washington, DC, 2007.
- [39] Matt Bodimeade. (2012, July) Companies and Markets. [Online]. <http://www.companiesandmarkets.com/News/Energy-and-Utilities/Advanced-metering-infrastructure-market-dominated-by-the-US/NI3894>
- [40] Henri Groenewald, "NRS049 – ADVANCED METERING INFRASTRUCTURE (AMI) FOR RESIDENTIAL AND COMMERCIAL CUSTOMERS," ESKOM, Johannesburg, Presentation 2009.
- [41] Monontši Nthontho, S.P Chowdhury, and Simon Winberg, "Smart communication networks standards for smart energy management," in *International Telecommunications Energy Conference (INTELEC)*, Asterdam, 2011, pp. 1-9.
- [42] John Caskey, "Are Smart Meter Really Smart?," *Metering International*, no. 4, 2010.
- [43] A Gabaldbn et al., "Assessment and Simulation of Demand-Side Management Potential in Urban Power Distribution Networks," in *IEEE Bologna PowerTech Conference*, Bologna, 2003, pp. 1-5.
- [44] Government of Ontorio IT standards, "Advanced Metering Infrastructure," Government of Ontorio, Ontorio, IT Standard GO-ITS51, 2007.
- [45] Shiming TIAN and Ren Xu, "Key Technology Research of CHINA Advanced Metering Infrastructure," in *Power System Technology (POWERCON)*, Hangzhou, 2010, pp. 1-7.

- [46] Nuri. (2011) Thinking About Smart Grid. Brochure.
- [47] Yi Qian and H. Sharif, "A Secure and Reliable In-network Collaborative Communication Scheme for Advanced Metering Infrastructure in Smart Grid," in *Wireless Communications and Networking Conference (WCNC)*, Quintana-Roo, 2011, pp. 909 - 914.
- [48] Nogil Myoung, Younghyun Kim, and Sangyeom Lee, "The Design of Communication Infrastructures for smart DAS and AMI," in *International Conference on ICT Convergence (ICTC)*, Jeju Island, 2010, pp. 461-462.
- [49] C. Selvam, K. Srinivas, G.S. Ayyappan, and M. Venkatachala Sarma, "Advanced Metering Infrastructure for Smart Grid Applications," in *International Conference on Recent Trends in Information Technology (ICRTIT)*, Chennai, 2012, pp. 145-150.
- [50] James St.Pierre, Overview of NIST Smart Grid Cyber Security Working Group, 2010.
- [51] Jun Wang, C. M Victor, and Leung, "A survey of technical requirements and consumer application standards for IP-based smart grid AMI network," in *International Conference on Information Networking (ICOIN)*, Kuala Lumpur, 2011, pp. 114-119.
- [52] ECP. (2011, April) ECP. [Online]. <http://www.uschinaecp.org/working-groups/>
- [53] Chengbing Wei, "A Conceptual Framework for Smart Grid," in *Power and Energy Engineering Conference (APPEEC)*, Asia-Pacific, 2010, pp. 1-4.
- [54] Coalton Bennett and Darren Highfill, "Networking AMI Smart Meters," in *IEEE Energy 2030 Conference*, Georgia, 2008, pp. 1 - 8.
- [55] Muhammad Mehroze Abdullah and Barry Dwolatzky, "Smart Demand-Side Energy Management Based on Cellular Technology - A way towards Smart Grid Technologies in Africa and Low Budget Economies," in *IEEE AFRICON*, Nairobi, 2009, pp. 1-5.
- [56] Fadlullah Md Zubair, Mostafa M Fouda, and Nei Kato, "Toward Intelligent Machine-to-Machine Communications in Smart Grid," *IEEE Communications Magazine*, vol. 49, no. 4, pp. 60-65, April 2011.
- [57] Bob Heile. (2011, March) IEEE SmartGrid. [Online]. <http://smartgrid.ieee.org/news-smart-grid-newsletter/3953-advanced-metering-infrastructure-will-have-unexpected-impacts-on-utilities>
- [58] ZigBee Alliance. (2011) ZigBee.org. [Online]. <http://www.zigbee.org/Standards/ZigBeeSmartEnergy/Overview.aspx>
- [59] P Wang, J. Y Huang, Y Ding, P Loh, and L Goel, "Demand Side Load Management of Smart Grids Using Intelligent Trading/Metering/ Billing System," in *IEEE PES General Meeting*, Minneapolis, July 2010, pp. 1-6.
- [60] Daintree, "Getting Started with ZigBee and IEEE 802.15.4," Daintree, California, Primer 2008.

- [61] Manas Saksena. (2011, October) EE Times Design. [Online]. <http://www.eetimes.com/design/smart-energy-design/4229848/SEP--Smart-Energy-Profile--2-0-Uncovered>
- [62] Martin Gilje Jaatun, Jan Tore Sørensen. (2007, August) A Description of the Manufacturing Message Specification (MMS). Memo PDF document.
- [63] Ken Masica, "Recommended Practice Guide Securing WLANs using 802.11i," Lawrence Livermore National Laboratory, California, UCRL-TR-225541, 2007.
- [64] RSA. (2012, January) RSA Laboratories. [Online]. <http://www.rsa.com/rsalabs/node.asp?id=2084>
- [65] Guillaume Lehenbre. (2005, June) Wi-Fi security – WEP, WPA and WPA2. <http://hakin9.org>.
- [66] D-Synergy. (2012, January) D-Synergy. [Online]. <http://www.d-synergy.com/firetide-mesh>
- [67] Firetide. (2012, January) Firetide. [Online]. <http://www.firetide.com/innercontent.aspx?taxid=8&id=74>
- [68] Firetide. (2008) HotView Pro™ Network Management Software. Datasheet.
- [69] AudioCodes Ltd. (2010) Microsoft Unified Communications Network Architectures. White Paper.
- [70] Netgear. (2005, October) Virtual Private Networking Basics. PDF Manual.
- [71] Peter J. Welcher. (2003, February) Introduction to MPLS. White paper.
- [72] Forrest Small, Tom Brunetto Frances Cleveland, *Smart Grid: Interoperability and Standards - An Introductory Review.*: Utilities Standards Board, 2008.
- [73] Spintelligent. (2011, March) African Utility Week. [Online]. <http://www.african-utility-week.com/en/index.php>
- [74] Iskraemeco. (2011) Energy Measurement and Management. Brochure.
- [75] Jim Roche. (2011, November) AMR vs AMI. [Online]. <http://www.elp.com/index/display/article-display/341596/articles/utility-automation-engineering-td/volume-13/issue-10/features/amr-vs-ami.html>
- [76] Jin Xiao, Jae Yoon Chung, Jian L, Raouf Boutaba, and James Won-Ki Hong, "Near Optimal Demand-Side Energy Management Under Real-time Demand-Response Pricing," in *International Conference on Network and Service Management (CNSM)*, Niagara Falls, 2010, pp. 527 - 532.
- [77] Q.B. Dam, S. Mohagheghi, and J. Stoupis, "Intelligent Demand Response Scheme for Customer Side Load Management," in *Energy 2030 Conference*, Atlanta, 2008, pp. 1-7.
- [78] Rob van Gerwen, Saskia Jaarsma, and Rob Wilhite, "Smart Metering," *Leonardo-Energy*, pp. 1-9, July 2006.
- [79] Henri Groenewald. (2008) NRS049 --Advanced metering infrastructure metering infrastructure(AMI). Presentation.

References

- [80] Jian Chen, He Zheng-you, and Wei Jiang, "The overview of protection schemes for distribution systems containing micro-grid," in *Power and Energy Engineering Conference (APPEEC)*, Wuhan, 2011, pp. 1-4.
- [81] S Conti and S Raiti, "Integrated Protection Scheme to Coordinate MV Distribution Network Devices, DG Interface Protections and Micro-Grids Operation," in *International Conference on Clean Electrical Power (ICCEP)*, Capri, 2009, pp. 640-646.
- [82] Alfredo Vaccaro, Marjan Popov, Domenico Villacci, and Vladimir Terzija, "An Integrated Framework for Smart Microgrids Modeling, Monitoring, Control, Communication and Verification," *Proceedings of the IEEE*, vol. 99, no. 1, pp. 119-132, January 2011.
- [83] Xi Li, Zhongqiu Wang, Gengyin Li, Ming Zhou, and K. L. Lo, "The Generating Mechanism and Optimal Control of Power Quality in Micro-grids," in *International Conference on Power System Technology (POWERCON)*, Hangzhou, 2010, pp. 1-7.
- [84] India Energy Portal. (2012, March) India Energy Portal. [Online]. http://www.indiaenergyportal.org/subthemes.php?text=dis_gen&themeid=14
- [85] NERSA, "NERSA Consultation Paper - Review of Renewable Energy Feed - In Tariffs," NERSA, Pretoria, Consultation paper 2011.
- [86] A Prasai et al., "Protection of meshed microgrids with communication overlay," in *Energy Conversion Congress and Exposition (ECCE)*, Georgia, 2010, pp. 64-71.
- [87] Glover J Duncan, Sarma S Mulukutla, and Overbye J Thomas, *Power System Analysis and Design*, 4th ed., Harjan James, Ed. Ontario, Canada: Thomson Learning, 2008.
- [88] S Chowdhury, S.P Chowdhury, and P Crossely, *Microgrids and Active Distribution Networks*, 1st ed. London, United Kingdom: Institute of Engineering and Technology, 2009.
- [89] Zhu Yongli, Song Shaoqun, and Wang Dewen, "Multiagents-based wide area protection with best-effort adaptive strategy," *Electrical and Power Energy Systems*, vol. 31, pp. 94-99, October 2009.
- [90] Vajira Pathirana, "A Power System Protection Scheme Combining Impedance Measurement and Travelling Waves: Software and Hardware Implementation," University of Manitoba, Winnipeg, PhD Thesis 2004.
- [91] Razani A Haron, Mohamed Azah, and Shareef Hussain, "A Review on Protection Schemes and Coordination Techniques in Microgrid System," *Journal of Applied Sciences*, vol. 12, pp. 101-112, January 2012.
- [92] A Treyt and A Bratukhin, "Real-time Energy Management via Powerlines and internet," The REMPLI consortium, Vienna, Project Report 2008.
- [93] IAD. (2008, April) IAD. [Online]. http://www.iad-de.com/technology/rempli/rempli_overview.htm
- [94] Roman Frigg and Stephan Hartmann. (2011, April) stephanhartmann.org. [Online].

References

- http://stephanhartmann.org/Hartmann_Models.pdf
- [95] OPNET Technologies. (2011, June) OPNET Modeler. [Online].
http://www.opnet.com/solutions/network_rd/modeler.html
- [96] Melvinia Chidi, Mononts'i P Nthontho, S.P Chowdhury, and S Chowdhury, "Viability of grid-connected domestic solar photovoltaic systems in South Africa," in *IEEE PES General Meeting*, San Diego, 2012.
- [97] Shirley Salvoldi, Mobolaji Bello, and Danie Pienaar. (2012, March) Small scale embedded generation (SSEG) grid connection – Eskom Experience and input. Presentation slides.
- [98] J Dekker, M Nthontho, S Chowdhury, and S.P Chowdhury, "Investigating the effects of solar modelling using different solar irradiation data sets and sources within South Africa ," *Solar Energy*, vol. 86, no. 9, pp. 2354-2365, September 2012.
- [99] RETScreen International. (2011, December) Natural Resources Canada. [Online].
http://www.etscreen.net/ang/speakers_notes_overview_intro.php
- [100] NREL. (2011, November) System Advisor Model (SAM). [Online].
<https://sam.nrel.gov/content/welcome-sam>
- [101] The MathWorks. (2012, January) Matlab, The Language for Technical Computing. [Online].
<http://www.mathworks.com/products/matlab/>
- [102] The MathWorks. (2012, January) Simulink - Simulation and Model-Based Design. [Online].
<http://www.mathworks.com/products/simulink/>
- [103] Councillor Kgosientso Ramokgopa. (2011, September) City of Tshwane. [Online].
<http://www.tshwane.gov.za/AboutTshwane/NewsandEvents/news/Pages/Budget-Speech.aspx>
- [104] SAITNews. (2011, May) SAITNews Tracking IT in the public sector. [Online].
<http://saitnews.co.za/e-government/tshwane-spend-millions/>
- [105] Eldo. (2011, December) Eldo Energy. [Online]. <http://www.eldoenergy.com/solutions/household/>
- [106] Africa Adaptation Programme. (2009, September) UNDP - AAP. [Online]. <http://www.undp-aap.org/sites/undp-aap.org/files/Lesotho.pdf>
- [107] Mononts'i Nthontho, S.P Chowdhury, and Simon Winberg, "Investigating Implementation of Communication Networks for Advanced Metering Infrastructure in South Africa," in *ITU Kaleidoscope 2011. The fully networked human? Innovations for future networks and services*, Cape Town, 2011, pp. 1-8.
- [108] Free Sun Power. (2011, July) Free Sun Power. [Online]. <http://www.freesunpower.com/index.php>
- [109] Sustainable. (2012, March) Sustainable.co.za. [Online]. <http://www.sustainable.co.za/solar-power.html>

References

- [110] Ntsakisi Maswanganyi. (2012, April) Business Live. [Online].
http://www.businesslive.co.za/southafrica/sa_markets/2012/04/13/cpi-expected-to-be-6.0-year-on-year-in-march
- [111] Hossein Mousazadeha et al., "A review of principle and sun-tracking methods for maximizing solar systems output," *Renewable and Sustainable Energy Reviews*, vol. 13, no. 8, pp. 1800–1818, October 2009.
- [112] Maciej Kryza, Mariusz Szymanowski, and Krzysztof Migala, "Spatial information on total solar radiation: Application and evaluation of the r.sun model for the Wedel Jarlsberg Land, Svalbard," *Polish Polar Research*, vol. 3, no. 1, pp. 17-32, December 2010.
- [113] City of Cape Town. (2011, October) Smart living handbook.
<http://www.capetown.gov.za/en/EnvironmentalResourceManagement/Pages/SmartLivingHandbook.aspx>.
- [114] City of Tshwane. (2012, January) Tshwane.gov.za. [Online].
http://www.tshwane.gov.za/Business/Tender%20Results/tenderresults2009_10.pdf
- [115] City of Tswane. (2011, July) Get a Tender. [Online].
http://www.getatender.co.za/index.php?option=com_mtree&task=listcats&cat_id=222&limitstart=740
- [116] ISO. (2012, March) International Organisation for Standardization. [Online].
http://www.iso.org/iso/catalogue_detail?csnumber=46486
- [117] Usama Nadeem. (2011, May) Usama's Blog. [Online].
http://blogs.warwick.ac.uk/usamanadeem/entry/iso_1401_usama/
- [118] David M. Shailer, *The Project Manager's Toolkit*, 2nd ed. Oxford, UK: Butterworth-Heinemann, 2001.
- [119] Plow & Hearth. (2012, January) Plow & Hearth. [Online]. http://www.plowhearth.com/Portable-Electric-Stove_p6257.html
- [120] UNDP. (2011, December) United Nations Development Programme. [Online].
<http://www.undp.org/ls/>
- [121] Jason Knott. (2012, February) CEPro. [Online].
http://www.cepro.com/article/8_million_smart_meters_already_deployed_study_finds/K501
- [122] Indiamart. (2012, February) Maxwell India. [Online]. <http://www.indiamart.com/maxwell-india/electro-mech-energy-meters.html>
- [123] T. Makonese, D.K. Kimemia, and H.J Annegarn, "Assessment of free basic electricity and use of pre-paid meters in South Africa," in *Domestic Use of Energy Conference (DUE)*, Cape Town, 2012, pp. 165-172.

- [124] E. Uken, "Can energy efficiency solve South Africa's problems?," in *Domestic Use of Energy Conference (DUE)*, Cape Town, 2012, pp. 85-89.

Appendix A: Case Study 2 Project Terms of Reference

This appendix gives details of the requirements that were provided in the AAP's request for proposals for implementation of off-grid solar PV solar home systems at Poriking in Lesotho. It presents the basis for the project plan shown in Chapter 7.

Terms of Reference for the Company

A.1. Objective

Working closely with the Africa Adaptation Programme (AAP) and the Department of Energy (DOE), the main objective for the successful company is required to supply and construct portable Solar Home Systems for hundred (100) households at Poriking, in accordance with the acceptable proposed design.

A.2. Description of a System

The system has the following components: A Solar Photovoltaic (PV) panel, a battery, Three (3) Direct Current (DC) lights, Multi cell phone Adapter, a socket for cell phone charging, a socket for radio and a socket for a fan of a potable energy saving stove.

A.3. Requirements of the System

The proposed design, with detailed specifications of the components, of a system will meet the following requirements:

1. Provide electrical energy for eight (8) hours per day to power three (3) DC lights, cell phone, fan for potable energy saving stove. The charging voltage for the fan is 7.5 Volts.
2. Two (2) lights are for internal house lighting while one (1) will provide security lighting outside a house.
3. The lights will be the Light Emitting Diode (LED) and or Compact Fluorescent Lights (CFL) types.
4. Bear a logo of the manufacturer including the address.
5. The laboratory performance tests of the system.
6. The system shall have advantage if an authentic proof of accreditation by reputable institution(s) is provided.
7. Samples of the proposed system will be made available whenever required on or after

the submission of proposals.

A.4. Specific duties

1. Design an appropriate solar home system (SHS)
2. Demonstrate the assembly of the components of the system

A.5. Delivery Schedule and Payment schedule

The company is expected to propose the earliest possible time to deliver the systems at Poriking following the issuance of a purchase order by AAP, as well as the maximum possible time for the demonstration of the assembling of SHS.

A.6. Evaluation of proposals

The Consultant shall have passed the evaluation if she/he obtains a total score (S) of at least 70%; $S = w_t s_t + w_f s_f$

Where

$w_t = 0.85$ is the weight for technical score.

s_t = technical score.

$w_f = 0.15$ is the weight for financial score.

$s_f = 100 \times \frac{f_m}{f}$ is the financial score.

f_m = the lowest price and

f = the price of the proposal under consideration.

Technical evaluation

The consultant shall have passed the technical evaluation if she/he obtains a technical score s_t of at least 70% and then only can the financial proposal be considered.

	Points
1. Qualifications and competence of the consultant	50
a. General qualifications	20
b. Adequacy for the project.	15
c. Experience of the consultant related to the assignment	10
d. Languages	5
2. Adequacy of the proposed work plan and methodology in responding to the terms of reference	50
a. Understanding of the assignment	5
b. Suitability of the proposed organizational arrangements and resources	25
c. Phasing of activities and inputs	20
Total points	100

Appendix B: Quotations used in Case Study 2

This appendix presents one of the quotations used to estimate the component prices. It was sort from Sinetech via email.

Attention : Mononts'i Paul Nthontho
Tel no : +27 7129 31001
email : monontsi.nthontho@uct.ac.za
Date : 12/01/19

Quote ref no : SJ110101169

Dear Mononts'i.

Thank you for your e-mail. We have quoted on the products and brands that we stock. Unfortunately we do not carry Tubular 2V batteries, but you are more than welcome to veiw the range that we stock on our website and specify the unit that you are interested in and we will send a quotation. Please specify which unit you are interested in for the lightning protection. We are pleased to offer you the following quotation :

1 x Model: Omni180M : 180W Omnipower solar panels @ R 4 549.00 each (excl. VAT)
Assembled in South Africa with some German components
25 year performance warranty
Availability : Special Order.

1 x Model: Flexmax 60 MPPT , 60Amp, 12/24/36/48VDC, Charge Controler,
Priced @ R 6 445.00 each (excl. VAT)
Availability : Ex-stock subject to prior sales.

1 x Model: Sine 048/04/LP00/CB : 12/24/48 Volt 4Way combiner box, no lightning protection
with 10A Circuit breaker
Can handle up to 24 Solar Panels with MPPT Charge controller
Priced @ R 1 201.00 each (excl. VAT)
Availability : Ex-stock subject to prior sales.

Payment terms : EFT before collection. If you place an order, we set the goods aside for you and send you a Pro Forma Invoice for payment. On clearance of the payment, the goods can be collected.

QUOTATION TERMS & CONDITIONS – please note the following:

1. Prices quoted are based on the quantities specified in the quotation and Sinetech reserves the right to revise prices in the event of the quantities being reduced or increased.
2. All payment terms are Electronic Transfer before collection unless otherwise specifically stated in our quotation. We do not accept cheques or credit cards.
3. Prices quoted are subject to exchange rate fluctuations and any variation will be for the customer's account.
4. Prices quoted are ex-works Randburg, Johannesburg unless otherwise specified.
5. Prices quoted exclude VAT at 14%. VAT is payable on all invoices except on exports where Sinetech is arranging the export transport.
6. Delivery times, where specified are estimated. Sinetech will endeavour to adhere to such estimated delivery times. Should any delays which are beyond Sinetech's control take place, Sinetech will not be liable for any costs or losses incurred by the customer through such a delay.
7. While Sinetech provides professional advice regarding the usage of goods supplied, the suitability of the goods for the use contemplated by the client is the sole responsibility of the client, and the Company shall in no way be responsible for the suitability of the goods sold for any particular end use.
8. Units are packed in cardboard packaging. Units will only be palleted or crated on request and this special packaging will be charged for as an extra.
9. Sinetech is not responsible for any loss or damaged caused while goods are in transit where the Customer has rejected our quotation for special packaging.
10. Where the goods are not delivered by Sinetech, or collected by the Customer, but are collected or delivered to an independent carrier, collection/delivery to the carrier shall be deemed to be delivery to the Customer. Where the Goods have been delivered to the carrier, Sinetech is not responsible for goods lost or damaged in transit.
11. Quotations are valid for 15 calendar days from the date of the quotation.
12. All quotations are subject to our payment terms.
13. Warranty & Returns: Units are warranted against faulty workmanship and components for a period of twelve months from date of supply (with the exception of generators which carry their own warranty and are guaranteed for a period of 12 months or 2000 hours whichever comes first from the date of delivery against faulty workmanship or material). Fair wear and tear excepted. No other warranty is given or implied. A copy of our full Warranty Policy and Returns Policy is available on request or from the home page of our website www.sinetech.co.za/warranty.pdf
14. Any item not specified is excluded from this quotation. Delivery, commissioning, installation and electrical work are excluded unless specifically quoted.
15. The issuing of a quotation or a Pro Forma invoice issued as a quotation represents no obligation until Sinetech accepts the Customer's official purchase order.
16. All quotations and prices therein are provided
17. E&OE (errors and omissions excepted).

Please contact me if I can be of further assistance.

Kind regards.

Johan Pieterse

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