Design and Simulation of Photovoltaic, Diesel Hybrid AC Mini-Grid System for Rural Electrification

A Thesis

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by

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Approval Certificate

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Dedicated to
My beloved family

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Abstract

A hybrid photovoltaic-diesel-battery mini-grid model has been designed and simulated in MATLAB/Simulink for study and analysis purposes. Each component of the mini-grid model has been designed to simulate the model accurately. These include PV array, battery, diesel generator, inverter, maximum power point tracking (MPPT) based charge controller and loads. To make the model more realistic, a detailed load model has been presented where each type of load has been configured with its individual load profile. Some household appliances have been designed to investigate their different characteristics. An MPPT based on incremental conductance (INC) algorithm has been implemented for maximum power extraction from the PV array.

A three-phase four-wire inverter with filter has been designed to generate a 400V 50Hz AC for distribution system. For AC distribution system, a 3-phase 4-wire network is designed using PI section block considering distribution line parameters to simulate voltage drop and line loss in the network. To control power flow from/to the battery, a bidirectional buck/boost converter with controller has been designed. Based on the daily energy consumption and load profile, appropriate size of PV array and energy storage system has been designed. A power management algorithm has also been developed and simulated to control power flow from PV array, diesel and battery.

Grid voltage, current and frequency have been observed using the simulation results. Characteristics of balanced/unbalanced, fixed/variable loads have been studied here. The daily mini-grid load profile has also been simulated and studied. The placement of PV array and diesel generator has an impact on a mini-grid's efficiency, and also introduces the possibility of different technical issues. Hence, the PV array and diesel have been connected to different locations of the mini-grid to determine the optimal position with minimum voltage drop and line loss. On the other hand, fault analysis is an important consideration for design and operation of a mini-grid. Faults in different locations of mini-grid model have been simulated to investigate the characteristics and its effects on mini-grids. The designed model can be a useful tool for study and analysis of mini-grid system.

TABLE OF CONTENTS

List of Tables

LIST OF FIGURES

LIST OF ABBREVIATIONS

Organizational, Institutional and Economical Acronyms

BPDB	Bangladesh Power Development Board
IDCOL	Infrastructure Development Company Limited
IEA	International Energy Agency
NREL	National Renewable Energy Laboratory
SREDA	Sustainable and Renewable Energy Development Authority

Technical and Scientific Acronyms

AC	Alternating Current
Ah	Ampere Hour
AVR	Automatic Voltage Regulator
DC	Direct Current
DG	Diesel Generator
DoD	Depth of Discharge
ESS	Energy Storage System
GHG	Greenhouse Gases
HES	Hybrid Energy System
HOMER	Hybrid Optimization of Multiple Energy Resources
INC	Incremental Conductance

k	Boltzmann Constant
kW	Kilo Watt
kWh	Kilo Watt Hour
LCOE	Levelized Cost of Electricity
MG	Mini-Grid
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
N	Diode Ideality Factor
NPC	Net Present Cost
P&O	Perturb and Observe
PQ	Power Quality
PV	Photovoltaic
PVHMS	Photovoltaic Hybrid Mini-grid System
PWM	Pulse Width Modulation
RE	Rural Electrification
RES	Renewable Energy Sources
SHS	Solar Home System
SoC	State of Charge
TWh	Tera Watt Hour

CHAPTER 1

INTRODUCTION

1.1 Introduction

Access to electricity is a fundamental contributor to development as a whole - it is the “golden thread" that weaves together economic growth, human development and environmental sustainability. According to “Energy Access Outlook 2017” report released by International Energy Agency (IEA), an estimated 1.1 billion people, comprising of 14% of the global population - have no access to electricity [1]. Around 84% of those without electricity access reside in rural areas and more than 95% of those living without electricity are in countries in Sub-Saharan Africa and developing Asia. Bangladesh is one of the countries belonging to these statistics, where energy and power generation is insufficient in proportion to the demand.

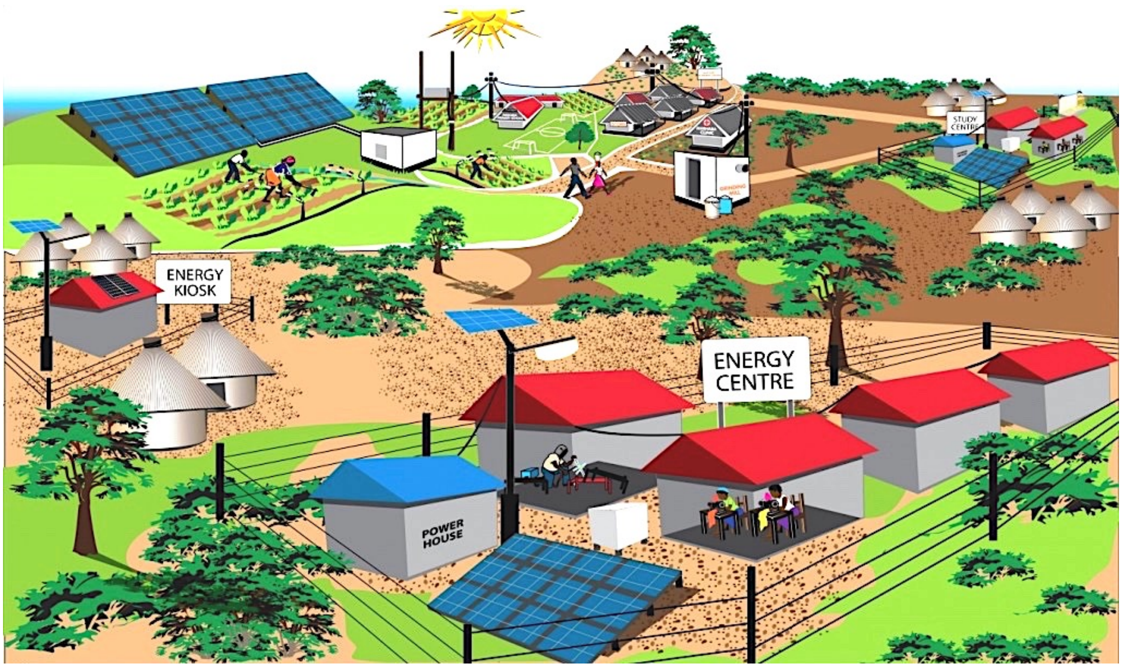


Fig. 1.1: Rural electrification based on renewable energy [2].

Sometimes rural areas in developing nations have to depend on fossil fuel based generation i.e diesel for electrification at relatively high costs. To solve this energy crisis in rural areas and meet the electricity demand, renewable energy based off-grid electrification can be better alternative solution. A typical off-grid electrification based on renewables is shown in Figure 1.1.

A very popular method for off-grid electrification is solar home system (SHS) which has been used for the long time to fulfill basic electrical needs of a household. But SHS is not economically viable for multiple households and small-scale business having technical difficulties. Recently mini-grid has been introduced world wide to solve this problem with relatively large scale electrification in rural area.

A solar mini-grid generates electricity primarily via solar power with other renewable sources or conventional energy source and distributes it via poles and wiring infrastructure that serves households, businesses and institutes within a particular region. Instead of systems based on conventional energy, hybrid mini-grid system based on renewable energy resources can provide an environment-friendly and a cost-effective energy solution with higher reliability and power quality in remote locations. In addition, a hybrid energy system (HES) can also utilize energy from other renewable sources - wind, hydro, geothermal energy etc. This option serves well for regions where the possibility of grid expansion is little in near future. Mini-grid plays an important role in the regions of South Asia and Africa because these areas are blessed with abundant solar energy potential, due to their major season being summer. According to records, 2,700 solar mini-grids have been installed by the end of 2017 in these areas and installation target is 31,000 mini-grids within 2023 [3].

Implementation of hybrid mini-grid system involves significant complexities and challenges which results in high mortality of projects. Several studies have been conducted worldwide in the area of HES specially hybrid solar mini-grid system for rural electrification. Most of these studies are limited to the techno-economic feasibility analysis. For successful design, implementation and operation of mini-grid systems, technical issues including challenges need to be studied on analysis stage prior to the implementation. Hence, it is important to shed light on the technical analysis of such systems on a magnified scale to ensure its proper operation.

1.2 Renewable Energy Scenario in Bangladesh

Bangladesh is one of the most overpopulated ($1015km^{-2}$) developing countries in South Asia [4]. The country produces its electricity mainly from natural gas followed by liquid fuels. Natural gas, refined petroleum products and coal are the main sources of energy supply in Bangladesh. With the current reserve and the rate of consumption, natural gas is expected to be dried out within the next $10-12$ years [5] [6]. Although the installed capacity of Bangladesh Power Development Board (BPDB) has been increased to 17965 MW till January 2019 , there is a scarcity of electricity in the hot summer season which is a barrier to industrial development as well as socio-economic development [7]. Combustion of fossil fuels releases greenhouse gases (GHGs) into the atmosphere which causes global warming. As a result of this greenhouse effect and global warming, Bangladesh can and will be adversely affected. These problems can be mitigated by incorporating renewable energy sources (e.g. solar, wind, hydro, biomass, etc.) to the country's electricity generation.

Table 1.1: List of 19 operational mini-grids in Bangladesh. Source: Ref. [8].

Sl.	Project Name	Location	Capacity(kWp)
1	650 kWp Solar Mini-grid Pilot Project	Sunamganj	650
2	PGEL Solar Mini-grid Project	Chittagong	100
3	Shouro Bangla Solar Mini-grid Project	Narsingdi	140
4	GHEL Solar Mini-grid Project	Cox's Bazar	100
5	HBPL Solar Mini-grid Project	Rajshahi	140
6	SEBL Solar Mini-grid Project	Bhola	180
7	GEAL Solar Mini-grid	Kurigram	160
8	AVA Solar Mini-grid	Rajshahi	150
9	Solargao Solar Mini-grid Project	Sirajgong	130
10	Super Star Solar Mini-grid Project	Manikganj	228
11	PEL Solar Mini-grid Project	Kushtia	210
12	Uddipan-2 Mini-grid Project-2	Faridpur	160
13	Solar Electro Bangladesh Ltd. - Mini-grid Project-2	Shariatpur	250
14	Solar Electro Bangladesh Ltd. - Mini-grid Project-3	Shariatpur	250
15	Envis Energy Limited Mini-grid Project	Sirajgonj	250
16	Blue Marine Energy Limited-Mini-grid Project	Cox's Bazar	250
17	Brit Bangla Trade Initiatives Ltd. Mini-grid Project	Gaibandha	250
18	Eastec Ltd. Mini-grid Project	Chapainawabganj	250
19	Vincen G-Tech Ltd. Mini-grid Project	Jamalpur	250

Bangladesh is blessed with several renewable energy sources which could be utilized to meet the increasing power crisis. The government of Bangladesh has set up a plan to generate 5% of the country's total electricity from renewable sources within 2015 and 10% within 2020 [9]. By January 2019, the country installed 5.5 million SHSs, which are stand-alone photovoltaic systems that offer a cost-effective mode of supplying power for lighting and appliances to remote off-grid households [10] [8]. Infrastructure Development Company Limited (IDCOL) has a target to finance 6 million SHS by 2021 with an estimated generation capacity of 220 MW of electricity [10].

Similar to SHS, solar mini-grids are now viewed to have the capability of providing a solution for rural off-grid areas. IDCOL and BPDB have taken many mini-grid projects and already implemented some of that projects. According to Sustainable and Renewable Energy Development Authority (SREDA), 19 installed mini-grids of a cumulative capacity of 4.098 MW in Bangladesh have already began operation which are shown in Table 1.1. These projects provide grid quality electricity to households and small commercial users and thereby encourage commercial activities in the project areas. Another 09 solar mini-grid projects are under implementation with a cumulative capacity of 1.758 MW. Majority of these projects are being financed by IDCOL and they have a target to finance 61 more projects in this years. However BPDB has installed 650kWp solar mini grid project at Shalla, Sunamganj which is the largest solar mini-grid project in south asia. The mini-grid project has successfully created access to low-emission electricity for almost many rural households in Bangladesh.

1.3 Background and Motivation

While the world's struggle against the adverse effects of climate change and global warming is soaring year by year, electricity demand is still being met by generation of brown energy–diverging from the goal of reducing carbon footprints to the atmosphere. In 2017, energy growth rate has been more than twice than 2016, totalling to 25570 TWh, with the global energy demand increasing by 2.1%. Notable growth was also registered in Southeast Asia (which accounted for 8% of global energy demand growth) and Africa (6%), although per capita energy use in these regions still remains well below the global average. Worldwide electricity generation has increased by 3.1%, or 780 TWh in 2017 than previous year.

Increasing electricity demand has imposed a great burden on existing brown electricity producing resource. Approximately 64% of the world's electricity is still generated by burning fossil fuels, mostly coal and natural gas, causing an emission of 42% of global greenhouse emissions. Global energy production contributed to a historic high of 32.5 gigatonnes of global CO_2 emissions in 2017 [1]. In Bangladesh, 73% of electricity is usually generated using coal and furnace oil which release higher levels of harmful emissions which contains NOX and SO_2, besides releasing products as ash - that do not burn and are non-biodegradable. These wastes rather pollute the environment in alarming levels [11] [12].

Consequently, the increasing energy demand growth will lead to a further increase in the emission of poisonous substances resulting in environmental pollution, instability and global warming. Therefore, initiatives need to be taken to develop a sustainable future with renewable energy, while the large population growth instantaneously increases the demand for electricity. Shifting to renewable energy generation will not only help to fulfill the goal of mitigating the greenhouse gas emissions, but also to find a way to alternate energy sources other than fossil fuels.

On a positive note, renewables saw the highest rate of growth of any energy source with electricity generation increasing by 6.3% (380 TWh) in 2017 than previous year. Renewables now account for 25% of global electricity generation [13]. China and the United States led the unprecedented growth in 2017, contributing around 50% of the increase in renewables-based electricity generation, followed by the European Union, India and Japan. Global solar PV capacity approached 400 GW by the end of 2017. It was an extraordinary year for solar PV additions in China, with over 50 GW of new capacity, exceeding the combined capacity additions of coal, gas and nuclear, and up from 35 GW in 2016.

As developed regions are engineering ways to generate surplus energy, the rural areas in developing nations are still striving to obtain the electrification to lead a basic lifestyle. Providing access to electricity for the roughly billion people who currently have no access or limited access to any reliable service is a fundamental social and economic development challenge. A significant part of the energy-deprived population lives far away from the power grid. With the current scenario, the power system is dominated by a centralized configured power generation system and grid extension still remains the preferred mode for electrification. Due to the increasing electricity demand, the current centralized energy generation system can be questioned for reaching out to the deprived population. In order to provide an affordable energy access to everyone and to combat climate change, sustainable energy solutions are essential. A better solution for meeting this demand is renewable energy based off-grid electrification. Renewable solutions are cheaper, cleaner and more effective in producing electricity without relying on imported/transported fuels. Integration of solar photovoltaic system with diesel generator for remote and rural areas would assist in expanding the electricity access in the tropical region.

Traditionally, remote communities worldwide consist of autonomous power systems supplied by diesel-engine generator sets (gensets) at relatively high costs. Integration of renewable energy sources (RESs) such as PV with diesel or gasoline generators which create hybrid system can substantially reduce the cost of electricity generation and emissions in these remote communities. The addition of a diesel generator to the renewable energy system provides power on demand, improves reliability and reduces the initial cost of the system. Similarly, renewable energy addition to a conventional fossil fuel operating generator reduces fuel consumption, thus improving the economics and environmental attributes of the power source.

Off-grid rural and remote area electrification through decentralized solar-diesel-battery hybrid mini-grids has become very popular all over the world. Many countries in Latin America such as Costa Rica, Brazil, Mexico, Argentina and Chile and developing

Asia such as Thailand, Nepal, India, Sri Lanka, Indonesia, Cambodia, Bangladesh and China have become successfull in rural electrification programs using solar-diesel hybrid mini-grid system [14] [15].

Sometimes successful design, implementation and operation of hybrid mini-grid systems can be more complex than grid extension. Again, implementation of off-grid electrification programs has been fraught with challenges, resulting in high mortality rate of projects [16]. It is necessary to study and analyze technical complexities and challenges related to mini-grid for proper implementation.

1.4 Present State of the Problem

Photovoltaic hybrid mini-grid systems (PVHMS) are expected to play a major role in facilitating rural electrification in regions that are deprived of electricity, namely the developing world [17]. In the national renewable energy policy of such a region as Bangladesh, off-grid and remote area electrification through decentralized renewable hybrid mini-grid (HMG) system has been prioritized. Due to the presence of multiple generation units, implementation of hybrid mini-grid system faces many challenges. Mini-grid faces major challenges such as the smooth deployment of renewables, fault, harmonics, unbalanced voltage/current and line loss etc. In addition, transient and dynamic behaviour of mini-grids with static, dynamic loads are considered as an important issue. As hybrid system analysis is quite a complex study, a technical simulation model is necessary on analysis stage prior to implementation of mini-grid. Generally, a mini-grid based decision tool is implemented on Microsoft Excel spreadsheets or HOMER software to perform comparative cost analysis between different operational scenarios, performance analysis, sensitivity analysis etc [18] [19]. But such models fail to address the challenges of mentioned above. In contrast, a simplified technical model of a hybrid mini-grid designed in MATLAB/ Simulink environment can simulate various characteristics of mini-grid. The model can also be used to analyze power flow, system stability, fault, harmonics, voltage drop, line loss, transient/dynamic behaviours, unbalanced conditions etc. To find out optimum place for PV array and diesel with minimum voltage drop and line loss in mini-grid network, model can play significant role. Such a model is yet to be reported.

1.5 Literature Review

Remote areas in developing countries are in dire need of affordable and reliable efficient energy for speeding up the process of its development. Traditionally, for remote areas where electricity has not reached yet, people depend on decentralized conventional fossil fuel based generators i.e diesel generator for electrification at relatively high costs.

Renewable energy sources can be an alternative option of conventional energy sources for rural electrification. As a sustainable energy source, solar photovoltaic is a very good choice for remote area. For rural electrification, there are two popular methods which include solar home system and solar mini-grid system.

SHS based on photovoltaic has been used for many years in remote areas to fulfill basic household electric needs. It has been recognized as a promising technology to mitigate energy poverty and promote renewable energy in order to achieve Goal 7 of the United Nations Sustainable Development Goals by 2030. Bangladesh has established one of the biggest market of SHS in the world in the last two decades. Halder et al. reviewed the potential of available renewable energy resources in Bangladesh, ranking solar energy as having enormous potential in both public and private sectors amongst all renewable resources [20]. It acknowledged that grid-connected solar PV concept would bring a new dimension in the sector of solar energy utilization. Total installed capacity of SHS has reached 150 MW in the year 2013-2014 with 185.19% increase over 2015. Bangladesh has a potential of 50,174 MW grid connected solar PV. In addition, studies conducted by Baky et al. expressed about enormous potentiality of solar energy in Bangladesh [21]. According to SREDA, 65,000 SHSs are now being installed every month under a project of Infrastructure Development Company Limited (IDCOL), resulting in a 58% annual increase every year [8]. Moreover, around 70,000 people are directly or indirectly involved with this program.

However, the recent trend is shifting towards electrification using mini-grids. Studies conducted by Alam et al. included all non-electrified households being surveyed about their willingness to switch to SHS to explore their preferential choice between SHS and RMG (Renewable Mini-Grid) [22]. The results of the survey were strongly inclined towards the willingness to switch to mini-grid based electricity and their willingness to pay for electricity. D. Chattopadhyay et al. showed mini-grid technically and economically more viable than SHS, as it suffered from a number of technical and economic inefficiencies [23]. Generally, SHS provides the most basic form of electrification, which is often limited to lighting and mobile charging. In contrast, mini-grids can support multiple households and small-scale businesses.

Research on hybrid power systems (HPS) based on renewable sources started about 30 years ago [24]. The first paper on hybrid system appeared in the mid-eighties, but literature on hybrid systems did not blossom until the early 1990s [25] [26]. Currently many researchers claim and have proven that hybrid power systems are the most suitable for rural areas as hybrid power systems are reliable and environment-friendly than other option to supply electricity to the remote areas. Phuangpornpitak et al. showed that integration of a solar photovoltaic system with diesel generator for remote and rural areas would assist in expanding the electricity access in the tropical region [27]. Rehman et al. has presented a PV-diesel hybrid power system with battery backup for a village being fed with diesel generated electricity to displace part of the diesel by solar and showed the system to be more economical than the diesel-only system [28].

Renewable energy sources can be integrated with mini-grids to reduce the emission of CO_2 and fuel consumption. Though the single-handed use of renewables in the mini-grid might seem as an appealing option with the aim of reducing emissions, this would fail due to the several technical difficulties - the most important being the scarcity of the renewable sources in extreme weather conditions etc. Therefore, the integration of renewables with diesel- thus forming hybrid mini-grids - becomes more justified. Moner-Girona et al. analyzed results from 27 installed hybrid PV mini-grids in Sub-Saharan Africa and has shown a projected emission reduction of 12000 tonnes over the next 20 years [29].

Due to the presence of multiple generation systems, hybrid system analysis is quite complex and requires to be analyzed thoroughly. This requires simulation tools for the design, analysis, optimization and economic viability of the systems. Sinha et al. have demonstrated 19 different software tools for such analysis of renewable energy system [30]. Among these software tools, Hybrid Optimization Model for Electric Renewables (HOMER) is found to be the most widely used tool in hybrid system analysis followed by RETScreen [31] [32]. HOMER is a computer model developed originally by the National Renewable Energy Laboratory (NREL) [33]. HOMER simplifies or helps the designer to compare various power system options based on technical and economic aspects. It is suitable for carrying out quick feasibility, optimization and sensitivity analysis in several possible system configurations [34]. But this software tool can not be used for technical analysis of hybrid systems. For example, HOMER does not consider depth of discharge (DoD) of battery, variations in bus voltage etc.

Halabi et al. have analyzed the performance of a hybrid system based on economic and environmental constraints, besides, placing emphasis on comparative cost analysis between different operational scenarios. HOMER software has been used to model, simulate and analyze hybrid systems [19]. The study also showed comparative cost analysis between different configurations including net present cost (NPC) and levelized cost of energy (LCOE). It was found that hybrid PV/diesel/battery system provided the best performance compared to all other scenarios and 100% RE system showed the best environmental characteristics with the highest costs.

Integration of solar PV systems into the mini-grid network causes some critical decision-making situations/technical challenges to maintain the quality, stability and reliability of the network. Over time, mini-grid based decision tools have been implemented on Microsoft Excel spreadsheets or HOMER software to perform the techno-economic evaluation which fails to address technical challenges. In contrast, a simplified technical model of a hybrid mini-grid system can simulate different technical characteristics.

A handful of researches have been carried out on design and simulation of mini-grids.

F. Katiraei et al. have implemented a simulation model of a pv-diesel mini-grid in the PSCAD/EMTDC environment for dynamic analysis [35]. The model has been used to study dynamics for changes in pv penetration level and load variation. Some case studies have been proposed for future investigations like grid stability, power quality, voltage and frequency regulations. Although, an energy storage system has not been included in the model, so operation of diesel generator faces a real challenge at night because of minimum load. Operation of diesel genset below 40 to 50% of its rated capacity causes premature aging of the diesel generator and significantly increases fuel consumption.

Islam et al. have showed a simulation model of a stand-alone solar-wind-diesel hybrid energy system in MATLAB/SIMULINK platform for power management strategy [36]. The study from Opiyo et al. shows different storage-focused PV-based mini-grid architectures including AC/DC-coupled centralized/decentralized storage for rural developing communities [37]. Sabu et al. have presented a harmonic performance analysis of an autonomous minigrid integrated distributed power system [38].

A complete simulink based technical hybrid mini-grid model including all component models can be used to analyze various characteristics, conditions and challenges of mini-grid.

1.6 Objective and Scope of this Thesis Work

The aim and objective of this thesis work are stated here as follows-

i Establish modeling of each component in mini-grids.

ii Design and simulate a hybrid AC mini-grid model based on photovoltaic, diesel with energy storage system (ESS).

iii Develop power management algorithm for mini-grid model.

iv Study dynamic load profile of mini-grid.

v Determine the effect of distributed generation and major loads centers in the mini-grid and optimal position for sources.

vi Study and investigate the effects of fault in mini-grids.

Possible Outcome of the Research

Successful completion of this work will help to optimize the design and performance of a hybrid mini-grids system.

1.7 Thesis Organization

This thesis comprises of five chapters.

Chapter 1 serves to introduce to the reader the background and present state of the problem. It later discusses the motivation and objectives of this research work done through this thesis. It also covers the literature review of the state-of-the-art works so far in the respective field.

Chapter 2 discusses various topology of solar system, components of hybrid mini-grid and technical challenges for implementation from a theoretical perspective.

Chapter 3 elaborates on the modelling of the components of a hybrid mini-grid in MATLAB/SIMULINK, detail load profile of mini-grid and power management.

Chapter 4 illustrates the results obtained from the simulations, along with discussions based on the detailed analysis performed on the implemented models - regarding power quality, power flow, loading behaviour, power management, line loss and fault condition.

Finally, Chapter 5 wraps up the work done in this thesis, discussing recommendations and potential suggestions for future works towards better mini-grid operation and design.

CHAPTER 2

THEORETICAL FRAMEWORK

This chapter aims to discuss different configuration topologies of photovoltaic system, descriptions of several components of hybrid mini-grid and challenges. We begin with different photovoltaic energy systems used in practice, with subsequent emphasis on the potentials of an off-grid mini-grid system. As this thesis work implements a hybrid mini-grid model, the several components of such systems have been elaborated - solar PV, backup diesel generators, energy storage systems, inverters, DC/DC converters and various loads. Technical challenges to implement such systems have also been addressed.

2.1 Photovoltaic Energy Systems Topology

Photovoltaic power systems are generally classified according to their functional and operational requirements, component configurations and how the equipments are connected to other power sources and electrical loads. Photovoltaic systems can be designed to provide DC/AC power, where services can operate interconnected with or independent of the utility grid, and can be connected with other energy sources and energy storage systems. Therefore, the two principal classifications of these systems are stand-alone systems, utility-interactive grid-connected systems as shown in Figure 2.1. The following subsections discuss the further classifications of these categories.

Grid-connected PV systems can either contribute its production to the grid, or only consume electricity from the grid. Hence, this system can branch two subsystems - directly connected to the utility and bimodal PV systems. In the case of bimodal systems, a storage system would be necessary as it is a contributor to electricity storage and supply.

On the other hand, stand-alone PV systems are expected to generate electricity on its own. When such systems generate enough to supply the connected loads, it will not require storage systems - thus known as direct-coupled systems. When stand-alone systems do require storage systems, it can be connected directly to AC loads through an additional power conditioning component, or inverters. The other common type of stand-alone system is the hybrid PV system, which uses other energy sources in parallel to the

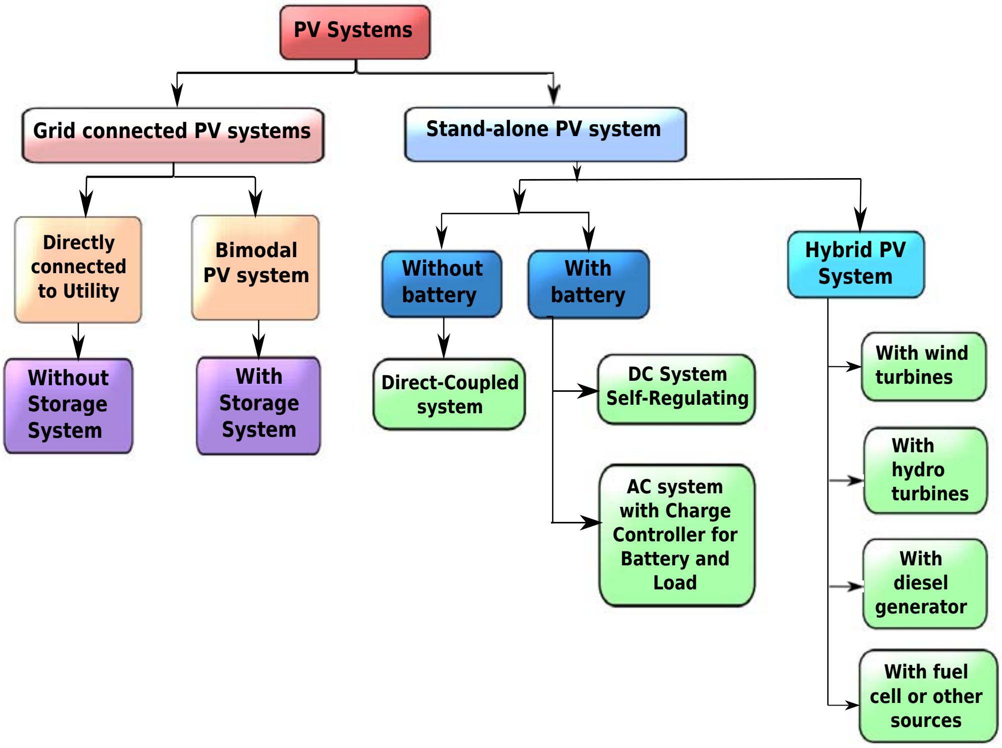


Fig. 2.1: Type of PV systems. Figure reproduced from Ref. [39].

PV array to supply loads. These energy sources can be wind turbines, hydro turbines, diesel generators, or fuel cells. Hybrid PV systems can also use batteries for energy storage.

2.1.1 Stand-alone or Off-grid Photovoltaic System

Stand-alone solar Power Systems or off-grid power systems operate independent of the electric utility grid (off-grid), primarily used in remote rural areas where the electric grid is not reachable, or where the connection fees for access to the grid are higher than the cost of an alternative energy system.

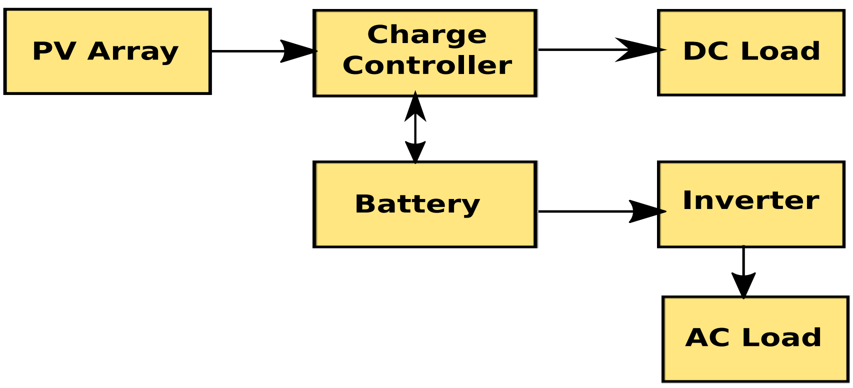


Fig. 2.2: Diagram of stand-alone PV system with battery storage. Figure reproduced from Ref. [40].

The DC power generated by these systems is stored in batteries and converted to

AC power for households or commercial uses. Figure 2.2 shows a diagram of a typical stand-alone PV system powering DC and AC loads.

An off-grid system typically has five elements:

(a) Renewable electricity source - solar PV/wind

(b) Back-up generator (diesel)

(c) Inverters/converters as required to convert DC electricity to AC (and possibly DC-DC)

(d) Batteries to store electricity generated by the renewable energy sources

(e) Master controller and/or battery management system to control the operation of the system

2.1.2 Grid Connected Photovoltaic System

In a grid connected PV system, also known as a "grid-tied" or "on-grid" solar system, the PV solar panels or array are electrically connected or "tied" to the local main electricity grid which feeds electrical energy back into the grid. The main advantage of a grid connected PV system is its simplicity, relatively low operating and maintenance costs as well as reduced electricity bills. In grid-connected systems, photovoltaic power systems supply power to the site loads when needed and provide electricity to the grid when there remains excess.

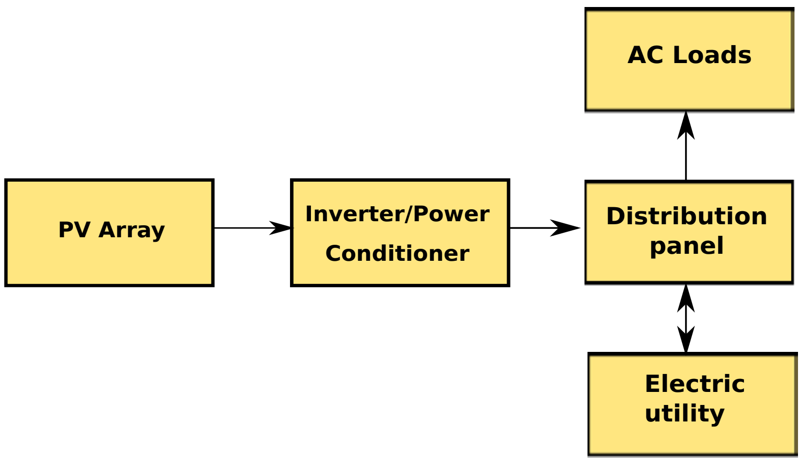


Fig. 2.3: Diagram of grid-connected photovoltaic system. Figure reproduced from Ref. [40].

They range from small residential and commercial rooftop systems to large utility-scale solar power stations. Unlike stand-alone power systems, a grid-connected system rarely includes an integrated battery solution, as they are still very expensive. Grid connected systems connected to the grid via an inverter since photovoltaic delivers only DC power. Figure 2.3 shows a diagram of a typical grid-connected photovoltaic system powering DC and AC loads.

2.2 Off-grid Solar System: Solar Home System and Solar Mini-grid

Access to energy is a human right, but extending this right to every human being who both requires and desires it cannot be done solely through national electrical grids. The solution will most likely involve the implementation of Solar home systems(SHSs), mini-grids and other decentralized options. This is especially true in the case of isolated communities.

SHS is typically used for providing basic electricity services to rural households that are not connected to electric grid. It can be considered as an alternative to conventional fuels (e.g. kerosene, candle, battery operated torch, recycled battery used to power TV) used for providing electricity for basic amenities in households that are not connected to the grid. SHS have been widely deployed in the developing world, particularly in Bangladesh and India as part of their rural electrification programs [41] [42]. A typical SHS consists of a solar module, battery, charge controller, compact fluorescent lights or LEDs, mobile phone charging point and possibly a power point for small DC appliances such as TVs, fans or radios.

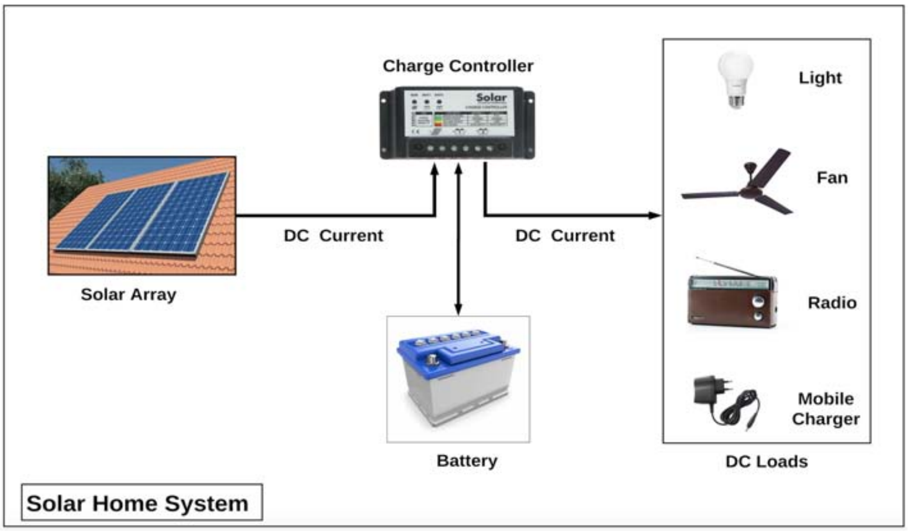


Fig. 2.4: Illustration of a solar home system.

Figure 2.4 shows overview of a typical solar home system. Although they are the most popular solution for off-grid rural electrification to date, there have been a number of issues with them including difficulty for users to find the upfront capital costs to purchase a system, over-use resulting in shorter battery life, poor-quality products and/or installation and insufficient system maintenance [43].

An alternative model to the SHS is the mini-grid (also called a micro-grid or pico-grid depending on the system size). Figure 2.5 shows overview of a typical mini-grid system. Mini-grids offer an alternative that entirely avoids many of the challenges that new and expensive grid infrastructure investments require. As mini-grids rely on local resources to generate electricity, technical management is less complex than for national utilities. It is becoming increasingly competitive compared to the cost of traditional grid extension programs, aided by battery storage, and are a key component in achieving universal access to electricity for all. The reasons for this are the rapidly decreasing costs of the technology, increasing reliability and a solid deployment track record, all of which have strengthened the case for the accelerated adoption of stand-alone and mini-grid solar solutions across the continents.

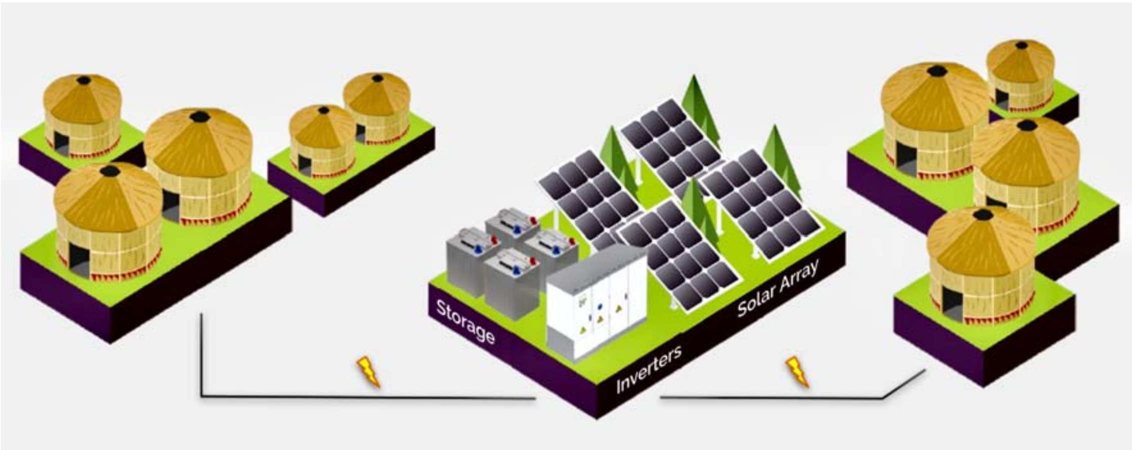


Fig. 2.5: Highlights of a typical mini-grid [44].

Mini-grids consist of power generation unit e.g. an array of PV modules, a bank of batteries, an inverter to convert from generated DC power to AC power and a distribution system including poles, wires and consumer units [45], [46], [47]. In addition to providing power to homes, mini-grids can be used to power services such as water pumping and street lighting. Another advantage of minigrids is that by supplying AC, appliances are more readily available and cheaper for the consumers. Loka et al. [48] reviewed a PV-based microgrid in India and found the levelized cost of electricity (LCOE) for an equivalent diesel generator, which was estimated to be more than twice the cost of the PV microgrid.

2.3 Hybrid Solar Mini-grids

There is a huge potential for utilising renewable energy sources, for example solar energy, wind energy or micro hydro-power, to provide a quality power supply to remote areas. The abundant energy available in nature can be harnessed and converted to electricity in a sustainable way to supply the necessary power to elevate the living standards of people without access to the electricity grid. The advantages of using renewable energy sources for generating power in remote areas are obvious: the cost of fuel transportation is often expensive, and there is increasing concern about fossil fuels, the issues of climate change and global warming etc. The disadvantage of stand-alone power systems using renewable energy is that the availability of renewable energy sources has daily and seasonal patterns which result in difficulties in regulating the output power to cope with the load demand. Combining renewable energy generation with conventional diesel power generation will enable the power generated from renewable energy sources to be more reliable and affordable. This kind of electric power generation system, which consists of renewable energy and fossil fuel generators together with an energy storage system and power conditioning system, is known as a hybrid power system [49].

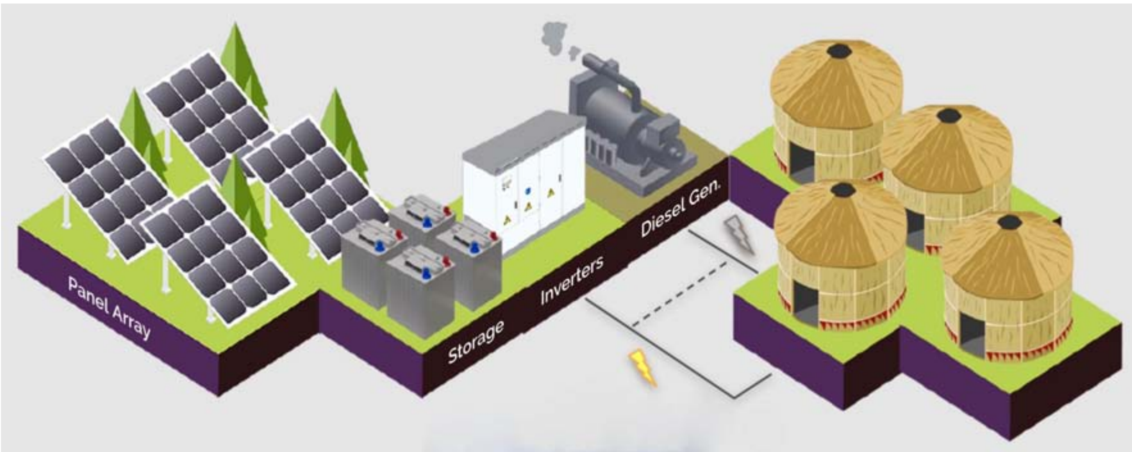


Fig. 2.6: Highlights of a hybrid mini-grid [44].

A hybrid power system has the ability to provide 24h grid quality electricity to the load. Hybrid solar systems are now by far the best replacements for traditional diesel-powered off grid systems. A hybrid solar system combines a PV plant with existing power sources, such as traditional diesel generators, or other non-renewable energy sources and is designed to guarantee stability of the power supply. This system offers better efficiency, flexibility of planning and environmental benefits compared to the diesel generator stand-alone system. The usual maintenance costs of a diesel generator can be decreased as a consequence of improving the efficiency of operation and reducing the operational time, which also means less fuel usage. Furthermore, the system provides an opportunity for expanding its capacity in order to cope with increasing demand in the future. This can be done by increasing either the rated power of the diesel generator, renewable generator or both.

Hybrid systems are designed by the interconnection of several units such as DC and AC energy sources (PV, diesel), energy storage units (Battery), AC and DC loads, AC/DC or DC/DC converters. The architecture of a typical PV-diesel hybrid system is shown in Figure 2.6, which consists of solar array, storage battery, inverter and diesel generator [50].

2.3.1 Hybrid Solar-Diesel Topology

In a hybrid solar diesel mini-grid system, solar PV supplies the load demand and excess energy from the PV above the hourly demand is stored in the battery until the battery is fully charged. The main purpose of the storage of electricity into the battery system is to import or export energy depending upon the situation. A diesel backup system is operated at times when the PV system fails to satisfy the load and when the battery storage is depleted.

The hybrid power systems which utilize renewable energy generators can be classified into two basic configurations: series hybrid system and parallel hybrid system based on how the load is supplied from RESs and a diesel generator.

2.3.1.1 Series Hybrid Power System

In a series hybrid system configuration as shown in Figure 2.7, power generated by a diesel generator and solar PV array are used to charge a battery bank before it is supplied to load [51] [52].

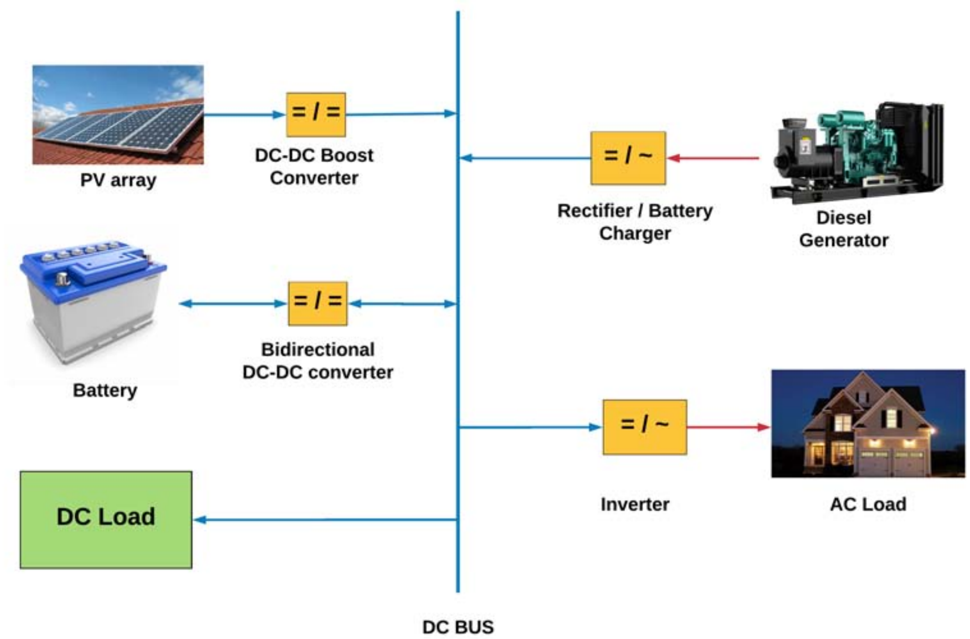


Fig. 2.7: Series hybrid solar-diesel configuration.

Each component has to be equipped with individual charge controllers and in case diesel generators, with a rectifier. The inverter will convert the DC power stored in the battery bank to AC at a standard level of voltage and frequency, and then supply it to the AC load. Battery charging can be controlled either by controlling the excitation of the alternator or by utilizing solar charger regulators that can prevent overcharging of the battery bank from the PV array when the renewable power exceeds the load demand and when the batteries are fully charged. In a similar fashion, they will protect the battery bank from deep discharge when demand exceeds the supply if it happens.

This type of configuration is also termed as Centralized DC-bus topology in the sense that all the energy generators and the battery are connected at the DC-bus and the AC load is supplied via a single point. Here, it has to be noted that the AC powers from the diesel generator must be converted into DC by utilizing AC/DC converters or rectifiers before power is delivered to the DC bus where the Battery is connected. This configuration type results in relatively simple implementation.

2.3.1.2 Parallel Hybrid Power System

In a parallel hybrid system configuration, the diesel generator and renewable energy sources supply a portion of the load demand directly. There are two types of sub-configurations of this hybrid system. These are the DC-coupled and AC-coupled configurations [53] [54]. The DC-coupling configuration system, shown in Figure 2.8, utilizes a bi-directional inverter, which is operated in parallel with the diesel generator and can act as inverter and rectifier/battery charger. It is a DC-coupled configuration hybrid system in a sense that the renewable energy sources are connected together at the DC bus to the battery and supply the AC load via the bi-directional inverter.

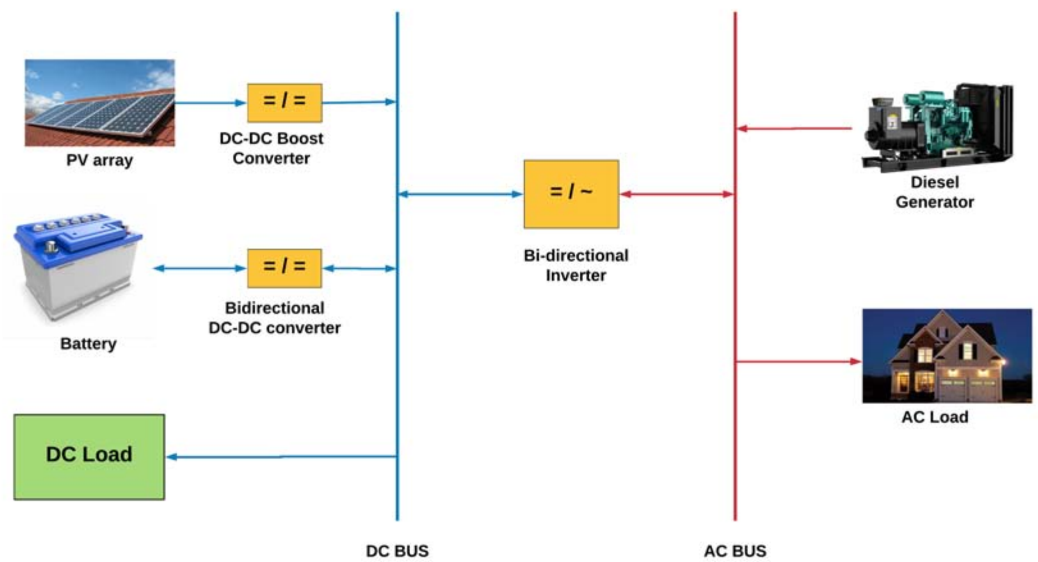


Fig. 2.8: DC coupling of parallel hybrid solar-diesel configuration.

The parallel hybrid power system with DC-coupling configuration can further be improved by connecting all of the renewable generators to the AC bus to perform an AC coupling configuration as shown in Figure 2.9. The load can be supplied from the renewable energy supplies in parallel with the diesel Genset. A bidirectional inverter is utilized here such that the battery can either supply the load or be charged depending upon the load requirement and the status of other energy sources. Over and above, the DC power obtained from the PV-array system and battery must be converted to AC before it is fed into the AC bus. This type of configuration is also referred to as centralized AC bus topology in a sense that all the energy generators are connected at the AC bus and the load is supplied at a single point.

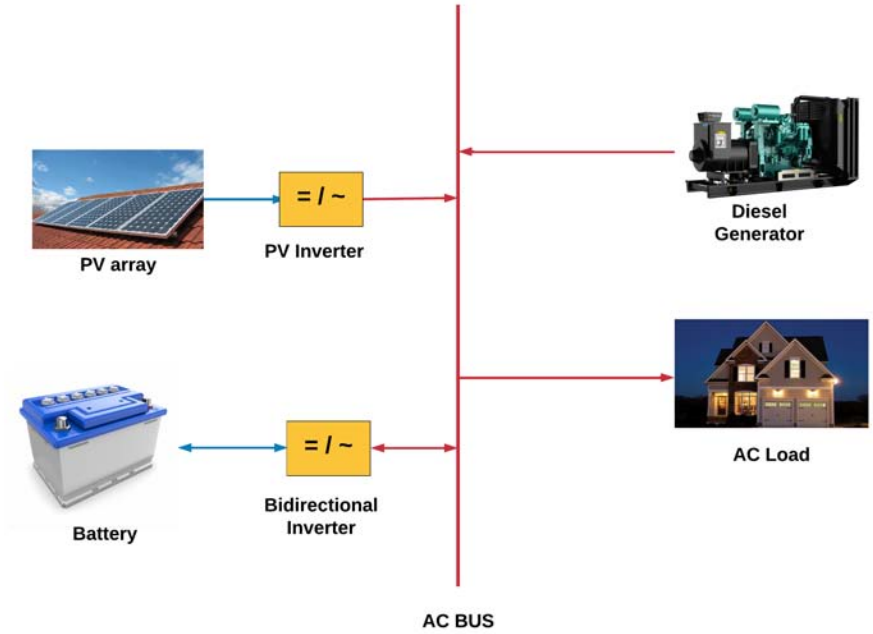


Fig. 2.9: AC coupling of parallel hybrid solar-diesel configuration.

2.4 Components of PV-Diesel Hybrid Mini-grid

PV-diesel hybrid mini-grids are designed by the interconnection of several units such as PV array, diesel generator as backup source, energy storage units, AC and DC loads, AC/DC and DC/DC converters etc. In this section, components of PV-diesel hybrid mini-grid have been briefly discussed.

2.4.1 Solar Cell, Module and Array

Solar photovoltaic system generates electrical power by converting solar radiation into direct current electricity using semiconductors that exhibit the photovoltaic effect. Photovoltaic power generation employs solar panels composed of a number of solar cells containing a photovoltaic material. Materials presently used for photovoltaics include monocrystalline silicon, polycrystalline silicon, amorphous silicon, cadmium telluride, and copper indium gallium selenide/sulphide. Due to the growing demand for renewable energy sources, the manufacturing of solar cells and photovoltaic arrays has advanced considerably in recent years. PV systems include cells, modules, strings, and arrays.

Solar Cell

A photovoltaic cell (also called a "solar cell") is the basic building block. The most common type of cell is made from silicon doped with minute quantities of boron, phosphorous, gallium, arsenic, or other materials. Each cell develops about half a volt of DC electrical potential when exposed to light. The maximum amperage of the cell is proportional to its surface area, and depends on the intensity of the light. The equivalent circuit of a solar PV cell can be expressed like following

A mathematical equation of load current can be obtained from the equivalent circuit in Figure 2.10. The load current equation is given below [55] [56]:

$$I = I_{PH} - I_S \left[\exp\frac{q(V+IR)}{NKT} - 1\right] - \frac{(V+IR_S)}{R_{SH}} \tag{2.1}$$

where, I is the load current, I_{PH} is the photocurrent, I_S is the diode saturation current, q is the electron charge, V is the cell terminal voltage, N is the diode ideality factor, K is the Boltzmann constant, T is the cell temperature, R_S and R_{SH} is the series and shunt resistance respectively. The behavior of a solar PV cell directly depends on these parameters.

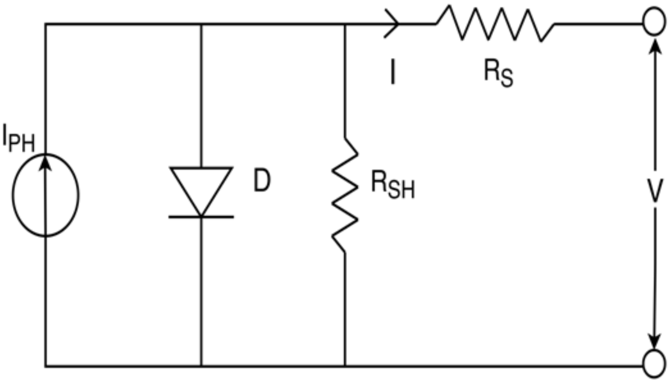


Fig. 2.10: Equivalent circuit of solar photovoltaic cell.

This model generates the effect of varying solar irradiation and cell temperature. Output of a PV module varies as a function of solar irradiance which can be obtained from the following equation [57] [58]:

$$I_{PH} = \left[I_{SC} + K_i\left(T - T_{ref}\right)\right]\frac{B}{1000} \tag{2.2}$$

Here, I_{SC} is the short circuit current, K_i is the temperature coefficient of short circuit current, T is the cell temperature, T_{ref} is the reference temperature and B is the solar irradiation in W/m2.

Effect of varying temperature on PV module can be achieved from a mathematical expression. The diode saturation current varies as a cubic function of cell temperature and can be expressed as following [57] [58]:

$$I_S(T) = I_{RS}\left(\frac{T}{T_{ref}}\right)^{\frac{3}{N}} e^{-\frac{qV_t}{NK\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)}} \tag{2.3}$$

In this equation, I_{RS} is the diode reverse saturation current and Vt is the thermal voltage. The cell reverse saturation current can be obtained from the equation given below [57] [58]:

$$I_{RS} = \frac{I_{SC}}{[e^q V_{OC}/NKT]} \tag{2.4}$$

Module and Array

The main component of a solar energy system is the photovoltaic (PV) module, consisting of photovoltaic cells. To increase the power, the cells are connected in series-parallel configuration on a module. Several module are grouped together to form an array. The PV array is composed of several PV modules which are connected in series and parallel in order to form an appropriate output voltage and power. A solar panel (also solar module, photovoltaic module or photovoltaic panel) is a packaged, connected assembly of photovoltaic cells. The solar panel can be used as a component of a larger photovoltaic system to generate and supply electricity in commercial and residential applications. Figure 2.11 shows PV cell, module and array.

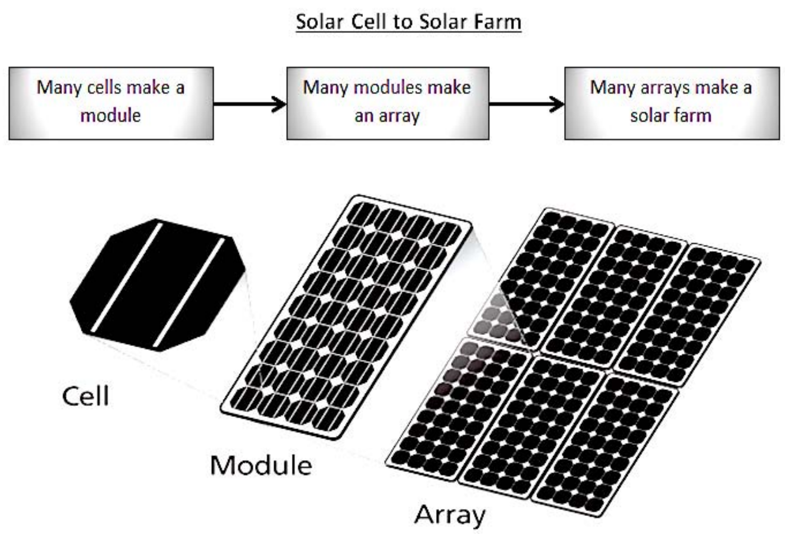


Fig. 2.11: Solar cell, module and array [59].

2.4.1.1 Effect of Solar Irradiance and Temperature Variation

The variation in I-V and P-V characteristics of the PV cell for changing the irradiance levels with constant temperature is shown in Figure 2.12 and 2.13 which represent the standard behaviors of the photovoltaic cell and photovoltaic array respectively. Figures show that with the increase of solar irradiance with constant temperature, generated current and maximum output power both increase.

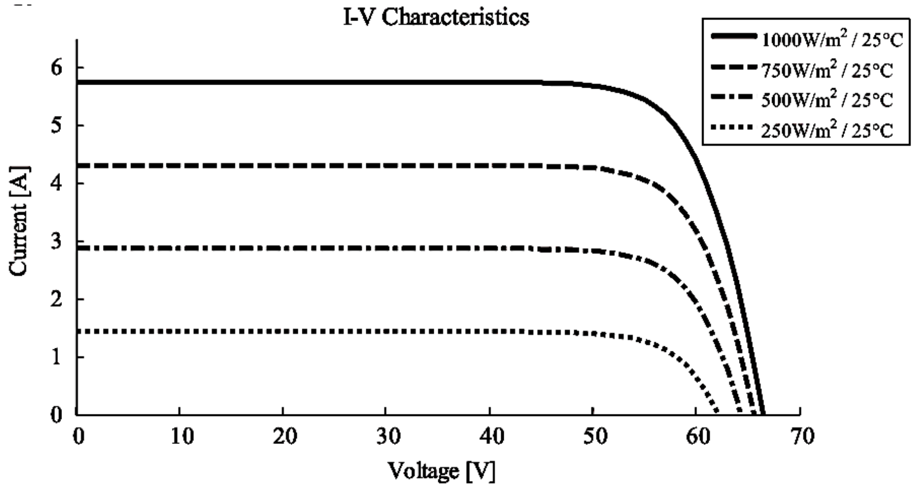


Fig. 2.12: I-V characteristics for different irradiation levels for constant temperature [60].

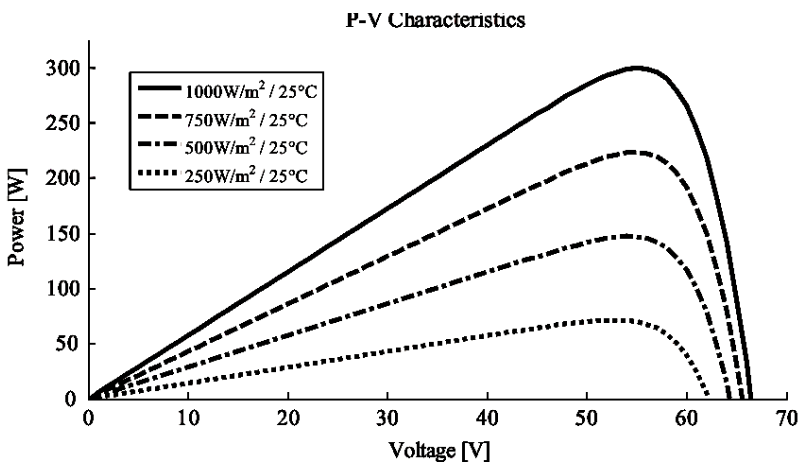


Fig. 2.13: P-V characteristics for different irradiation levels for constant temperature [60].

In contrast, with constant irradiance and varying temperature conditions result in changing I-V and P-V characteristics as shown in Figure 2.14 and 2.15.

The change in temperature will affect the power output from the cells. The voltage is highly dependent on the temperature and an increase in temperature will decrease the voltage. Figure 2.14 shows the effect of temperature on I-V characteristic of PV module at constant radiation. With decreasing temperature, PV current decrease slightly but

PV voltage increase clearly. Figure 2.15 indicates, output power of photovoltaic module increases with decreasing temperature with constant irradiation.

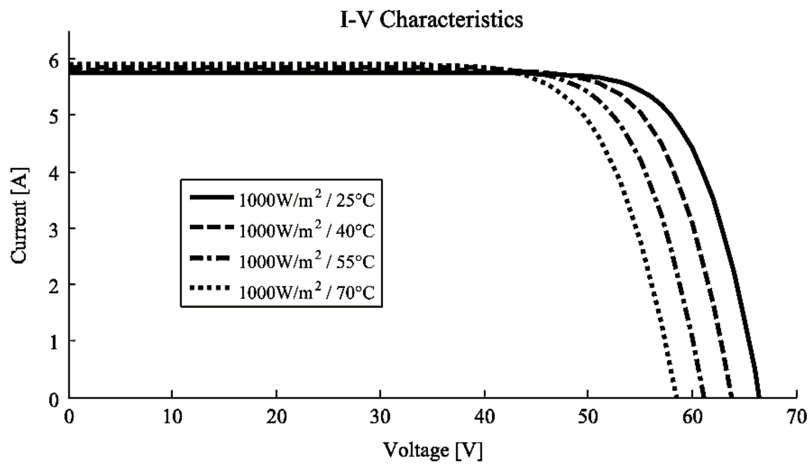


Fig. 2.14: I-V characteristics for different temperature levels for constant irradiance [60].

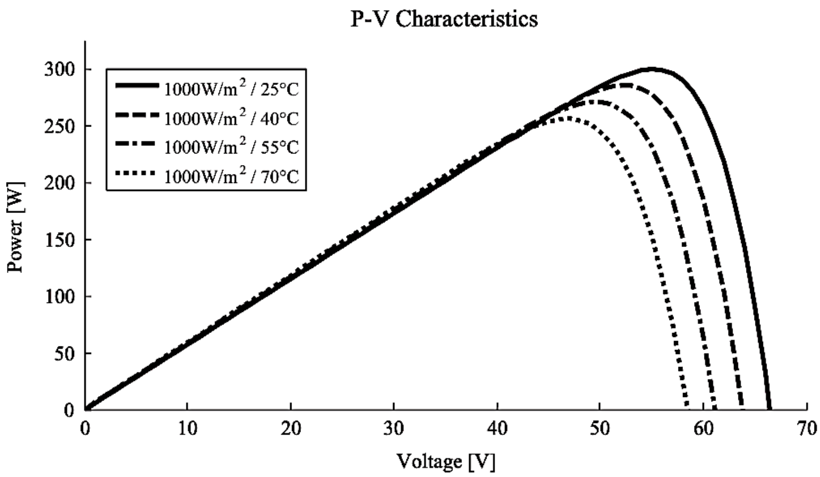


Fig. 2.15: P-V characteristics for different temperature levels for constant irradiance [60].

2.4.1.2 MPPT Techniques for Solar PV

Maximum power point tracking (MPPT) is a technique that ensures the maximum power extraction from non-linear energy sources like solar PV systems. Maximum power point trackers (MPPTs) play an important role in PV power systems because they maximize the power output from a PV system for a given set of conditions, and therefore maximize the array efficiency. Hence, an MPPT can minimize the overall system cost. MPPTs find and maintain operation at the maximum power point, using an MPPT algorithm. The algorithm allows the controller to operate PV module at optimum voltage and current so the extraction of maximum power is ensured. There are different techniques used to track the maximum power point. Few of the most popular techniques, as discussed in [61] consist of the following:

(a) Perturb and observe (Hill Climbing method)

(b) Incremental Conductance (INC) method

(c) Fractional short circuit current

(d) Fractional open circuit voltage

(e) Neural networks

(f) Fuzzy logic

Among the above MPPT techniques, the most commonly used and thus chosen technique for this thesis implementation is the Incremental Conductance (INC) method. Hence, this method is elaborated as below.

Incremental Conductance

Incremental conductance method (called INC for short) is one of the common used MPPT control algorithms. INC method could estimate the relation between the operating point voltage, V and the maximum power point voltage, V_{max}. The method of increasing conductivity follows three conditions: $V < V_{max}$, $V > V_{max}$ and $V = V_{max}$.

When light intensity and outside temperature changes, then INC method controls the output voltage to track the maximum power point voltage smoothly and also reduces oscillation phenomena near the maximum power point. However, this control algorithm is very complicated and the setting of adjusting voltage ΔV influences the maximum power point tracking accuracy greatly. The INC algorithm is derived by differentiating the PV array power with respect to voltage and setting the result equal to zero. This is shown in Equation (2.5).

$$\frac{dP}{dV} = \frac{d(VI)}{dV} = I + V\frac{dI}{dV} = 0;\ \text{at the MPP} \tag{2.5}$$

At the MPP, both side of Equation (2.5) must be equal zero. If the operating point is off of the MPP, a set of inequalities can be derived from Equation (2.5) that indicates whether the operating voltage is above or below the MPP voltage The left-hand side of equation represents the opposite of the PV array's instantaneous conductance, while the right-hand side represents its incremental conductance. These relationships are summarized in equations (2.6) as in [62], [63]:

$$\frac{dI}{dV} = -\frac{I}{V}; \left(\frac{dP}{dV} = 0\right) \text{ at MPP thus } V = V_{max} \tag{2.6a}$$

$$\frac{dI}{dV} > -\frac{I}{V}; \left(\frac{dP}{dV} > 0\right) \text{ left of MPP thus } V < V_{max} \tag{2.6b}$$

$$\frac{dI}{dV} < -\frac{I}{V}; \left(\frac{dP}{dV} < 0\right) \text{ right of MPP thus } V > V_{max} \tag{2.6c}$$

Equations (2.6b), (2.6c) are used to determine the direction in which a perturbation must occur to move the operating point toward the MPP, and the perturbation is repeated until equation (2.6a) is satisfied. Once the MPP is reached, the MPPT continues to operate at this point until a change in current is measured. This change in current will correlate to a change in irradiance on the array. When the irradiance on the array increases, the MPP moves to the right with respect to the array voltage. To compensate for this movement of the MPP, the MPPT must increase the array's operating voltage. The opposite is true when a decrease in irradiance is detected (via a decrease in the measured current).

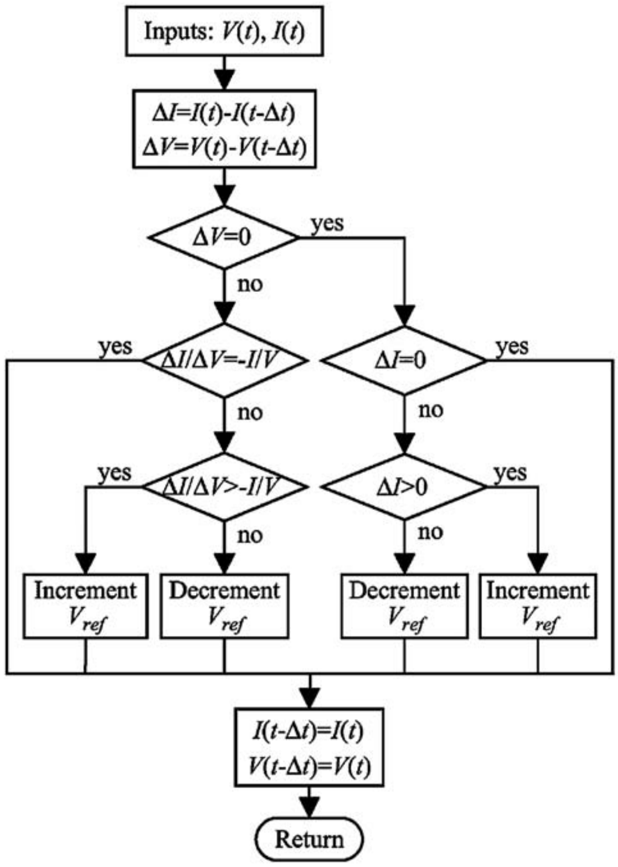


Fig. 2.16: Flow chart of incremental conduction (INC) algorithm as shown in [60].

Figure 2.16 shows a flowchart for the incremental conductance algorithm. The present value and the previous value of the solar array voltage and current are used to calculate the values of dI and dV. If $dV = 0$ and $dI = 0$, then the atmospheric conditions have not changed and the MPPT is still operating at the MPP. If $dV = 0$ and $dI > 0$, then the amount of sunlight has increased, raising the MPP voltage. This requires the MPPT to increase the PV array operating voltage to track the MPP. Conversely, if $dI < 0$, the amount of sunlight has decreased, lowering the MPP voltage and requiring the MPPT to decrease the PV array operating voltage. If the changes in voltage and current are not zero, the relationships in Equations (2.6b), (2.6c) can be used to determine the direction in which the voltage must be changed in order to reach the MPP. If $dI/dV > -I/V$, then $dP/dV > 0$, and the PV array operating point is to the left of the MPP on the P–V curve. Hence, the PV array voltage must be increased to reach the MPP. Similarly, if $dI/dV < -I/V$, then $dP/dV < 0$ and the PV array operating point lies to the right of the MPP on the P–V curve, meaning that the voltage must be reduced to reach the MPP. Herein lies a primary advantage of incremental conductance over the perturb-and-observe algorithm: incremental conductance can actually calculate the direction in which to perturb the array's operating point to reach the MPP, and can determine when it has actually reached the MPP. Hence, under rapidly changing conditions, it should not track in the wrong direction, as P&O can, and it should not oscillate about the MPP once it reaches it.

A power electronic interface is required to operate MPPT and extract maximum power from solar PV. A DC/DC boost converter regulates the voltage to meet the requirement of system bus voltage. MPPT controller generates the duty cycle to operate the boost converter and to step-up the voltage.

2.4.2 Backup Generator (Diesel)

Diesel generators are connected to the mini-grid system to provide back-up during periods of low solar radiation and random nature of renewable energy sources. The generator exists to supply power to the AC bus in case of shortage of production from solar PV array. The generator can also be used to charge the batteries during foggy and rainy days. Without any back-up generator, the battery bank can be damaged because of prolonged deep discharging and insufficient charging during rainy and foggy days. The generator is turned off when the batteries are fully charged.

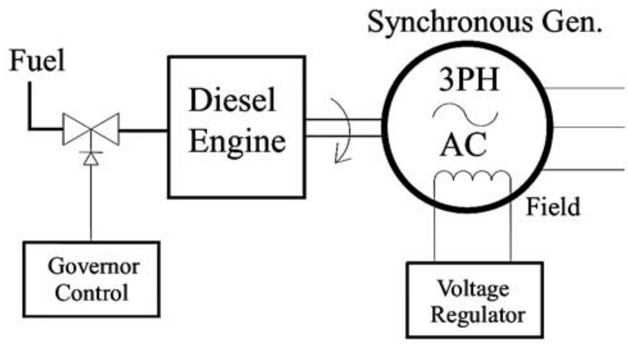


Fig. 2.17: Basic block diagram of a diesel generator [64].

A diesel generator (diesel engine-generator set) consists of two main components coupled by a common shaft: the diesel prime mover and the electrical generator. Figure

2.17 shows the basic block diagram of a diesel generator. The diesel engine converts chemical energy of the fuel to the kinetic energy of the rotating shaft to drive a synchronous machine. The fuel injection is controlled by a governor to regulate the speed of the engine. Hence, it regulates the output electrical frequency of the generator, since the shaft speed (ω) is related with the electrical frequency (f) and the number of poles (P) of the synchronous machine as,

$$\omega = \frac{120f}{P} \tag{2.7}$$

The synchronous machine has an excitation system to control the output voltage of the genset. The excitation system generates the rotor magnetic field. This field may be provided by means of permanent magnets or by a DC source that feeds the field windings. Normally the diesel genset uses an Automatic Voltage Regulator (AVR) to adjust the generator field voltage and/or the field current according to the variations in the output terminal voltage.

2.4.3 Energy Storage System (Battery)

Most of the stand-alone photovoltaic (PV) systems require an energy storage buffer to supply continuous energy to the load when there is inadequate solar irradiation. Energy storage is a critical component in a mini-grid. Energy storage system helps to maintain voltage stability and smooth out the fluctuations of renewable energy generation. Batteries which make use of a reversible chemical reaction to store energy and convert chemical energy into electrical energy are used as the energy storage element in mini-grid. Generally battery bank is connected to the DC bus. Batteries are not as fast at responding than super capacitors but they have the ability to store more energy which is a critical design consideration in mini-grid. Batteries can be damaged due to deep discharge therefore the state of charge should be limited to a reasonable region.
There are different types of batteries, but the most commonly used rechargeable batteries are:

(a) Lead acid battery

(b) Nickel cadmium (NiCad) battery

(c) Nickel metal hydride (NiMH) battery

(d) Lithium ion battery

(e) Lithium-polymer battery

(f) Zinc-air battery

Lead acid batteries are preferable for mini-grids because it offers the longest life cycle and can withstand slow, fast and over-charging. It is also low-cost per watt-hour. These reasons have led to its frequent use in solar mini-grid systems.

Lead Acid Battery

A lead acid battery is formed by series of electrochemical cells connected together to match the required voltage. The most common type of battery used in a hybrid micro-grid is the lead-acid, deep cycle type, although many models are available in the market. Each cell of a lead-acid battery comprises a positive electrode of lead dioxide and a negative electrode of sponge lead, separated by micro-porous material and immersed in an aqueous sulfuric acid electrolyte. Battery operation must also be carefully checked: a lead acid battery normally should never be operated under 50% or 45% State of Charge (SoC).

Ampere-hour (Ah)

The measurement of battery capacity is defined in Ampere Hours (Ah). In other words, it is an indication of how much energy can be stored by the battery and integrating discharging current in amperes over specific time. 1 Ah equals to the transfer of one-ampere over one-hour.

Depth of Discharge (DoD)

DoD, short for the Depth of Discharge, is used to describe how deeply the battery is discharged. The percentage of battery capacity (Ah) extract from a battery compared to the total charge capacity defined as Depth of Discharge. If a battery is 100% fully charged, it means the DoD of this battery is 0%, If the battery have delivered 30% of its energy, here are 70% energy reserved, we say the DoD of this battery is 30%.

State of Charge (SoC)

The amount of stored energy remaining in the battery defined as State of charge (SoC). The SoC denoted battery fully charged, half charged, and completely discharged. The SoC of 100% defined as battery fully charged, and 75% of SoC indicated three-fourth (3/4) stored capacity remained for available further requirement.

2.4.3.1 Charging and Discharging of Lead Acid Battery

In the PV system, a battery plays an important role. During the day, the electricity generated from solar is stored in the battery, which is discharged during load demand. During charging state, current flows from PV arary or diesel to battery which increases battery terminal voltage and SoC. This current flow is controlled by charge controller.

During discharging state, current drifts off from the battery to the loads. As charge decreases instantaneously, the battery voltage is drawn off quickly.

2.4.3.2 Battery Capacity

The measurement of battery capacity can be defined as Ampere Hours (Ah). In other words, it is an indication of how much energy can be stored in a battery and integrating discharging current in amperes over specific time. 1 Ah equals to the transfer of one-ampere over one-hour.
Battery capacity can be calculated using equation (2.8) as below:

$$\frac{\text{Nominal Voltage of Battery} \times \text{Capacity of Battery Storage}}{1000} = \text{Capacity (kWh)} \tag{2.8}$$

For example, a 100Ah 12V battery capacity calculation can be shown as below:

$$\text{Capacity of Battery} = \frac{12V \times 100Ah}{1000} = 1.2kWh$$

2.4.4 Charge Controller

When battery is included in a system, the necessity of charge controller comes forward. A charge controller controls the uncertain voltage build up. In a bright sunny day the solar cells produce more voltage that can lead to battery damage. A charge controller helps to maintain the balance in charging the battery There are four general types of charge controllers, categorized by the method used to regulate the charge from the solar modules to the batteries: shunt type charge controllers, series type charge controllers, PWM (Pulse Width Modulation) charge controllers and MPPT charge controllers [65] [66].

2.4.5 Load Side Inverter

Solar panel generates DC electricity but most of the households and industrial appliances need AC current. Inverter converts the DC current of panel or battery to the AC current. We can divide the inverter into two categories. They are:

- Stand alone
- Line-tied or utility-interactive

The load side converter, a three phase voltage source inverter, is used as interface between DC bus and the load side. Voltage source inverter is the most commonly used type. The input DC voltage may be from an independent source such as a battery or may be the output of a controlled rectifier. The DC-AC inverter is used for many applications including motor drives, uninterruptible power supplies and on renewable energy systems. This type of converter produces a sinusoidal AC output waveform whose magnitude and frequency can be controlled. The load side voltage source inverter control is responsible to regulate the voltage and frequency at the customer load. In the stand-alone solar power systems, there is no grid, the output voltages should be controlled in terms of amplitude and frequency. Pulse Width Modulation (PWM) control strategy is used to control the output load voltage during variation of required load power. The output voltage of the inverter is controlled by varying the pulse width.

Inverter Filter

When DC power is converted to AC power, the output contains undesirable components called ripple. In many applications of inverter, this ripple is not allowed to exceed a specified value. The more common filters are of L, C, LC and LCL. Compared with the L filter, the LCL filter is considered to be a preferred choice for its cost-effective attenuation of switching frequency harmonics in the injected mini-grid currents.

2.4.6 DC-DC Converter

A DC/DC converter converts a source of direct current (DC) from one voltage level to another level. There are two types of DC/DC converters: linear and switched. A linear DC/DC converter uses a resistive voltage drop to create and regulate a given output voltage, a switched-mode DC/DC converts by storing the input energy periodically and then releasing that energy to the output at a different voltage. There different types of DC-DC converters including buck, boost, buck-boost, bidirectional converter etc.

2.4.6.1 Bidirectional DC-DC Converter

A bidirectional converter is required to allow the flow of power from and to the batteries in the mini-grid which can be designed by combining the capabilities of the buck and boost converters replacing their diodes with switches as shown in figure 2.18. The top switch is used to operate the converter as a buck converter, transferring power from the high voltage side to the low voltage side and the bottom switch is used to operate the converter as a boost converter, transferring power from the low voltage side to the high voltage side.

The bidirectional converter will be controlled by a charge controller which will determine whether energy needs to be sent to or from the battery in order to smooth out the fluctuations of renewable energy sources and stabilize the voltage. The same values as the buck converter design was used for the bidirectional converter except for the inductor value.

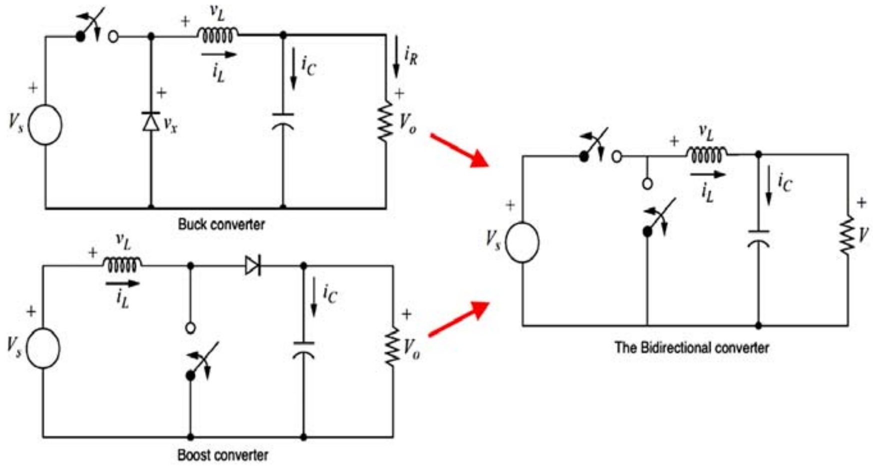


Fig. 2.18: Bidirectional converter construction [67].

2.4.6.2 Boost Converter

Boost converter steps up the input voltage magnitude to a required output voltage magnitude without the use of a transformer. The main components of a boost converter are an inductor, a diode and a high frequency switch. These in a co-ordinated manner supply power to the load at a voltage greater than the input voltage magnitude. The control strategy lies in the manipulation of the duty cycle of the switch which causes the voltage change.

2.4.7 Loads

An important governing element of any power generating system is load. Load has substantial impact on system design. Load is the driving factor behind any power system, large or small. A mini-grid can provide residential, institutional, commercial, agricultural and small-scale industrial demand.

Residential Load

Generally, household loads in rural area includes LED or CFL lights, cell-phone chargers, TVs, ceiling fans, fridges etc. Number of these appliances may vary user to user based on requirements. Again daily uses of these loads are different in summer and winter season.

Social Institutions

These would consist of mosques, madrasas, schools etc. The loads most commonly used in these entities are LED bulbs and ceiling fans.

Commercial Load

This category of load would consist of rice husking mills, saw mills, ice factories etc. The machines running in rice mills serve the factories for around 6 hours a day, consuming around 25 horse-power (HP). The other factories may use different machines with lower/higher rating, and they all are considered large loads in the mini-grid.

Agricultural Load

This category of load would consist of irrigation pumps with varying running hours, during different stages of cultivation. For example, during wheat, aman or jute cultivation - the operating hours rise up, leading to this load type to consume a significant amount of electricity.

2.5 Technical Challenges

Implementation of mini-grid in rural/remote areas faces different challenges including technical, economical, social and others. Here we will limit our discuss to only technical challenges for mini-grid implementation and operation.

2.5.1 Accurate Load Assessment

Accurate load assessment is highly important to design the optimum size of the power generation plant and the grid distribution capacity. Load assessment is the foundation of hybrid mini grid project portfolio. The main challenge for accurate load assessment is the unavailability of historical load data. In general, the load is estimated based on the previous electricity uses pattern of different consumers. In this case, load data is analyzed based on the assumption of the inhabitant's income capacity, small household loads using for lighting and cooling fans. This assumption can be varied after the mini grid implementation which can create impact on load factor and capital investment. The next constraint for the load assessment is the variation of load between day and night. Usually, the system is designed based on the postulation of peoples living habit of early sleep and sharp rising which might be changed after electrification. The more use of day load will reduce the cost of addition battery storage or diesel fuel and hence the electricity tariff. Seasonal variation of load is also impact to the system load assessment. Irrigation and small residential load are considered as a principle demand of the rural areas which may change during rainy and winter season. An accurate analysis of weather profile is needed not only for the load assessment but also for the accurate estimation of annual solar production [68].

2.5.2 Hybrid System Design

The next challenge is to design an optimum PV based hybrid system based on the estimated load data. More accurate load assessment will ensure the technical and economic viability of a hybrid mini-grid system. A PV based hybrid system will be built from the energy mixture of Solar PV and other resources for example wind, hydro, biomass or diesel generators. Therefore, the identification of optimum system is the key feature of the design [68].

2.5.3 Fault Management

Fault management is one of the major challenges for mini-grid. Most faults in an mini-grid system with a network of overhead lines are phase-ground faults. Approximate percentages of different types of fault occurrence are mentioned below [69]:

(a) Single phase-to-ground: 70%-80%

(b) Phase-to-phase-to ground: 17%-10%

(c) Phase-to-phase: 10%-8%

(d) Three-phase: 3%-2%

The protection system should cut off the faulty part from the mini-grid as rapidly as necessary to protect the rest part. Sometimes problems like selectivity (false, unnecessary tripping) and sensitivity (undetected faults or delayed tripping) may arise which causes interruption. So design a protection system that isolates the fault and allows the remainder of the mini-grid to keep operating is difficult task [70].

Fault protection system in a mini-grid should detect faults reliably and minimize false trips, be sufficiently fast to protect people and equipment and preferably isolate the fault by disconnecting the minimum portion of the mini-grid and therefore the minimum number of users. In conventional radial distribution networks, only source supply the high levels of fault current. Fault current levels decline the further the fault is from the source because of the line impedance between the source and the fault.

2.5.4 Large Intermittent Load

The existence of arc welding or other large intermittent daytime loads would cause rapid ramp-up/ramp-down in power production from PVs and would force the diesel generator to make rapid relative changes in power output to keep electricity within frequency specification. This type of loads cause great damage in mini-grid. Here, electric arc welding load is discussed briefly.

2.5.4.1 Arc Welding Load

Arc welding devices are highly non-linear loads, thus is the source of harmonic distortion. Arc welders commonly cause transients in local network due to the intermittent switching and therefore some electronic equipments may require protection from the impulsive spikes generated. A circuit using this form of machine is illustrated in Figure 2.19. Electrical welding machines are among the most pollutant loads due to their strong non-linear behavior. Welding machines are based on the Joule effect; they use the heat dissipated by a current circulation so as to join two metal parts. This requires the passage of a very high current value, and for this reason, welding machines usually use a step-down transformer in order to reduce the applied voltage to very low values.

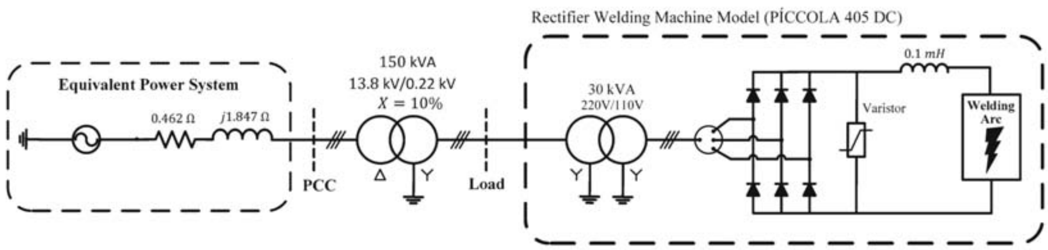


Fig. 2.19: Electrical circuit of rectifier arc welding machine [71].

During the welding process, short welding intervals (with high current flow) are followed by other no-load operations (normal operation). In each welding process, two voltage steps are produced: one at the time of generating the current and the other at the instant it is cut off. These voltage variations can cause problems in the nearby loads, as the voltage fluctuations may be outside the (minimum and maximum) tolerance limits of the voltage or even produce flicker. Among all the types of non-linear loads, the electric welding machine is one of the loads that has the largest impact on the electric power distribution system. It causes low power factor, large current, voltage fluctuations and significant variations in reactive power; it generates harmonic and current imbalances as shown in Figure 2.20.

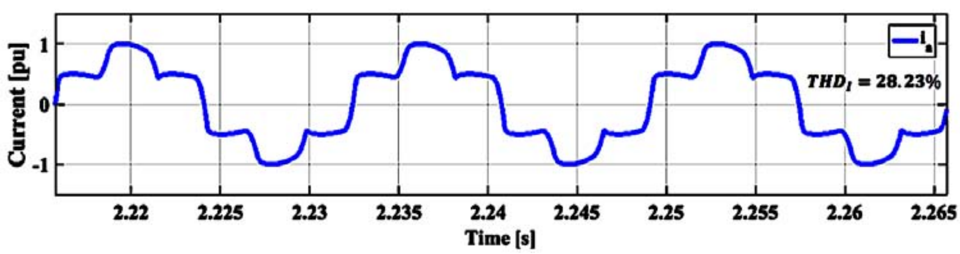


Fig. 2.20: Current waveform for the rectifier arc welding machine [71].

These disturbances lead to the deterioration of power quality (PQ) affecting the yield and quality of nearby loads, and endangering the operation of many users. Many disturbing load accesses lead to serious pollution and can be harmful to the distribution power grid. Hence, depending on the operation mode, a specific load can present intermittent behavior and cause serious PQ disturbances at the local system, such as voltage fluctuations, flicker, harmonics and inter-harmonics. An arc welding machine provides the required current and voltages at different stages of the arc process. Initially, a high voltage is produced at no load, which is also called open circuit voltage. When the electrode touches the work-piece, a short-circuit occurs and the current increases suddenly. After the reference current level is reached by the output current, the arc welding machine regulates the output voltage to maintain a constant current which is required for metal transfer. The voltage produced in the steady state is related to the current, which depends on the arc length and electrode diameter.

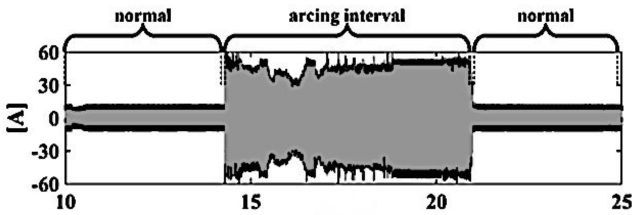


Fig. 2.21: Current at the rectifier arc welding machine terminal [71].

2.5.5 Others

Many components of the hybrid system are imported from overseas which affect the operation of mini-grid for lack of supply of spare parts. Sometimes, cooling system for the generators is not installed optimally, then dust frequently block the radiators which causes overheating and unscheduled interruptions of the electricity supply. Increasing demand of electricity and the use of less efficient equipments create fluctuations in the electricity supply, which damage both household and business appliances. Fluctuations in the electricity supply are also caused by the issues of the synchronization of the generators with the PV system, resulting in manual operation and unscheduled interruptions during the process.

CHAPTER 3

MINI-GRID AND COMPONENTS MODELING

In this chapter, the MATLAB/SIMULINK based modeling of each component will be discussed. The components include the photovoltaic system, energy storage system, diesel generator, inverter and converters used. Load profiles used in the simulations have been discussed. In addition, the sizing and configuration estimations of different components used in mini-grid model have been elaborated.

3.1 Architecture and Simulink Model of PV–Diesel–Battery Hybrid Mini-grid System

A hybrid mini-grid model is expected to consist of renewable or non-renewable energy sources for electricity generation. In the designed model, PV array is used as the renewable source, with diesel generator (backup source). The PV array is connected with a maximum power point tracker (MPPT) based boost converter in order to extract the maximum power from solar. A lead-acid battery serves as the energy storage system, required for the diurnal and unpredictable nature of the PV array's output.

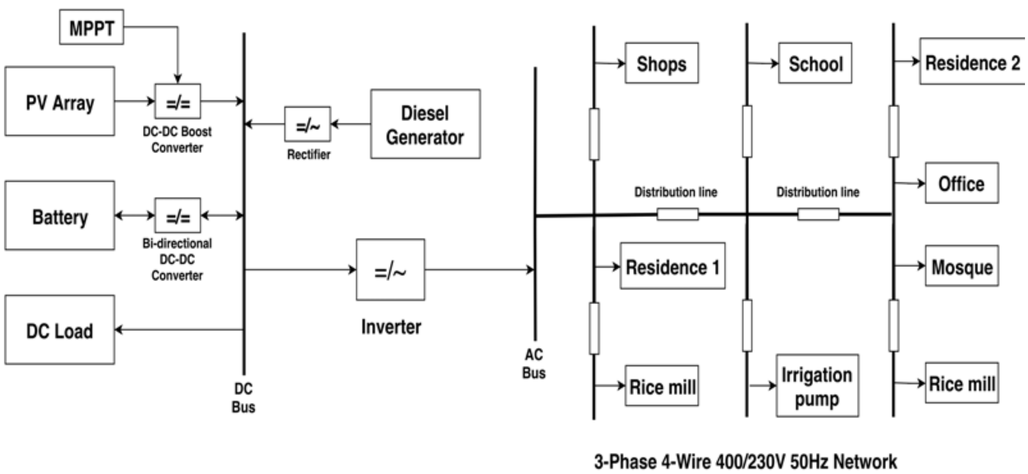


Fig. 3.1: Block diagram of architecture of PV–diesel–battery hybrid mini-grid.

Figure 3.1 shows a single-line diagram that represents architecture of the model.

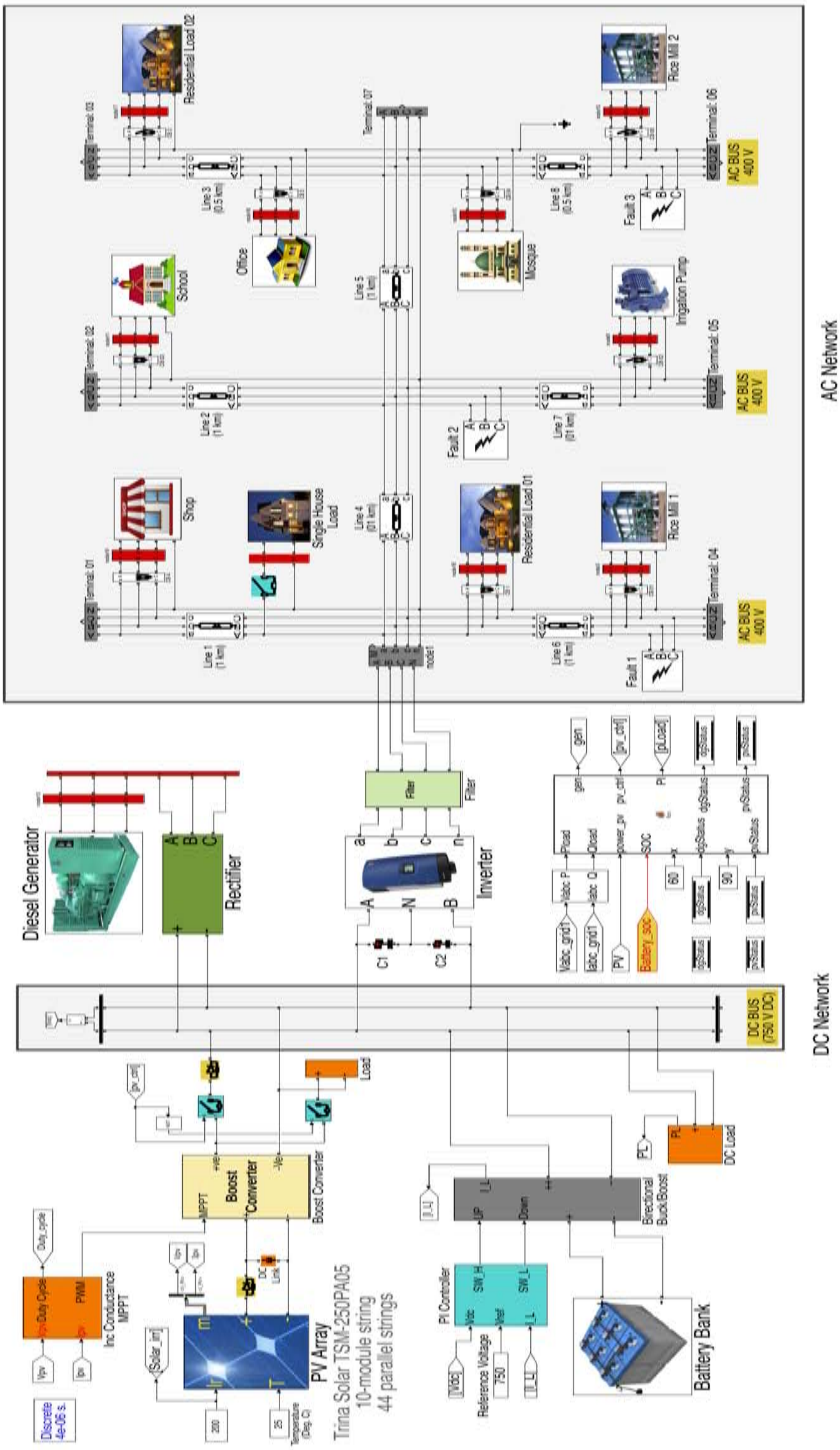


Fig. 3.2: Simulink model of photovoltaic, diesel hybrid AC mini-grid system.

The left side of the figure represents the electricity generation blocks. The right side of the figure shows a 3-phase 4-wire 400/230V 50Hz AC network with connected loads present in the mini-grid. A 3-phase inverter model is used to generate AC power from DC bus. On the other hand, a rectifier is connected between diesel generator and DC bus for charging the battery. Figure 3.2 shows the designed Simulink model of photovoltaic, diesel hybrid AC mini-grid system

3.2 Photovoltaic System Modeling

The electric power supplied by a PV module depends greatly on atmospheric conditions. The generated voltage v across the module has linear dependence on the junction temperature T, and the supplied current depends linearly on the irradiation level. Therefore, the power-voltage (P-V) characteristics depend on the temperature and on the irradiation. Under any atmospheric conditions, these P-V characteristics reveal a maximum power point (MPP) that represents the operation allowing the extraction of all available power from the PV module. Therefore, a PV system modeling must includes a maximum power point tracking (MPPT) system to generate maximum power from solar.

The photovoltaic system modelled in this work consists of the following components:

- a PV array block (complete power generating unit) consisting of PV modules and panels
- a maximum power point tracking (MPPT) algorithm based boost converter

3.2.1 Photovoltaic Array

Photovoltaic cells can be modelled in Simulink either by implementing the equations that represent the functionality of a solar cell, or by using the Simulink block which has pre-defined solar arrays for many different models.

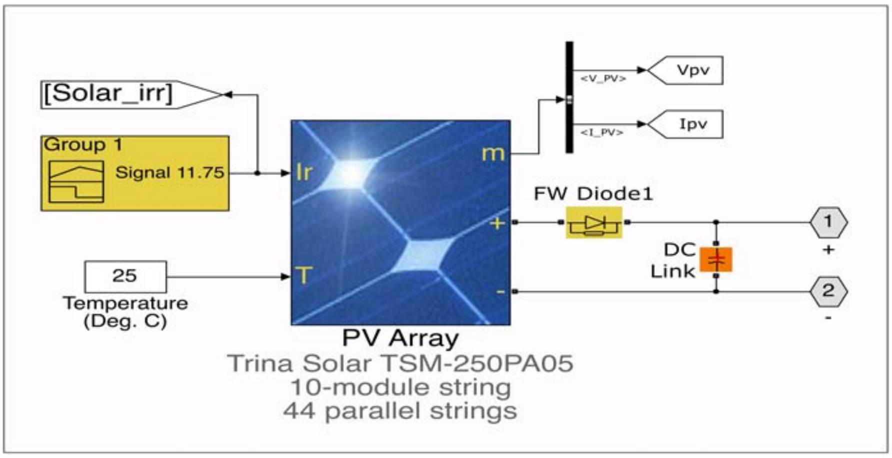


Fig. 3.3: Solar array Simulink model.

The solar array model used in this work is the Trina Solar TSM-250PA05 model from Simulink library shown in Figure 3.3. The corresponding I-V and P-V curves for this array under $1000W/m^2$ irradiance and 25°C temperatures are shown in Figure 3.4.

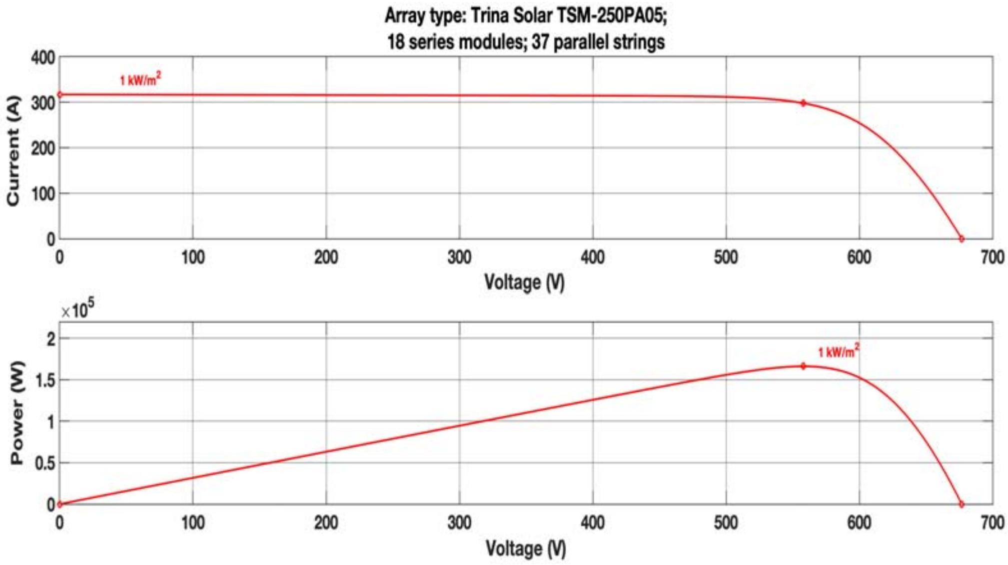


Fig. 3.4: Display of I-V and P-V characteristic of 166.4kW solar array.

The upper graph of Figure 3.4 shows the current versus voltage for Trina Solar TSM-250PA05. The curves illustrate that the current produced by the module is constant with increasing voltage until a certain voltage is reached, followed by a decrease substantially with increasing voltage.

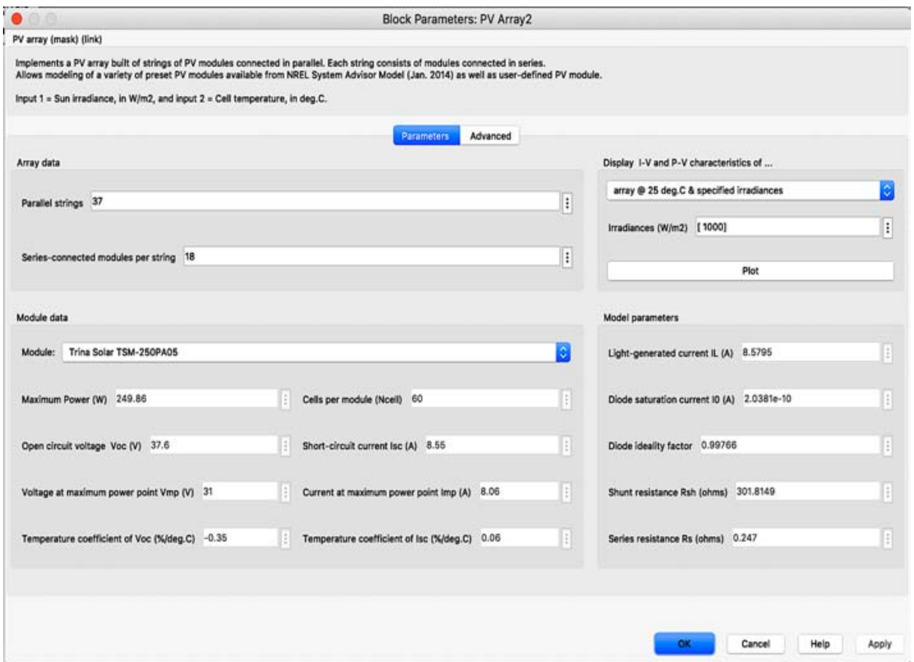


Fig. 3.5: Simulink PV array block parameters.

The bottom graph of Figure 3.4 is a plot of power P versus voltage V, where P is the product of V and current I. P increases with increasing V for all the curves until a certain voltage is reached and then the power begins to decrease with voltage. The knee of the P-V curve is where we want to operate at in order to extract maximum power from the array.

Figure 3.5 shows the input panel for the PV array in Simulink. The Array data tab lists the number of parallel and series strings in order to modify the PV array voltage and current. The Module data tab has specific operating information for the PV array. This data can be selected from many manufacturers, or the user can manually enter the specific data. The model parameters tab then lists the specific parameters for the PV array.

3.2.2 PV Array Connected with MPPT and Boost Converter

Maximum power point tracking (MPPT) system can be used to find the operating point at which the maximum power can be extracted from the PV array under varying irradiance and temperature. MPPTs use a simple structure with very few variables for implementing an iterative method to achieve impedance matching between the load and output impedance of the PV array.

In this thesis, the MPPT was modelled using an incremental conductance (INC) algorithm. This is a commonly used MPPT algorithm that works by perturbing the voltage in a certain direction and observing the change in power. If the power is increased, the voltage is perturbed in the same direction.

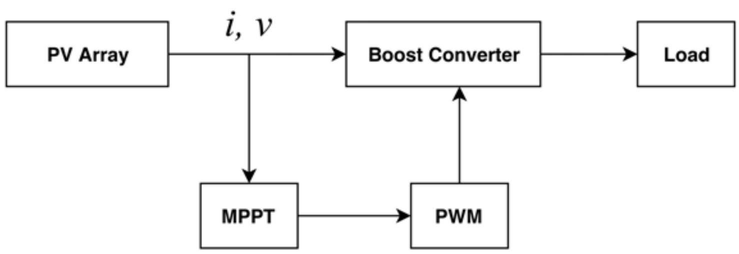


Fig. 3.6: MPPT block diagram.

Figure 3.6 shows how the MPPT is connected to the PV system. The voltage and current from the PV Array are fed as input to the MPPT. The algorithm determines whether the voltage needs to be increased or decreased in order to increase the power from the PV array. The MPPT then outputs a change in the duty cycle which is converted to a PWM signal and fed to the boost converter so that the voltage can be increased or decreased.

The MPPT algorithm was designed to perform simulations in MATLAB/SIMULINK by using SimPower System Toolbox. Figure 3.7 shows the subsystem of the incremental conductance MPPT. The voltage and current are read in order to compute the power. The

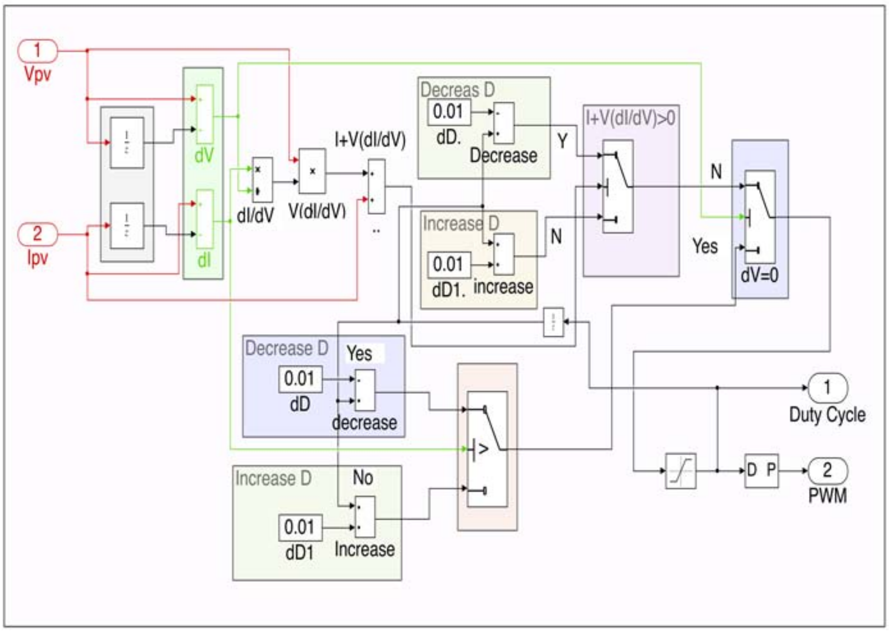


Fig. 3.7: Incremental conductance (INC) based MPPT algorithm.

voltage is then compared to the previous sample from which we can determine which direction provides the maximum power point. The duty cycle is then perturbed in the direction that will increase the power. The change in the duty cycle is fed into a PWM generator which operates the boost converter to perturb the voltage.

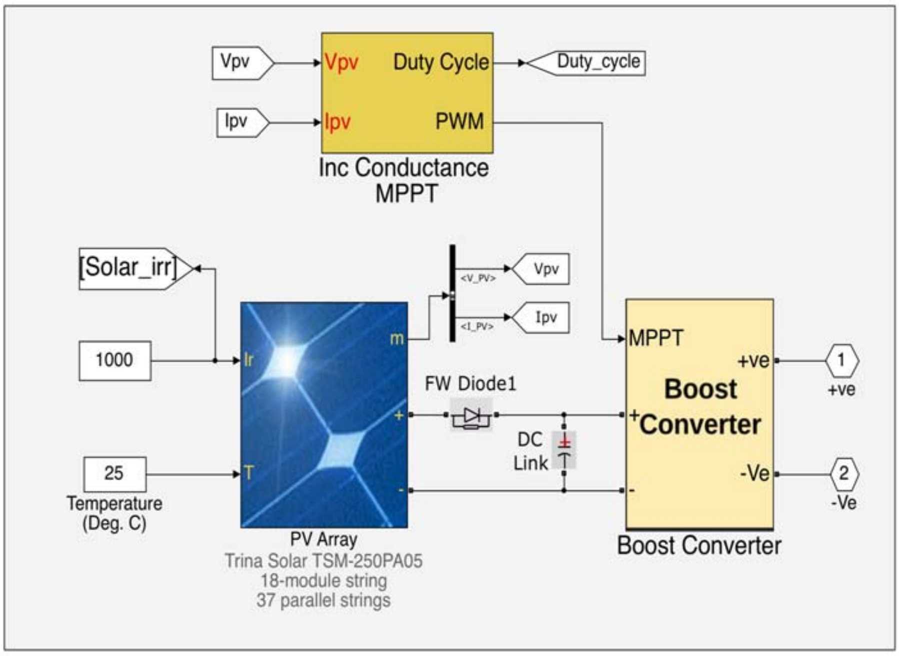


Fig. 3.8: Photovoltaic array with MPPT and boost converter.

Figure 3.8 shows the MATLAB/SIMULINK model for incremental conductance method with boost converter and connections of boost converter receiving a gate signal from MPPT output loops.

3.3 Battery Storage System

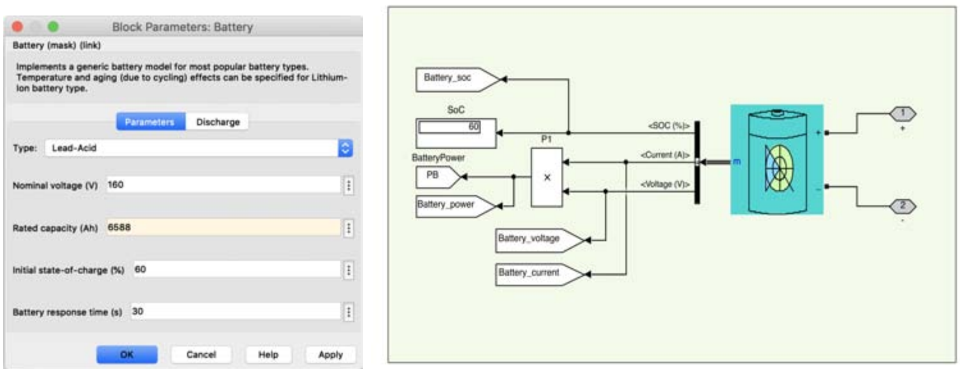
The integration of a rechargeable battery energy storage system is necessary to provide short-term power balancing and/or long-term energy management. The battery storage setup should ideally include a two way power flow converter to enable the transfer of electricity to and from the DC or AC power line. Lead-based, Lithium-based, Nickel-based or Sodium based deep cycling industrial batteries can be used depending on system requirements. When selecting batteries for use in off-grid or mini-grid RE systems, one should consider which battery technology best fulfills the system's specific technical and environmental requirements.

Due to lead acid batteries allow flexible scalability in rural projects and is cost-effective, the mini-grid model designed in this thesis consists of a Lead Acid Battery. The model design of the battery is discussed in this section, along with its design mechanism to enable charging and discharging.

3.3.1 Lead Acid Battery Model

The battery block existing in MATLAB/SIMULINK software's library provides a set of predetermined charge behaviour for four types of batteries: Lead-Acid, Lithium-Ion, Nickel-Cadmium and Nickel-Metal-Hydride. Therefore, this Lead-Acid Battery Model can be used to emulate the exact behavior of a real lead-acid battery, which has been used in this thesis.

The Lead-acid battery block is a generic dynamic battery model provided by Simulink, which can be parameterized to represent different types of rechargeable batteries. Here a generic dynamic battery model is configured for a lead acid battery.



(a) Parameters of Lead acid battery.

(b) Lead acid battery Simulink model.

Fig. 3.9: Lead acid battery model in Simulink.

The parameters of the lead acid battery are shown in Figure 3.9a. The nominal voltage of the battery, denotes as V_{nom}, represents the end of the linear zone of the discharge characteristics and is configured to 160V. The initial state-of-charge (SoC) of the battery is used as an initial condition for the simulation and does not affect the discharge curve. An SoC of 100% indicates a fully charged battery and 0% indicates an battery empty of charge. The response time of the battery value represents the voltage dynamics and can be observed when a current step is applied. The rated capacity is the minimum effective capacity of the battery.

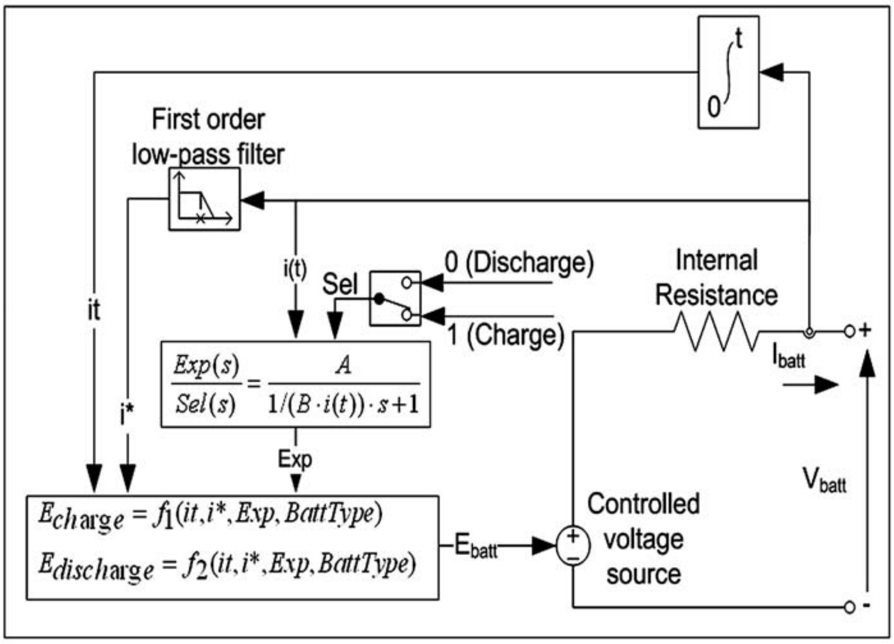


Fig. 3.10: Equivalent circuit diagram of a lead acid battery block.

Figure 3.10 shows the equivalent circuit of the battery model selected for this work. This model is based on a modified version of the parameterized battery model found in MATLAB/SIMULINK software. The model represents the inherent behaviour of the dynamics of a battery. It runs by sensing the current passing through the internal resistance of the battery. This current is fed to an integrator that relates the current with respect to time and thus allows to track the amount of current being delivered for a given period. The user can modify the battery parameters - namely battery type, voltage, state of charge and capacity.

3.3.2 Charging and Discharging of Battery

When the mini-grid's generated power exceeds the connected loads, excess or surplus power is stored to the battery. During night or peak load condition, battery supplies the stored power to the load as demanded.

A controller is essential to control the flow of current to and from batteries, protect batteries and regulate the DC bus voltage. In this thesis, a PI controller subsystem has been used to control a bidirectional converter to fix the DC bus voltage and regulate the bi-directional current flow. Figure 3.11 shows the charging and discharging of a battery bank through a bi-directional converter.

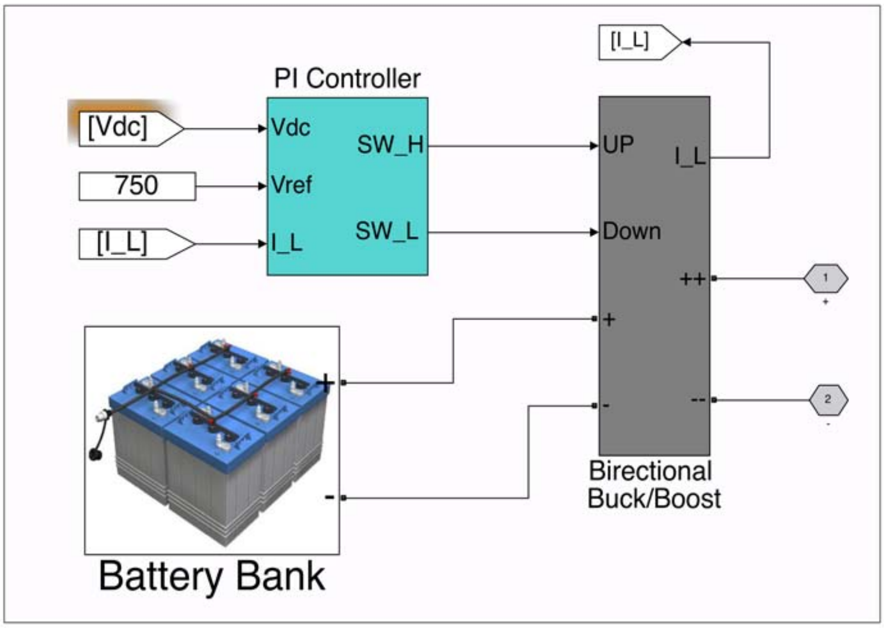


Fig. 3.11: Battery charging and discharging through a bi-directional converter.

A PI controller based control mechanism has been designed to control and operate the bi-directional buck-boost converter, as shown in Figure 3.12. The DC bus reference voltage, denoted by V_{ref}, has been set to 750V in this mini-grid . The difference between the DC bus voltage, V_{dc} and V_{ref} represents the error signal, which is fed into the first PI controller. The PI controller calculates the change needed to reduce the error.

The battery current, denoted by I_L, is subtracted from the output of the first PI controller and its output is fed to the second PI controller. Output of the second PI controller and repeating sequence are compared by a relational operator block which generates a gate pulse signal. A NOT gate is used to generate the inverted pulse signal. Outputs of the PI controller subsystem, SW_H and SW_L, are connected to a bidirectional buck/boost converter to keep the DC bus voltage constant, and control the battery charging (discharging). Bidirectional converter operate under buck mode to charge battery and operate under boost mode to discharge battery.

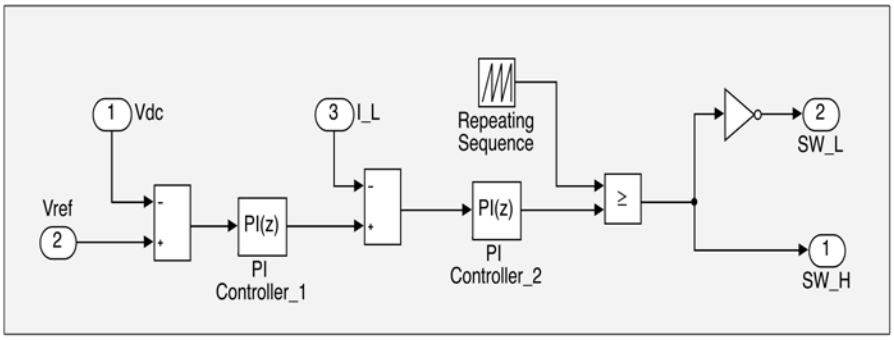


Fig. 3.12: PI controller block diagram.

Battery control system has been designed to operate battery in the region of 50-100% SoC. When it's SoC reaches 100%, the battery stops charging. Again battery are not discharged below 50% for long term operation. The diesel generator is turned on when battery SoC reaches below 50%, and is connected to DC bus through rectifier to charge battery shown in Figure 3.13.

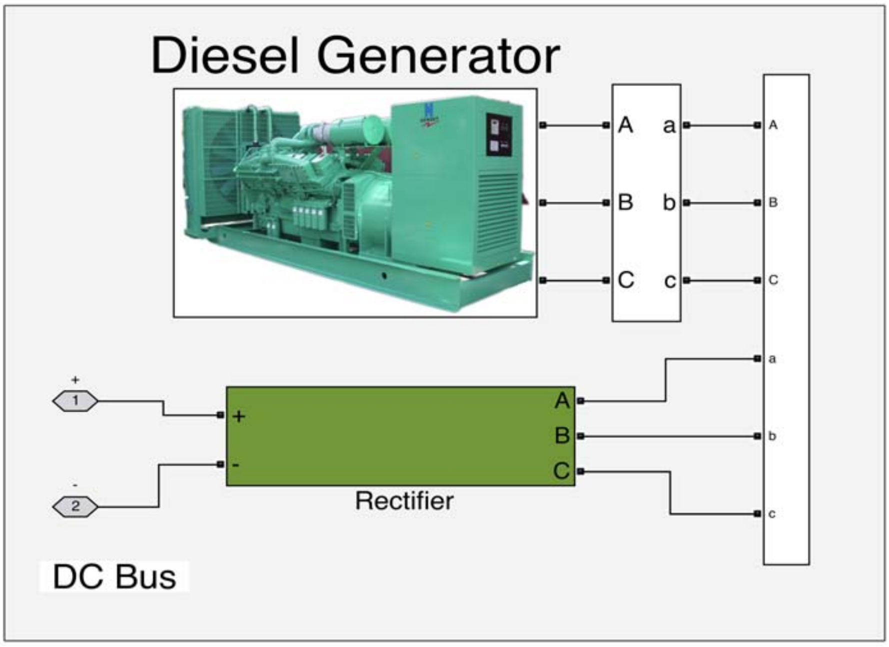


Fig. 3.13: Connection of diesel generator with DC bus.

3.4 Diesel Generator Model

A diesel generator (DG) is a device which converts fuel (diesel oil) energy into mechanical energy in its internal combustion engine and subsequently converts mechanical energy into electrical energy. The basic components of a diesel generation system are: internal combustion engine, governor, excitation system and synchronous generator. A governor can be defined as a mechanical or electromechanical device for automatically controlling the speed of an engine by relating the intake of fuel. The controller for the engine is a simple speed governor that keeps the turbine operating at its designed speed. The output of the speed governor is throttle signal that controls the fuel going into the engine.

The main characteristics of a diesel generator set are: rated power, rated voltage, rated frequency, number of phases etc. The main data of the diesel generator set used are as follows: rated power 80kW, rated voltage 400V, rated frequency 50Hz. Figure 3.14 shows a dynamic model of diesel generator from the Simulink library that gives a description of the fuel consumption rate as a function of speed and mechanical power at the output of the engine, and is usually modeled by a simple first order model relating the fuel consumption to the engine. The internal combustion chain is based on actuators

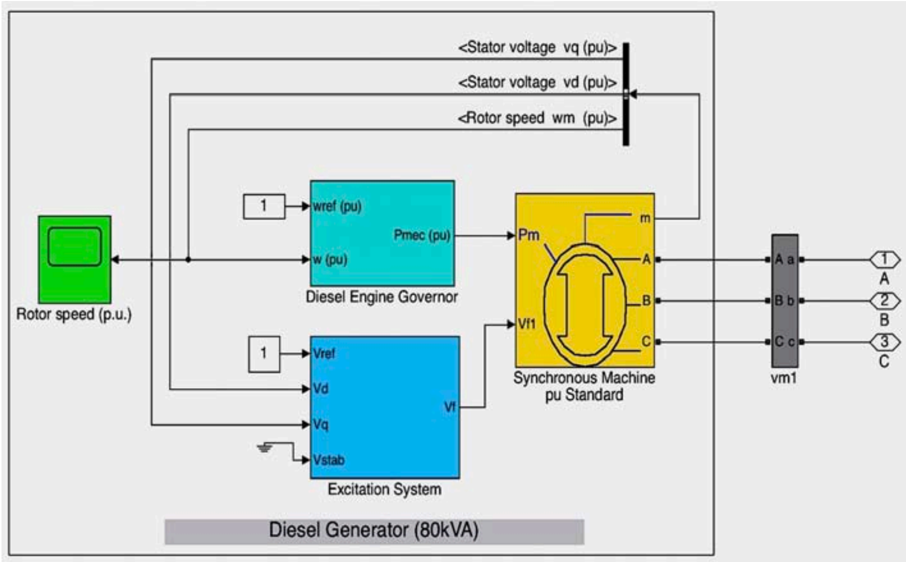


Fig. 3.14: Diesel generator model.

with simple traditional models to represent the mechanical part of a diesel generator. This DG model can be used for analysis of electric stability and performance of DG e.g. transient voltage and current, power system stability, load flow study.

The output voltage and speed of the Synchronous machine are used as feedback inputs to a Simulink control system that contains the diesel engine and governor block as well as an excitation block shown in Figure 3.15. The excitation system block has been used from Simulink library.

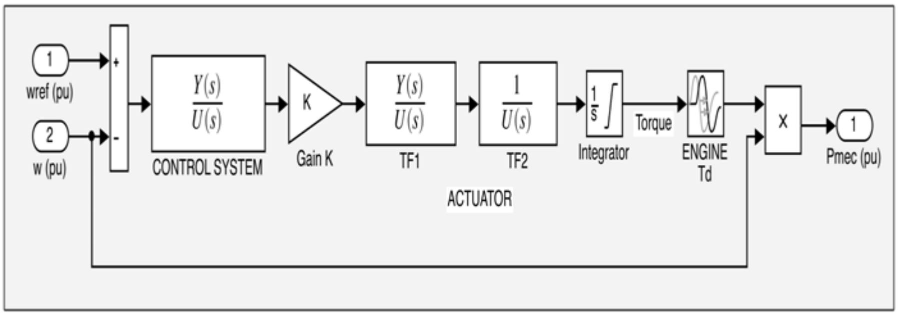


Fig. 3.15: Diesel engine and governor System.

3.5 Three Phase Inverter

A three phase inverter is used as an interface between the dc bus and load side. The load side represents a three phase 4 wire AC network with connected loads. The inverter converts 750V DC bus voltage to 400V AC. Figure 3.16 shows the three phase inverter designed in MATLAB/SIMULINK. IGBT (Insulated Gate Bipolar Transistor) has been used in universal bridge block. Two level PWM (pulse width modulation) generator block of 6kHz is connected to gate input of bridge block for 2-level 3-phase inverter design.

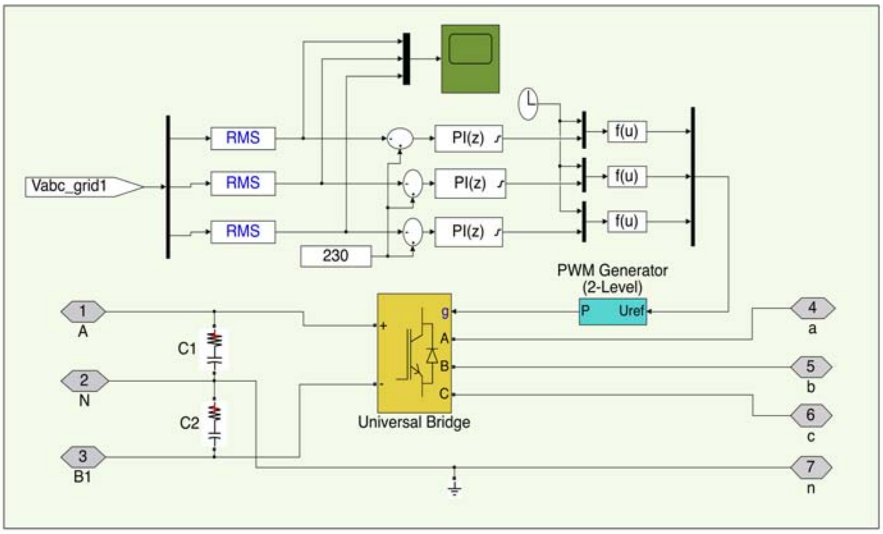


Fig. 3.16: Three phase inverter model.

The grid voltage is continuously compared with reference voltage to maintain a constant voltage (rms). The reference voltage (phase-neutral), V_{ref} has been set to 230V. The difference between the grid voltage, $V_{abc-grid1}$ and the reference value, V_{ref} is taken and the error signal is fed into the three different PI controller for individual phase. The PI controller calculates the changes needed to reduce the error. Three PI controller instead of one will stabilize the individual phase voltage more than single PI controller which is a better way to keep all the phase stable individually. Any changes in one phase will not affect other phases (e.g., voltage drop). Output of PI controller is modulation index, m.

To create individual phase expression, a mux block of each phase combines the output of PI controller with a clock. We get individual phase expressions as follows:

(a) Phase A: $u(2) * sin(2\pi * 50u(1))$

(b) Phase B: u(2)*sin(2*pi*50*u(1)+2*pi/3)

(c) Phase C: u(2)*sin(2*pi*50*u(1)+4*pi/3)

Another mux block combines these three phase expressions into a single vector output which is fed into a 2-level PWM (pulse width modulation) block to generate gate pulses for universal bridge block. Carrier frequency of PWM block is set to 6kHz. Output of the inverter is fed into filter to get a smooth 3 phase 400V 50Hz output.

Inverter Filter

Three phase inverter is interfaced with mini-grid load side by a filter which ensures high quality of grid current. Compared with the traditional L filter, LCL filter provides more attenuation to high frequency harmonics and exhibits better dynamic performance

Figure 3.17 shows filter model for three phase inverter.

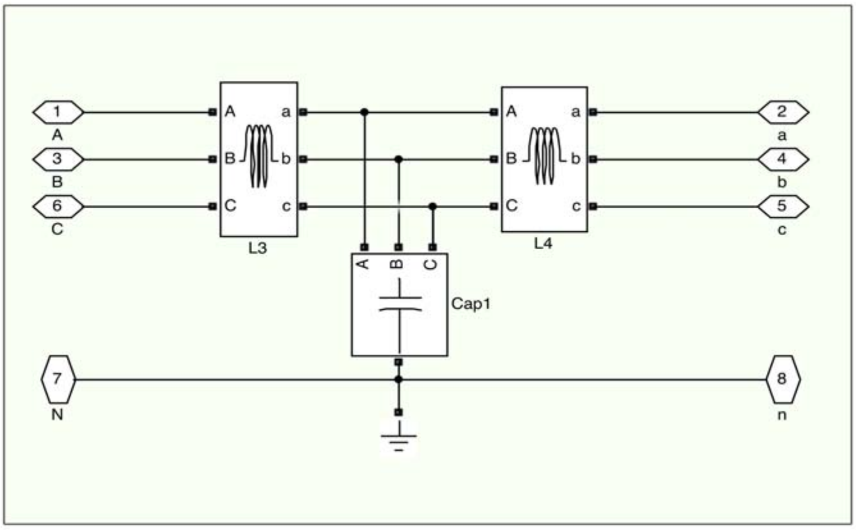


Fig. 3.17: Inverter filter design.

3.6 DC-DC Converter Modeling

DC-DC converters have been used in conjunction with different components of the mini-grid such as PV panel, battery bank etc. to change the voltage level and generate maximum power. Two DC-DC converter models are discussed here.

- Boost converter
- Bi-directional buck/boost converter

These DC-DC converters operate by periodically opening and closing a switch. The boost converter increases the input voltage. It is called a boost converter because the output voltage is larger than the input voltage. The buck-boost converter has the ability to increase or decrease the input voltage but with a polarity reversal. The converters contain a low pass filter after the switch at the output in order to obtain a purely DC output. The output voltage is changed by varying the duty cycle.

3.6.1 Boost Converter

The boost converter works by storing energy in an inductor when the switch is closed and delivering that energy to the load when the switch is open to boost the output voltage. The inductor needs to be large enough in order to keep the current positive and in continuos operation. The output of the boost converter is calculated by Equations 3.1 where V_O is the output voltage, D is the duty cycle, V_S is the input voltage.

$$V_O = \frac{V_S}{1-D} \tag{3.1}$$

Figure 3.18 shows boost converter designed in Simulink.

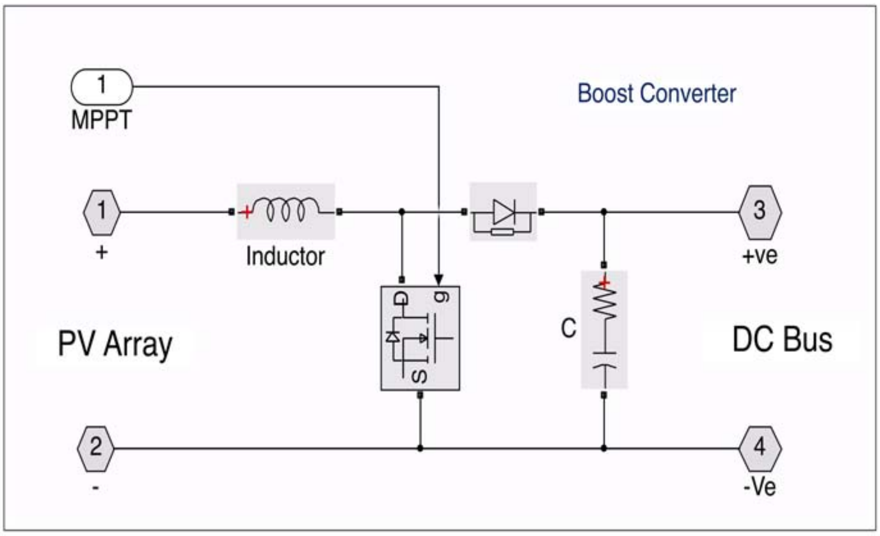


Fig. 3.18: Boost converter in Simulink.

3.6.2 Bi-directional Buck/Boost Converter

A bidirectional buck/boost converter is required to allow power flow from and to the battery bank. This converter is designed combining the capabilities of buck and boost converters and replacing its diode by switches.

Figure 3.19 shows bidirectional buck/boost converter designed in simulink. This converter has been used to maintain the DC bus voltage stable through charging and discharging the battery.

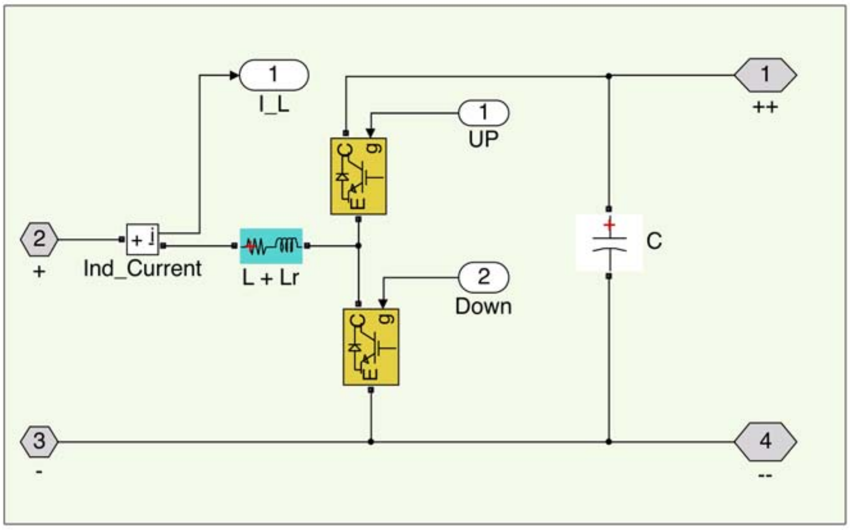


Fig. 3.19: Bidirectional buck/boost converter in Simulink.

3.7 Three-Phase Four-Wire Distribution Line

Generally, a distribution system consists of a three-phase four wire system which provides power to single phase and three phase loads, e.g. light loads and motor loads. In a mini-grid, small loads like households, shops etc. are connected in phase to neutral line and large loads like irrigation pumps, saw mills, rice husking mills are connected in 3 phase line. In 400V three phase distribution network, single phase loads are connected phase-neutral with 230V and for three phase loads it is phase to phase with 400V.

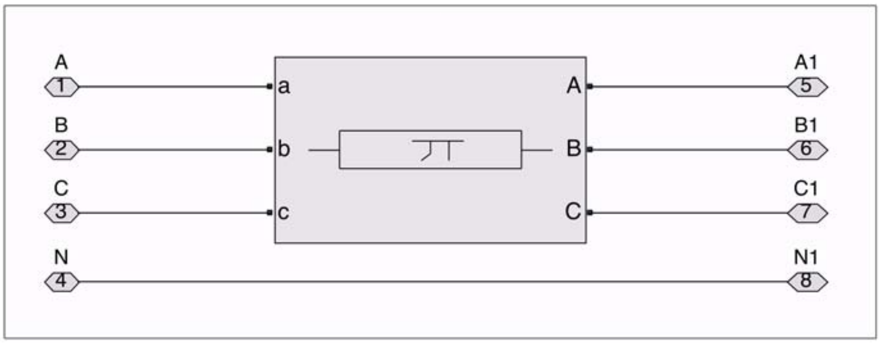


Fig. 3.20: Three phase four wire distribution line model in Simulink.

In a three phase four wire mini-grid system, loads can be connected in following manners:

- Phase to neutral connection
- Phase to phase connection
- Three phase three wire connection
- Three phase four wire connection

In this work, a three-phase PI Section Line block has been used to create three phase distribution line from Simulink library. Later 3 phase 4 wire system has been developed using this PI section block with neutral wire shown in Figure 3.20

The line parameters R, L, and C are specified as positive- and zero-sequence resistances, inductances and capacitances that take into account the inductive and capacitive couplings between the three phase conductors, as well as the frequency and line length. Figure 3.21 shows three phase distribution line parameters used in mini-grid model. In our mini-grid model, we have considered distribution line length of total 7km. This PI section block is very useful to calculate line loss and voltage drop in the network. At the time of line to ground fault, fault current flows through neutral which can be investigated using 3 phase 4 wire network.

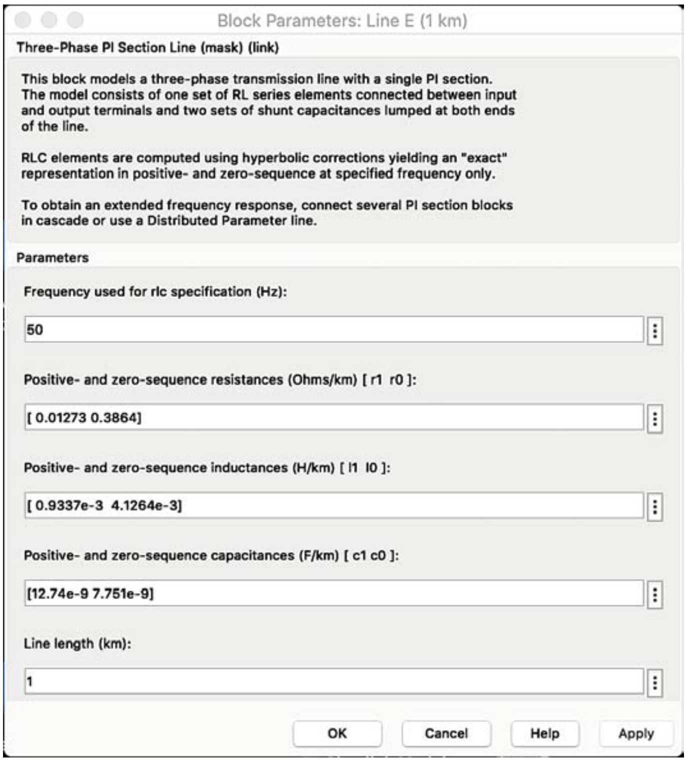


Fig. 3.21: Line parameter of three-phase PI section line block.

3.8 Load Profile and Load Modeling

The load required to be considered for modeling a mini-grid can be divided in several categories:

- residential
- social institutions (schools, madrasas, mosques)
- commercial (small shops, offices)
- small industries (rice husking mills)
- agricultural load (irrigation pumps)

To model a mini-grid that meets the requirements as closely as possible to that in the real scenario, one must quantify the total load arriving from each of the above categories. Therefore, statistics were collected from an existing mini-grid providing rural electrification to model a similar mini-grid. Table 3.1 shows the number of different load types covering the above categories. The household load, as observed in existing mini-grids, has been divided in four packages in terms of service type, as shown in Table 3.3. In each service type, there varies quantity of appliances - namely LED light, ceiling fan, TV and refrigerator.

Table 3.1: Summary of load classification in the modelled mini-grid.

Load type	**Quantity**
Households	330
Shops	41
Mosques, Madrasas & Schools	6
Offices	2
Rice mills	3
Water pumps	15
Total	**397**

Based on studies conducted on energy consumption patterns in rural areas, household appliances can be quantified with ratings of each. We have considered the rural households to be using efficient lamps of 7 Watts (W) each, ceiling fans of 25 W, TV of 50 W, and refrigerators of 100 W each. In this mini-grid model, daily operations of appliances have been set as follows during summer time: lights for 6 hours, fans for 24 hours, TV for 6 hours and refrigerators for 24 hours. Table 3.2 shows the seasonal load consumption of a regular house, for the categories of load appliances found in a house.

Table 3.2: Load consumption of a regular house in summer/winter.

Appliance type	**Capacity**	**No. of appliance**	Daily Consumption (kWh) (Summer)		Daily Consumption (kWh) (Winter)	
			Appliance wise	Consumer wise	Appliance wise	Consumer wise
LED light	7	4	0.07		0.07	
Ceiling Fan	25	2	0.44	0.72	0.11	0.4
TV	50	1	0.22		0.22	

To compute the overall load factor spanning over 24 hours of the day, we divide the day in three slots: 4am to 5pm, 5pm to 11 pm, 11pm to 4am. For each appliance, the overall load factor was computed by the weighted average from each time slot's value, based on the time span of each slot. Consequently, the overall load factors obtained by this process for a single household were as follows: 0.1 for LED lights, 0.4 for ceiling fans, 0.2 for TVs and 0.3 for refrigerators.

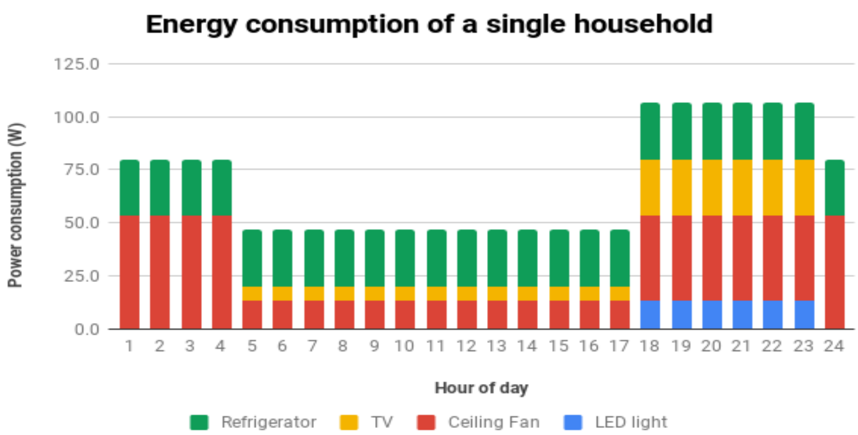


Fig. 3.22: Total energy consumption of a household within a period of 24 hours.

Similarly, the 41 shops as shown in Table 3.1 were also divided in three categories in terms of quantity of appliances in each category. Table 3.3 shows the three categories of shops, where the overall load factors were computed for each in order to calculate the total daily energy consumption in kWh.

For a total of 6 mosques, madrasas and schools, we considered LED lights and ceiling fans as appliances based on energy consumption statistics collected from rural areas.

The 2 offices in the model consists of LED lights, ceiling fans and computers as appliances. Each computer represents a load of 150W.

We have considered 3 rice husking mills, each of different capacity: 16 Horse Power (HP), 18HP and 20HP.

In addition, we have included irrigation pumps in our model design - where the usage of the pump varies, based on the cultivation of crops. For example, during the three major cultivations of wheat, Aman and jute during different times of the year all round, we consider 10 irrigation pumps during each cultivation period. Each pump is considered to represent 2000W, operating 8 hours a day during this period.

Table 3.3: Summary of mini-grid load data.

Service type	No. of consumers	Appliance			Running hours	Load factor	Daily consumption (kWh)		
		Type	Capacity	Quantity			Appliance	Consumer	Service
Household 1	140	LED light	7	3	6	0.1	0.05	0.48	67.2
		Ceiling Fan	25	1	24	0.4	0.22		
		TV	50	1	6	0.2	0.22		
Household 2	91	LED light	7	4	6	0.1	0.07	0.72	65.52
		Ceiling Fan	25	2	24	0.4	0.44		
		TV	50	1	6	0.2	0.22		
Household 3	85	LED light	7	6	6	0.1	0.1	0.97	82.45
		Ceiling fan	25	3	24	0.4	0.65		
		TV	50	1	6	0.2	0.22		
Household 4	15	LED light	7	5	6	0.1	0.08	1.67	25.05
		Ceiling Fan	25	3	24	0.4	0.65		
		TV	50	1	6	0.2	0.22		
		Refrigerator	100	1	24	0.3	0.72		
Shop 1	10	LED light	7	2	6	0.13	0.04	0.26	2.6
		Ceiling Fan	25	1	24	0.37	0.22		
Shop 2	24	LED light	7	4	6	0.13	0.08	1.1	26.4
		Ceiling Fan	25	3	24	0.37	0.67		
		TV	50	1	6	0.29	0.35		
Shop 3	7	LED light	7	3	6	0.1	0.06	1.57	10.99
		Ceiling Fan	25	2	24	0.4	0.45		
		TV	50	1	6	0.29	0.35		
		Refrigerator	100	1	24	0.3	0.72		

Continued on next page

Table 3.3 – *Continued from previous page*

Service type	No. of consumers	Appliance			Running hours	Load factor	Daily consumption (kWh)		
		Type	Capacity	Quantity			Appliance	Consumer	Service
Mosques, Madrasas & Schools	6	LED light	7	3	6	0.1	0.05	0.39	2.34
		Ceiling Fan	25	2	24	0.28	0.34		
Offices	2	LED light	7	4	6	0.1	0.07	1.12	2.24
		Ceiling Fan	25	3	24	0.25	0.46		
		Computer	150	1	6	0.17	0.6		
Rice mills	1	Machine (20 HP)	23872	1	6	0.25	143.23	143.23	143.23
	1	Machine (18 HP)	13428	1	6	0.25	80.57	80.57	80.57
	1	Machine (16 HP)	11936	1	6	0.25	71.62	71.62	71.62
Total load per day (kWh)									**580.21**

The designed mini-grid model consists of various forms of loads, whose hourly consumption over 24 hours of a certain day is delineated in Table A1 of the Appendix. From this data, the daily hourly total mini-grid load has been obtained. This data is plotted and illustrated in Figure 3.23. In this daily load consumption pattern, the peak daily load can be observed twice - from 9:00 hrs to 12:00 hrs, and from 15:00 hrs to 16:00 hrs - both to be 43kW. This peak arises due to the presence of small industrial loads, like rice mills. On the other hand, from 18:00 hrs to 23:00 hrs the mini-grid faces majority of the load from households and shops.

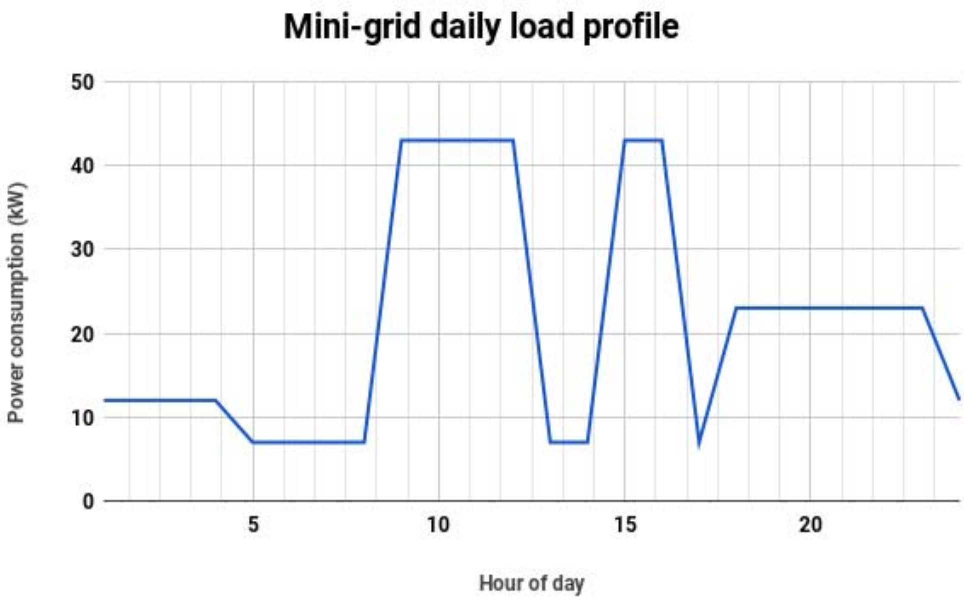


Fig. 3.23: Daily load profile of the mini-grid model.

Simulink Household Load Model

A typical household load model has been developed in Simulink illustrated in Figure 3.24. It shows an average household load model with five 7W LED bulbs, two 25W ceiling fans, two 5W mobile chargers and one 50W TV connected in a 230V AC line. No. of appliances are not same in all the households in a mini-grid. At the same time daily operation of this loads also are not similar for all houses. We have considered daily average running hours of this loads based on field data, LED light for 6 hours, ceiling fan for 24 hours, TV for 6 hours, mobile phone for 3 hours and refrigerator for 24 hours. To simulate the characteristics of this appliances, Simulink model of each appliance need to be developed.

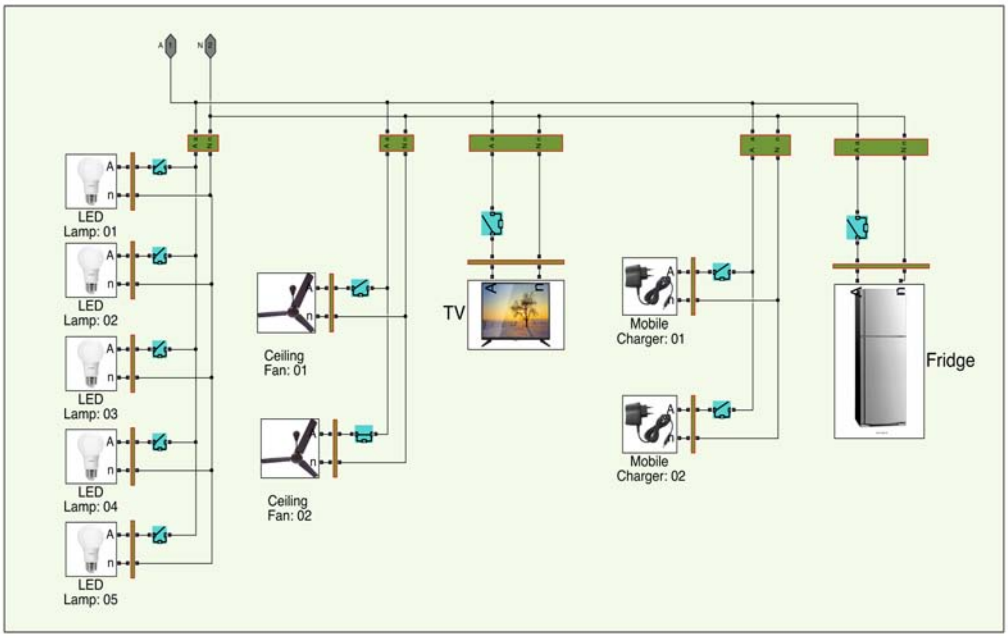
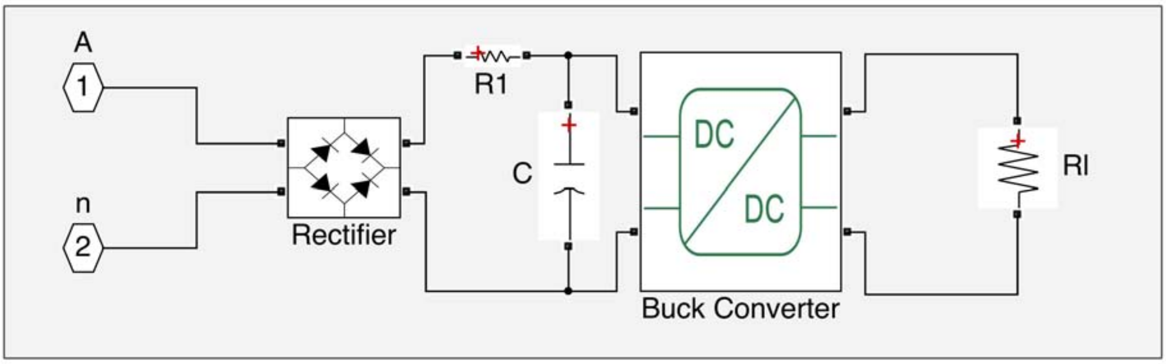
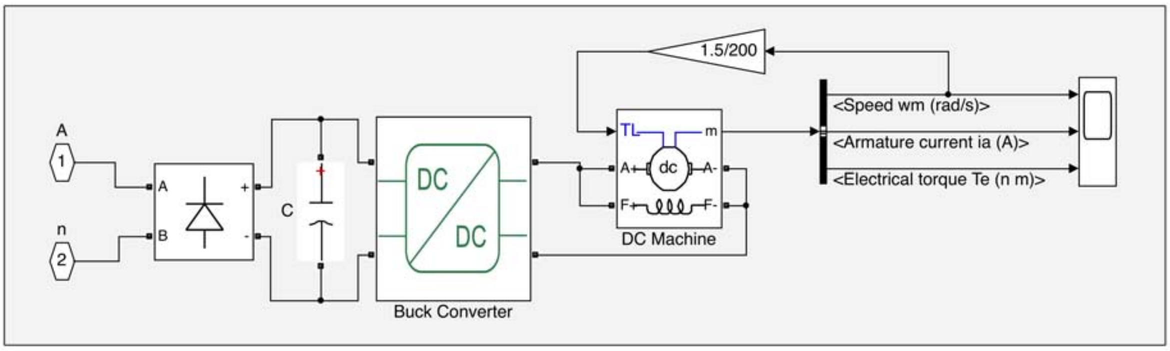


Fig. 3.24: Appliances connected in a single household.

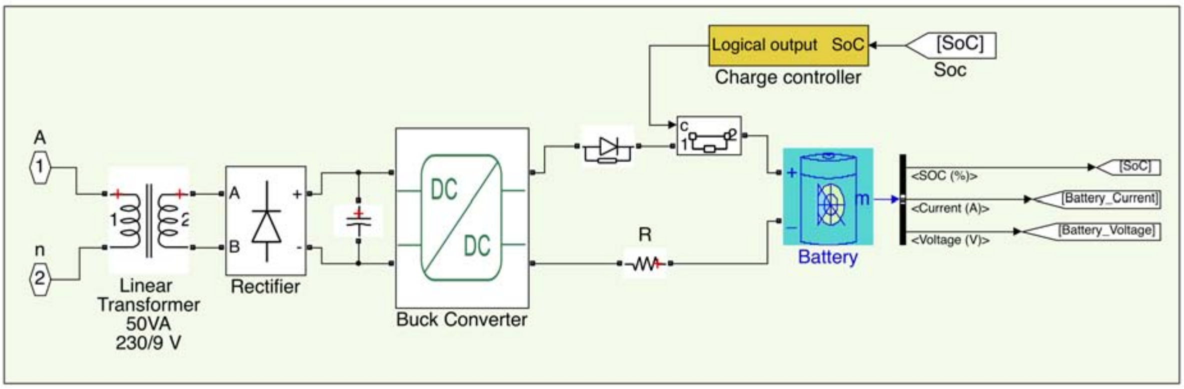
The three common appliances used in a regular household have been also designed in Simulink, as shown in Figure 3.25. Simple models were implemented for LED lights (Figure 3.25a) , ceiling fans (Figure 3.25b) and mobile chargers (Figure 3.25c). Rectifier and buck converter are common in all the models. Buck converters used in these models are designed with PI controller to keep the output DC voltage stable. In LED light model, output of buck converter is connected to a resistance which represent led array. In ceiling fan model, output of buck converter is connected to a DC motor to model a AC-DC fan. In mobile charger model, output of buck converter is connected to a 3000 mAh lithium ion battery similar to commonly used mobile.



(a) LED light



(b) Ceiling fan



(c) Mobile charger

Fig. 3.25: Illustration of Simulink models used to represent various load types in a household.

3.9 Mini-grid Components Sizing

Before we practically implement a mini-grid model, the rating and capacity of its components need to be calculated. It depends on the power handling, for which the daily energy consumption within the mini-grid needs to be analyzed. As the PV array will add to the generation for covering the daily consumption, its capacity also needs to be carefully calculated. The battery capacity calculation is done based on the night load consumption. In addition, the number of days the battery can supply power to the loads without recharge i.e. days of autonomy also needs to be considered to calculate the battery capacity.

3.9.1 Size of PV Array

Designing a solar PV system for mini-grid, it is important to find out the total energy consumption by all loads in mini-grid that need to be supplied by the solar PV system. The designed mini-grid model is elaborately illustrated in Figure 3.2 of Chapter 3. The designed min-grid model's load data is presented in Table 3.3. As shown in the table, the daily energy consumption is 580kWh, considering the peak sun hours as 5 hours with respect to Bangladesh. As PV system is not 100% efficient, we have considered derate factor for solar array which represents inefficiencies of solar system. According to the National Renewable Energy Laboratory's PV Watts calculator, a typical derate factor is 0.84. We have used Equation (3.2) to calculate the size of the solar array to be used in the mini-grid model.

$$\text{Size of PV Array} = \frac{\text{Daily Energy Consumption}}{\text{Peak Sun Hour} \times \text{Derate Factor}} \tag{3.2}$$

Here,

- Daily Energy Consumption = 580 kWh
- Peak Sun Hour = 5 h
- Derate Factor = 0.84

According to equation (3.2), size of the PV Array is as follows:

$$\begin{aligned} \text{Size of PV Array} &= \frac{580kWh}{5h \times 0.84} \\ &= 138\text{kW} \end{aligned}$$

In our mini-grid model, we have considered 2 days of autonomy for future emergency situations. Here 138kW PV array can only meet the daily load demand. Based on the consideration of future storage and cost of solar array, we have increased solar array capacity 20%. Solar acutal size of PV array is as follows:

$$\text{Size of PV Array considering days of autonomy} = 138kWh \times 1.20 = 165.6\text{kW}$$

In our mini-grid model, we have used Trina Solar TSM-250PA05 model from Simulink library whose power rating is 249.86W. Number of modules in PV Array can easily be calculated dividing size of PV array by module's power rating.

$$
\begin{aligned}
\text{Number of PV modules} &= \frac{165.6kW}{249.86W} \\
&= 662.7 \\
&\approx 666 \\
&= 37 \times 18
\end{aligned}
$$

Therefore, PV Array of mini-grid can be designed by arranging 37 no. of parallel strings of PV module with each string consisting 18 modules in series.

$$\text{Actual Size of PV Array} = 37 \times 18 \times 249.86 = 166.4\text{kW}$$

3.9.2 Size of Energy Storage System

The energy storage system should be large enough to store sufficient energy to operate the appliances at night and cloudy days. For energy storage system, we have used lead acid battery in the model. For the calculation of energy storage system's size it requires energy consumption at night, battery voltage, maximum depth of discharge (DoD) and days of autonomy. The designed model's detailed load profile is presented in Table A1 of the Appendix, where the daily night load is 220kWh and day load is 280kWh.

To find out the right size of battery storage system for mini-grid, calculation as follows:

$$\text{Battery capacity (Ah)} = \frac{\text{Daily Energy Consumption (Night)} \times \text{Days of Autonomy}}{\text{Battery Voltage} \times \text{Battery Losses} \times \text{Battery DoD}} \tag{3.3}$$

The following values have been considered for battery size calculation according to the mini-grid model:

- Daily Energy Consumption (at night) = 224 kWh
- Days of Autonomy = 02 days
- Battery Voltage = 160 V
- Battery Losses = 0.85
- Maximum Depth of Discharge(DoD) = 0.5 (50%)

According to equation 3.3, battery capacity for mini-grid:

$$
\begin{aligned}
\text{Battery Capacity (Ah)} &= \frac{224 \times 10^3}{160 \times 0.85 \times 0.5} \times 2 \text{ Ah} \\
&= 6.588 \times 10^3 \text{ Ah} \\
&= 6,588 \text{ Ah}
\end{aligned}
$$

3.10 Power Management

A power management algorithm has been designed to operate the implemented mini-grid model with reliable and stable performance to ensure power storage management and best utilization of solar power. The system maintains the battery's operating range in between 50% ≤ SoC ≤ 100% in order to preserve the battery's longevity.

To walk through the battery charging and discharging process, the line graph of battery SoC has been shown in Figure 3.26. In the case of low solar power availability e.g. at night, the battery will be used to supply power to the load until battery SoC drops to 50% - its lower limit of the operating range.

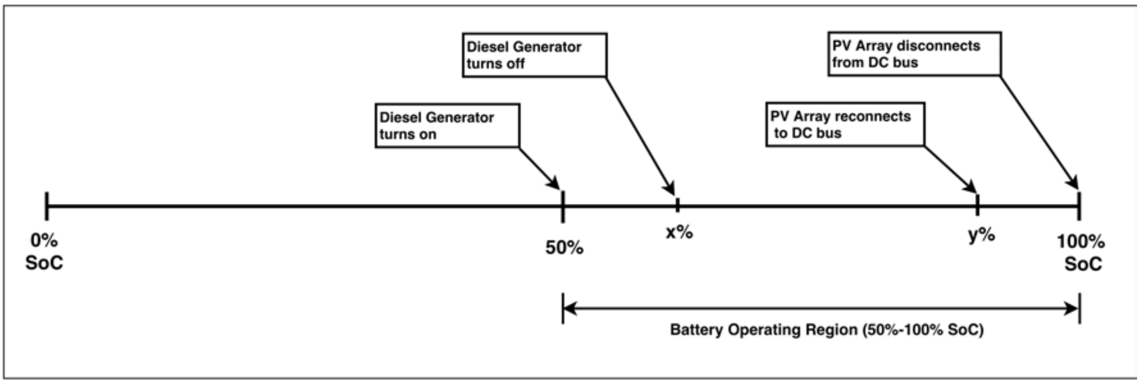


Fig. 3.26: Line graph of battery SoC.

As soon as battery SoC drops below 50%, the diesel generator begins to supply the load in addition to charge the battery till a user-defined SoC value of *x*%. When battery SoC hits *x*%, the diesel generator is turned off, with the battery taking over to supply the load until it discharges yet again to 50%. This control system is designed to minimize the use of diesel during low solar availability, along with switching between battery and diesel generator as discussed above.

On the other hand, during the day solar power is abundant in supply and can supply the load along with charging the battery. When the battery reaches 100% SoC, the system is designed to disconnect the PV array from DC bus and is connected to dump loads (e.g. water heater). The battery will supply to the load, till its SoC drops to another user-defined value of *y*%. When battery SoC hits *y*%, the PV array reconnects to the DC bus and it starts charging the battery along with supplying the load. This is also done to reduce switching between the battery and PV array, and minimize usage of battery in the mini-grid design.

There are two cases in the model implementation that this management system has to handle: 1) when the PV power, P_{pv} is greater or equal to load power, P_L and 2) P_{PV} is lesser than P_L. The control system designed for these two cases have been elaborated in Figure 3.27.

Case I: $P_{pv} \geq P_L$

This scenario arises when there is abundant PV power available to supply the load. In this situation, the diesel generator is kept turned off at all times. The state of the rest of the components will be determined by the battery SoC as follows. If SoC < 100%, the PV supply will charge the battery to increase the SoC level to 100%, as well as supplying power to the load through the inverter. When SoC=100% i.e. the battery is adequately charged, the PV will be disconnected from the DC bus as per design, allowing the battery to discharge and supply power to the load via the inverter. This is due to the model design, where the battery controls the DC bus voltage, and it is not possible to disconnect the battery from the system under any circumstances to keep this bus voltage stable. Therefore, the model is designed to disconnect the PV array from the DC bus under this condition. In this scenario, as PV power suffices to supply the load demand, it can charge the battery until its SoC reaches the upper operating range of 100%. When battery SoC = 100%, it will start discharging, by keeping the PV disconnected from the DC bus. But, it is also not feasible to drain the battery's SoC till 50% in the scenario where PV can easily supply power to the load. Therefore, the system is designed to drain the battery's SoC from 100% down to y%, and use the PV power to charge the battery again from y%. In this mini-grid model, $y = 90\%$ has been used.

Case II: $P_{pv} < P_L$

This scenario arises when the PV power is not enough to meet the load demand, e.g. during the absence of daylight. In this case, PV and battery are both used to supply the load.

When the battery SoC drops below 50%, the battery will not be discharged further, due to which the diesel generator needs to be turned on. The diesel generator's power will be used to charge the battery to restore its SoC, and fulfill the load demand.

As diesel generators contribute to brown energy generation and also incur high operating costs, the system requires optimizing its usage. This is done by using an intermediate SoC level of x%. After the battery charges to x% SoC, the diesel generator is turned off for battery discharging. To further reduce the switching between battery and diesel generator, the value of x is set as to maintain the optimum usages of both these energy sources. In the model, a value of x has been considered 60%.

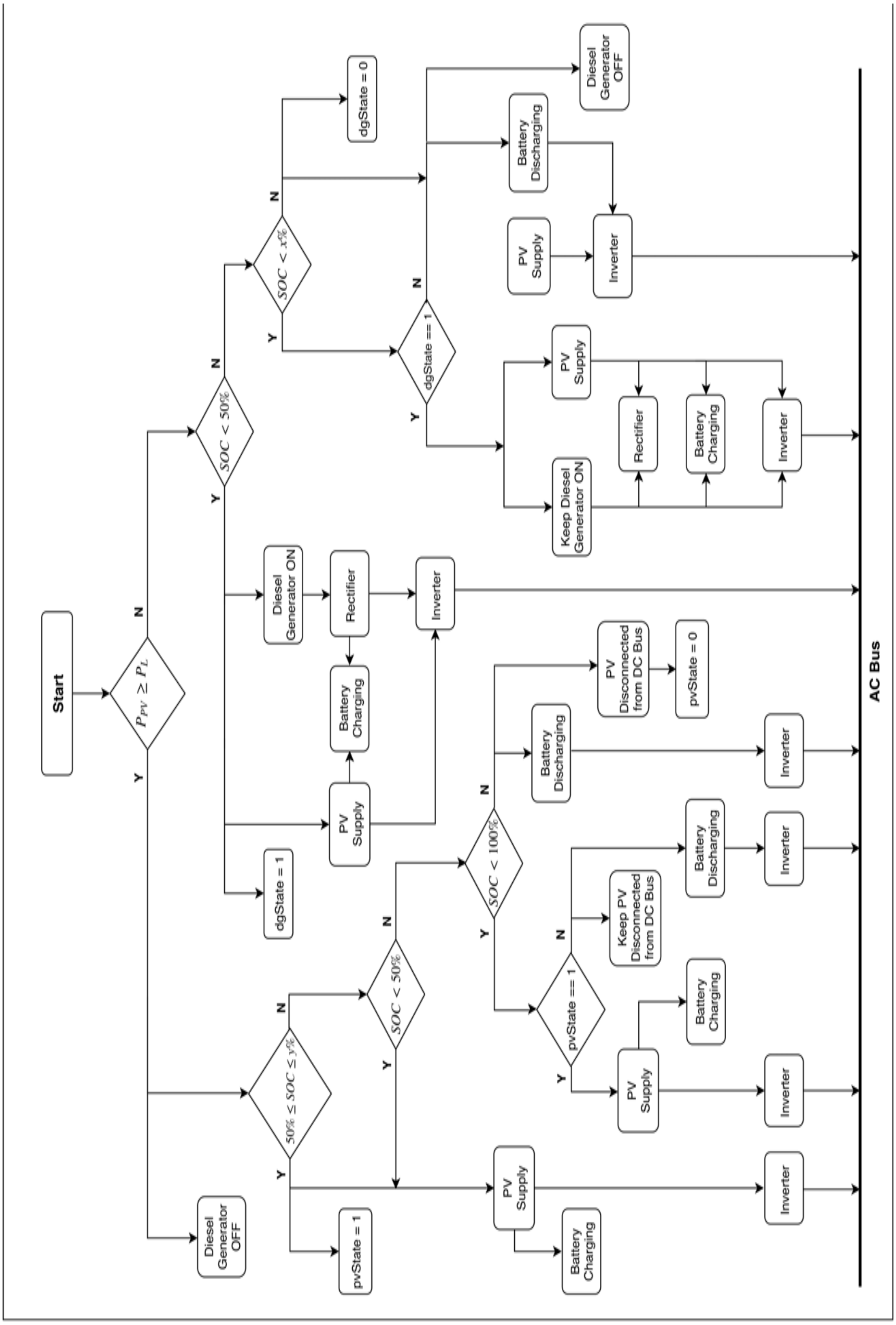


Fig. 3.27: Flow chart of power management algorithm for solar-diesel hybrid AC mini-grid.

3.10.1 Implementation of Power Management Algorithm

The system design discussed above has been implemented using Simulink function block as shown in Figure 3.28. The real and reactive powers, `Pload` and `Qload` respectively, have been extracted from the mini-grid sources. `power_pv` corresponds to the power generated from PV array, while `SOC` representing the battery's state of charge. User-defined inputs, `x` and `y` are handled such that diesel generator turns off at `x`% SOC after it turns on, and PV array reconnects at `y`% SoC after it got disconnected. Flags `dgStatus` and `pvStatus` are used in the function block to handle several scenarios. `dgStatus` = 1 when diesel generator is on, and 0 otherwise. Similarly, `pvStatus` = 1 when PV is connected to the DC bus and 0 otherwise.

The outputs of this function block represent the breaker control signals for the diesel generator, namely `gen` and PV array, denoted by `pv_ctrl`. A three-phase breaker is connected after the diesel generator. When `gen` = 1, the breaker gets logical signal to close the circuit, which will connect the diesel generator to the DC bus through rectifier. Similarly, the PV array is connected to DC bus through a breaker. When `pv_ctrl` = 1, the PV array will be connected to DC bus by closing the breaker and when equal to zero, otherwise.

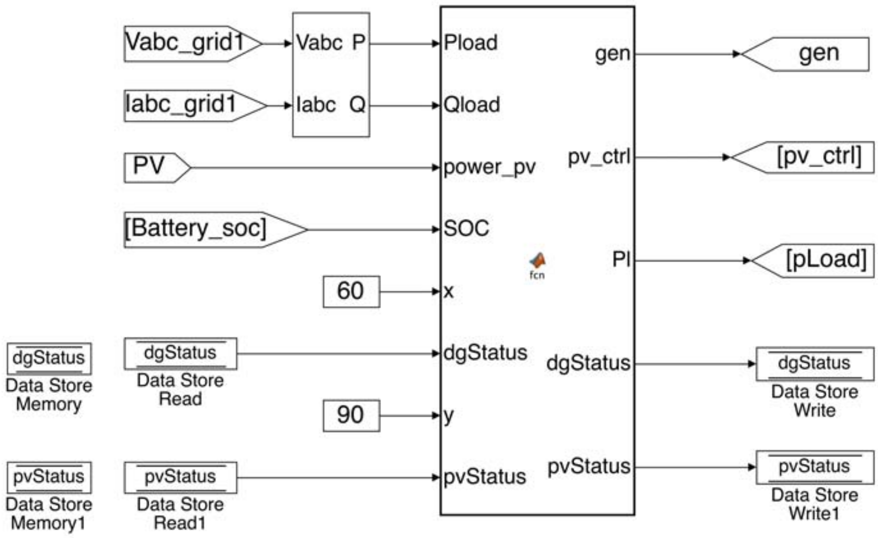


Fig. 3.28: Power management algorithm implementation in Simulink function block.

Chapter 4

Simulations, Results and Discussion

System design, modelling and simulations are essential to optimize, control and enhance system operations. This chapter presents the simulation, results and discussion for the photovoltaic-diesel hybrid mini-grid with energy storage applied for rural electrification. The results consist of the designed mini-grid model's grid voltage and current to compare them with the expected voltage and current levels. Simulations were also run with different types of loads to analyze static and dynamic characteristics of the loads. The model has been used to determine optimal position for PV array and diesel generator. Developed power management algorithm has been simulated to observe characteristics. Simulation results of the designed model's battery charging and discharging characteristics were obtained. The characteristics and impacts of faults in the mini-grid model were also studied and investigated.

4.1 Simulation Results of Grid Voltage and Current

The model includes a 3-phase 4-wire uni-grounded AC distribution network, where its system voltage and frequency is 400/230V and 50Hz. Simulations were run on the designed model by connecting static loads to measure the grid voltage, or the output voltage of the inverter. The results are shown in Figure 4.1, where the 3-phase rms voltage generated from inverter is demonstrated. Results have been shown upto the first 1.5 seconds of the simulation, where the first 0.7 seconds represent the transient period. The results show that the rms voltage across all phases reached a constant value of 400V.

Figure 4.2 shows the instantaneous 3-phase grid voltage and current characteristics of the mini-grid model obtained from the simulations. Both the voltage and current cycles repeat with a frequency of 50Hz. Figure 4.2a shows that the voltage amplitude of each phase is 565V as expected, i.e $400\sqrt{2}$V. Based on the connected loads in the model, the current rating obtained is 120A.

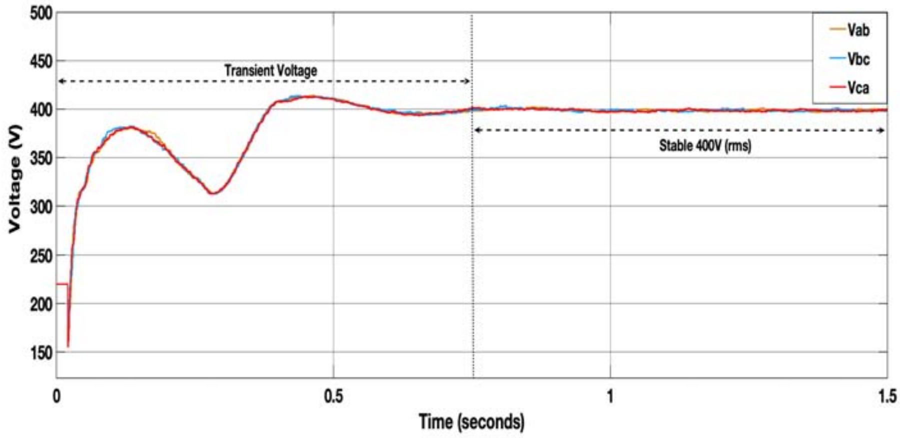
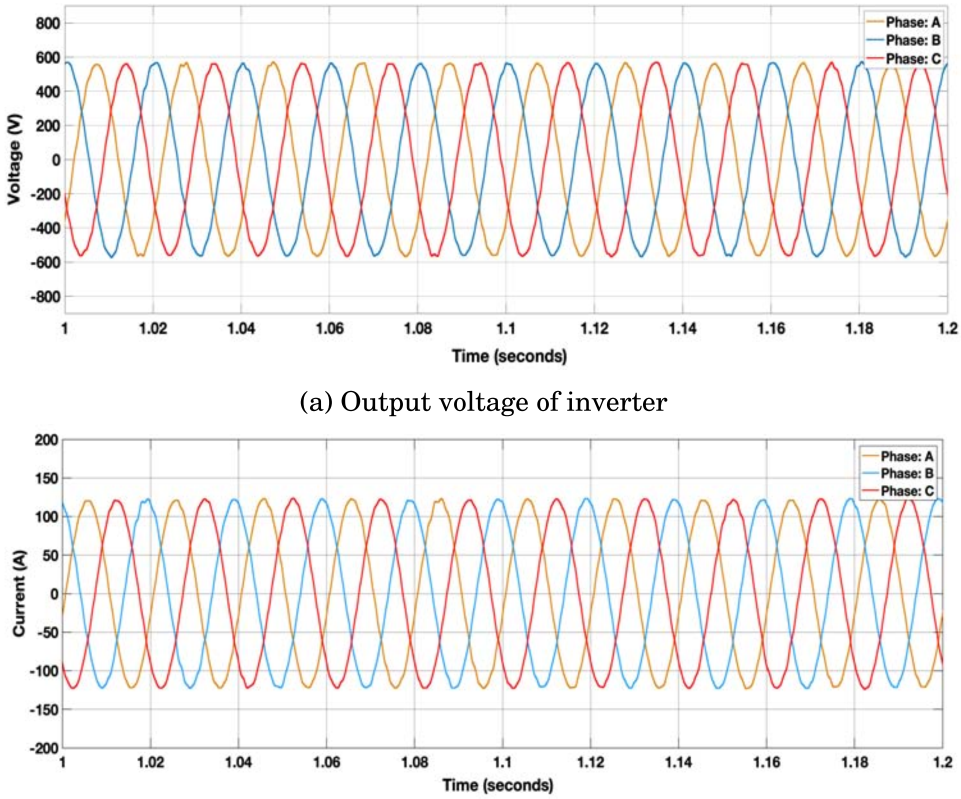


Fig. 4.1: Grid Voltage (rms).



(a) Output voltage of inverter

(b) Output current of inverter

Fig. 4.2: Simulation result of output voltage and current of inverter.

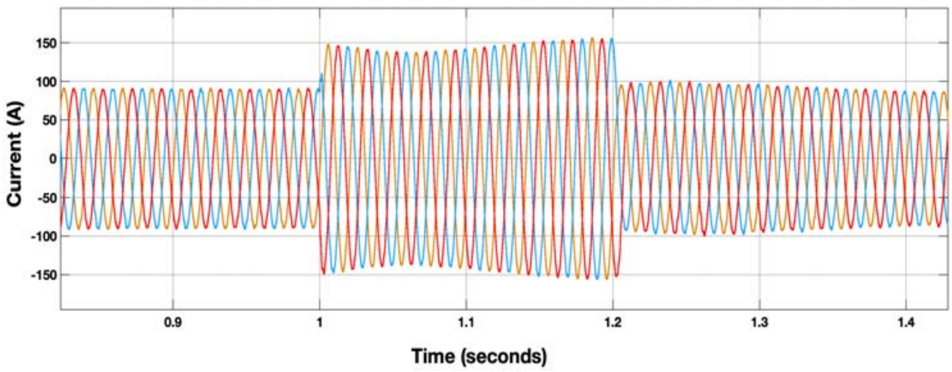
4.2 Simulation with Different Types of Loads

A mini-grid has to handle various forms of loads - fixed or variable, balanced or unbalanced. Moreover, the system is probable to be faced with a varying nature of load over a timespan of 24 hours, coming across households, industrial entities, agricultural institutions etc. Simulink model has been designed to visualize and simulate the response of the mini-grid with different forms of load.

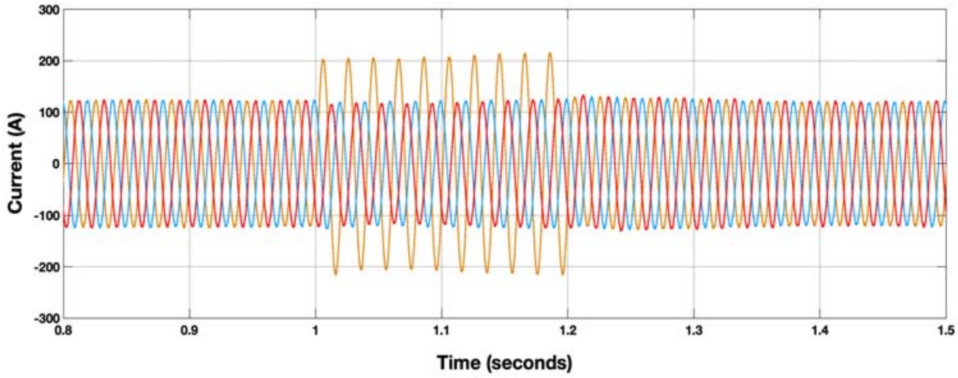
4.2.1 Balanced and Unbalanced Load

For a balanced load condition, load in a 3-phase system makes the lines / phases carry the same magnitude of current with an equal phase difference. For a star-connected balanced load with neutral as return path, no current will follow through neutral. In this case, the vector sum of all three phase currents meeting at common neutral point is zero.

For an unbalanced load condition, load makes the lines / phases carry different current magnitudes, and sum total of these at neutral point is not zero. The load in each phase is different, carrying different amounts of current. In this case, neutral carries the net unbalanced current. In addition, the reactive impedance components in the load creates a phase difference in line currents from respective voltages. Even if the magnitudes of current are equal, this will create an unbalanced current in neutral. In mini-grids, with so many single phase loads, or some two phase equipment in operation, currents in 3 phase system are never fully balanced, despite best efforts to achieve load balancing.



(a) Three-phase balanced load



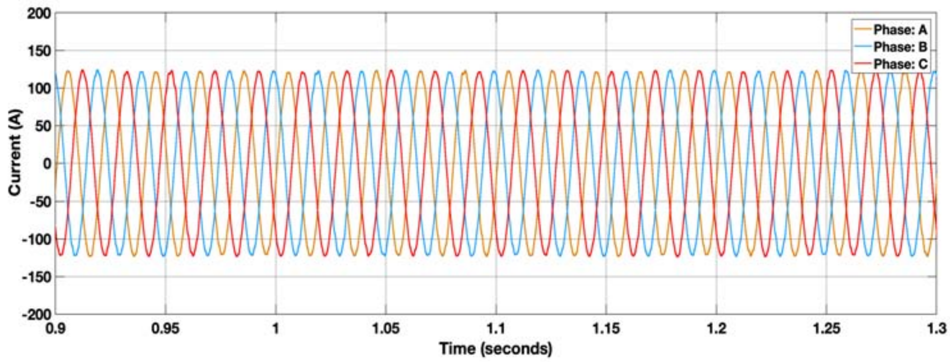
(b) Three-phase unbalanced load

Fig. 4.3: Illustration of balanced and unbalanced load.

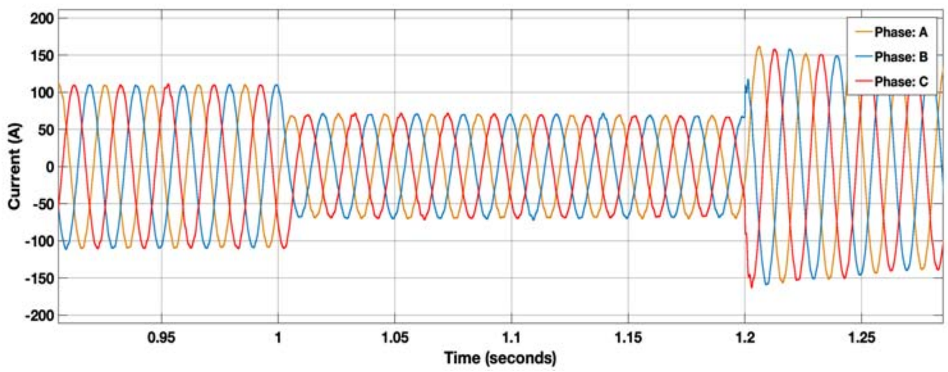
We illustrate these two forms of loads in Figure 4.3. In Figure 4.3a, three-phase balanced load is connected which changes over time. The system responds with all the three phases carrying the same current. In addition, the neutral current becomes zero in this condition. In contrast, Figure 4.3b portrays a scenario where from $t = 1$ to $t = 1.2$ an extra load is connected to Phase A of the system, to which the system reciprocates with an increased current flow in one phase compared to the other phases. Hence, the system results in being unbalanced within the specified time-frame.

4.2.2 Fixed and Variable Load

In a power system, fixed or static loads do not alter significantly over short time-intervals. Street lights, for instance, are on for hours every night which draw the same continuous current; office buildings draw more or less continuous, steady amounts of power over long periods of time. This has been shown in Figure 4.4a. This is opposed to dynamic/variable loads which change over time, e.g. large electric induction motors at industrial draw very large amounts of power to start. Variable loads simulated in the model have been shown in Figure 4.4b. As we can see, the load current remains at more than 100A till 1 second of the simulation, after which it plummets down to around 70A till 1.2s. In addition, the load current increases to around 150A after 1.2s. In general, all the loads are not simultaneously connected and disconnected to mini-grids. The demand changes each and every minute in a mini-grid, whose variation can be illustrated by a load curve or load profile.



(a) Fixed load



(b) Variable load

Fig. 4.4: Simulation of fixed and variable load.

4.2.3 Residential Load

The common appliances used in a regular household are LED light, ceiling fan, mobile charger etc. Simple models for these appliances were implemented in Simulink which have been discussed in chapter 3. Characteristic of these appliances have been studied here using simulation results.

LED Light

Figure 4.5 shows input voltage, input current and input power of LED light circuit model designed in Simulink which has been illustrated in Chapter 3. Inside the LED light model, there is a rectifier and buck converter, both of which have been used to generate 40V DC across LED light array inside the light bulb. Output voltage of the buck converter is kept constant 40V to maintain constant light output. The designed LED light model with a power rating of 20W has been fed 230V AC. The characteristics of input current shows the presence of switching elements inside light bulb.

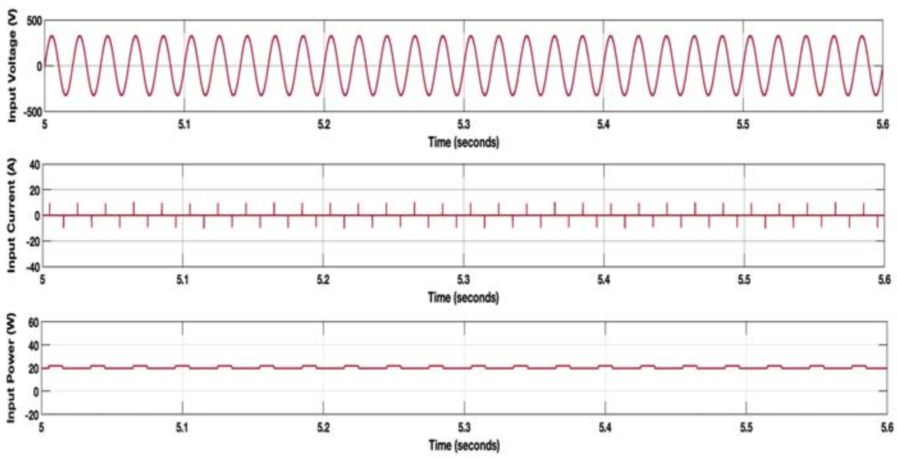


Fig. 4.5: Input voltage, input current and input power of LED light model.

Ceiling Fan

Figure 4.6 shows the input voltage, current and rotational speed of the ceiling fan model designed in Simulink, which is a simple model of an AC-DC ceiling fan. To investigate the characteristics of the model, it is fed 230V AC power. Similar to the LED light model, this ceiling fan model is designed with rectifier, buck converter etc and an additional DC motor. Speed of the ceiling fan is proportional to output voltage of buck converter. To observe its characteristics, the output voltage was kept constant. Rotational speed of the ceiling fan model was found to be 250rad/s with a constant input voltage of the DC motor.

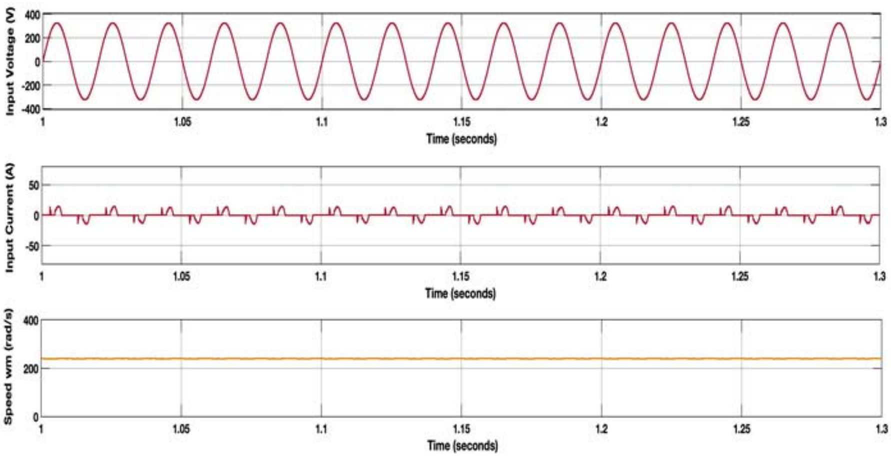


Fig. 4.6: Input voltage, input current and speed of ceiling fan model.

Mobile Charger

Figure 4.7 shows the input voltage, current, power and battery SoC of a simple battery charger model. To observe the charging characteristics of a mobile, a battery is connected with capacity of 3000 mAh and the charger has been fed 230V AC. Similar to the LED light and ceiling fan model, the charger has been designed using rectifier and buck converter to provide fixed DC voltage across a lithium ion battery. The charging current of the battery increases its SoC over time, as shown in Figure 4.7.

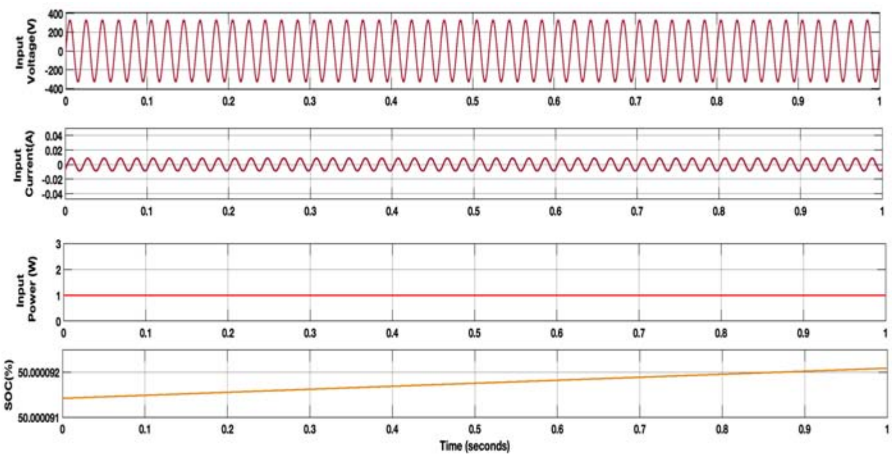
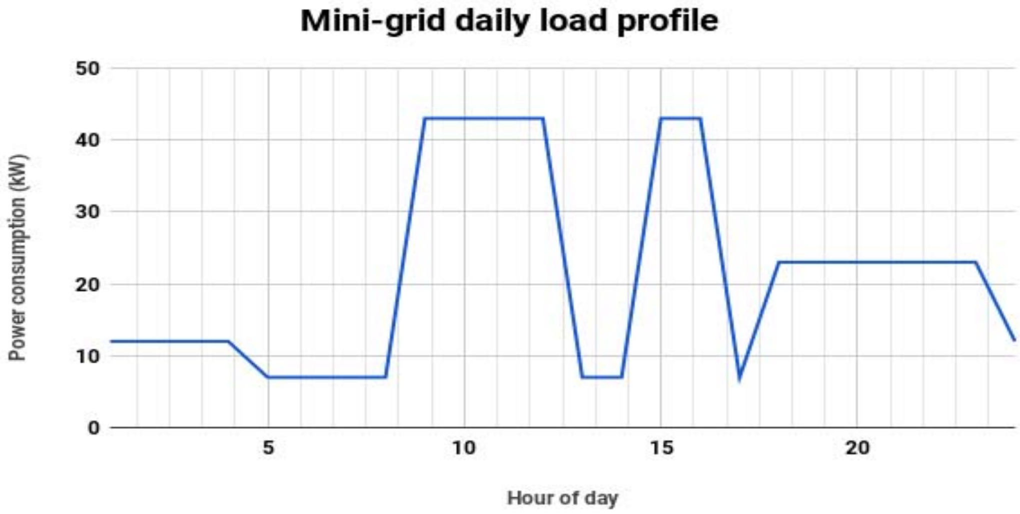


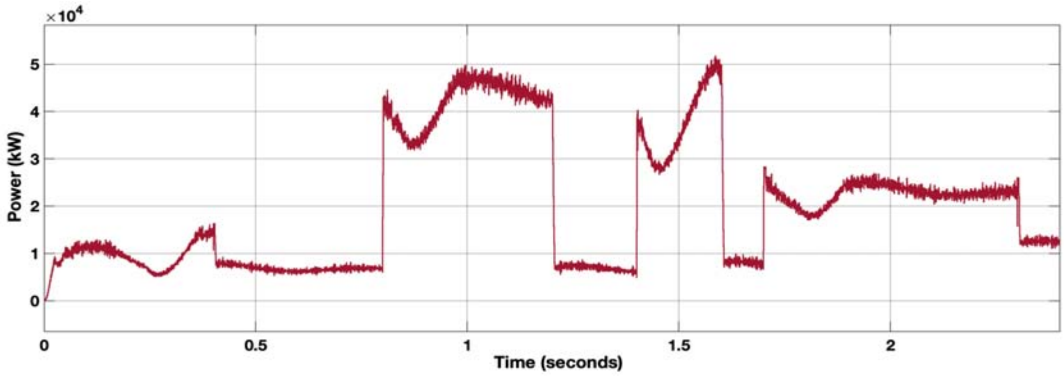
Fig. 4.7: Input voltage, input current, power and SoC of mobile charger model.

4.3 Simulation Result of Mini-grid Load Profile

In the designed mini-grid model, there are different types of loads connected in the distribution network whose daily hourly consumption is mentioned in Table A1 from Appendix. From this data, the hourly total load has been calculated which represents the daily consumption pattern or load profile of mini-grid which has been illustrated in Figure 4.8a. To simulate the mini-grid model with the hourly load consumption data, all the load models need to be configured individually.



(a) Daily load profile of mini-grid from field data



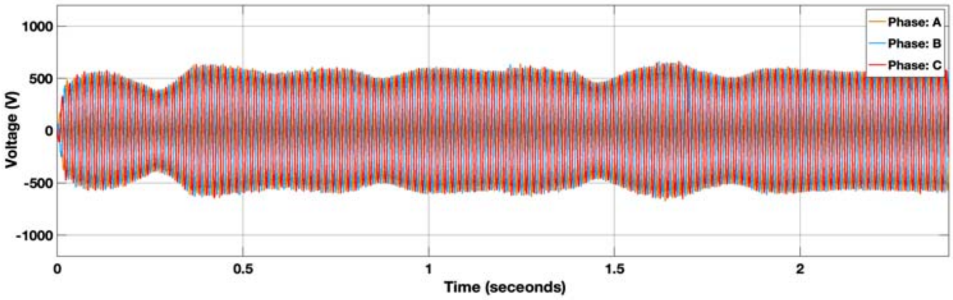
(b) Simulation result of load profile data of mini-grid

Fig. 4.8: Comparison between simulation result and load profile based on field data.

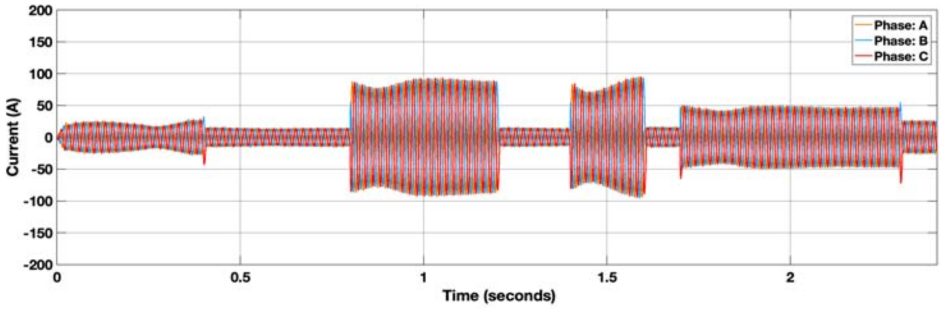
The simulated result portraying the load characteristics of power obtained is shown in Figure 4.8b. As this work proposes to perform a power quality analysis, the model has been simulated in discrete mode which is not suitable for long-duration data. Hence, the 24 hours of the day of simulation has been mapped to 2.4 seconds i.e. 0.1 seconds of the simulation corresponds to 1 hour in real-time.

As shown in the load curve of the simulation in Figure 4.8b, there is a noticeable distortion with power spikes. There are several reasons that can be held for this observation. Firstly, as the distribution line impedance has been considered in the simulation to keep the model realistic, it had an effect on the grid power. Secondly, sudden changes in load variation and switching of load have led to voltage and current fluctuations. Consequently this led to the generation of noise and spike in grid power.

Figure 4.9 shows the output voltage and current of the inverter during the simulation. As shown in Figure 4.9a, the output voltage is not constant - it changes according to the connected loads as in Figure 4.9b.



(a) Load side voltage of Inverter



(b) Load side current of Inverter

Fig. 4.9: Voltage and Current characteristics of load profile simulation in mini-grid model.

4.4 Simulation to Determine Optimal Source Location

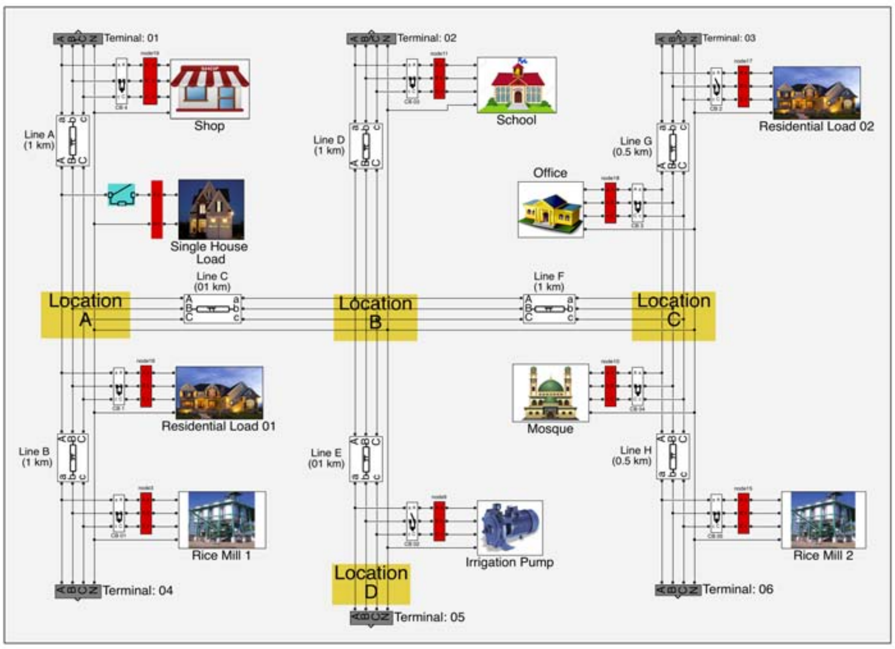


Fig. 4.10: Illustration of source placement in different locations of mini-grid.

When distributed generation systems are far from the load center - the areas more densely populated or with high volume consumers or industrial loads - there will be more transmission loss and consumers will get low voltage which can damage home appliances and other connected loads. To find the optimal placement for the PV array and diesel generator in mini-grid, four different locations A, B, C and D have been selected for source location as shown in Figure 4.10. The simulation summary results for different source locations are shown below.

Case I : ***PV array and diesel generator connected in location A of mini-grid***

Location A represents the extreme left end of the mini-grid where PV array and diesel generator have been connected. As sources are connected in one side of network, the expected behaviour is that the farthest terminals will face the greatest voltage drop. This is due to the increase in line impedance with increase in distance from the source. When the power sources are connected in this point, we observe the farthest points in this case to be Terminals 3 and 6. As shown in Figure 4.11, if we notice the voltage values at points A, B and C respectively - the values depict a decreasing pattern. In this case, the minimum voltage was recorded as 393.6V at Terminal 06, indicating that the greatest voltage drop incurred was 6.4V.

Similarly, if the line losses are observed in the figure, the line segments carrying greater current will incur a greater line loss. The line loss is greatest at line segment AB, because the greatest current flows in this segment. In this combination, the total line loss recorded was 0.352%.

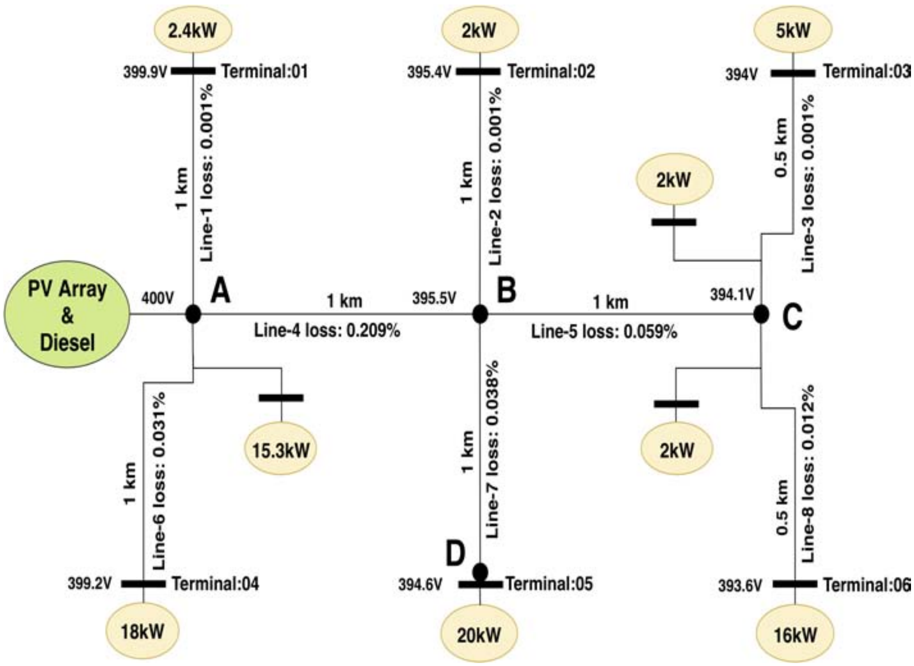


Fig. 4.11: PV array and diesel generator in location A.

Case II : ***PV array and diesel generator connected in location B of mini-grid***

The PV array and diesel generator have been connected in Location B, which represents the mid-point of the mini-grid network. Due to this, the source-to-load distances would be comparatively lesser than Case I. As Figure 4.12 shows the simulation results, the minimum voltage has been recorded at Terminal 04 with 396.8V, indicating a 3.2V drop. In this combination, as the loads are equidistant from the source, the current flow through each line is not significantly high. As a result, the line loss is lesser than that in Case I. The total line loss recorded for this scenario was 0.267%.

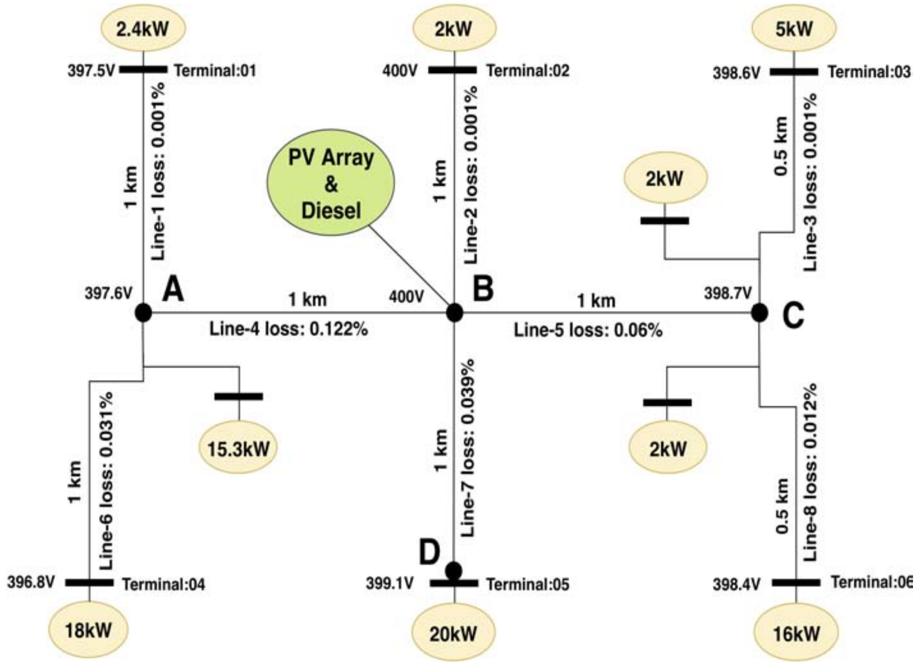


Fig. 4.12: PV array and diesel generator in location B.

Case III : ***PV array and diesel generator connected in location C of mini-grid***

Location C represents the extreme right end of the mini-grid. As a result, the expected behaviour is similar to Case I —the farthest terminals experience the greatest voltage drop. When the power sources are connected in location C, the farthest points in terms of distance are Terminals 01 and 04. As shown in Figure 4.13, the voltage drop increases from right to left from C towards A. In this case, the minimum voltage recorded was 390.3V at Terminal 04, incurring a voltage drop of 9.7V.

In terms of the system losses in this case, the line loss is greatest at line segment CB because of more current flow than other segment. Figure 4.13 shows line loss of different segments. The total line loss recorded for this scenario was 0.313%.

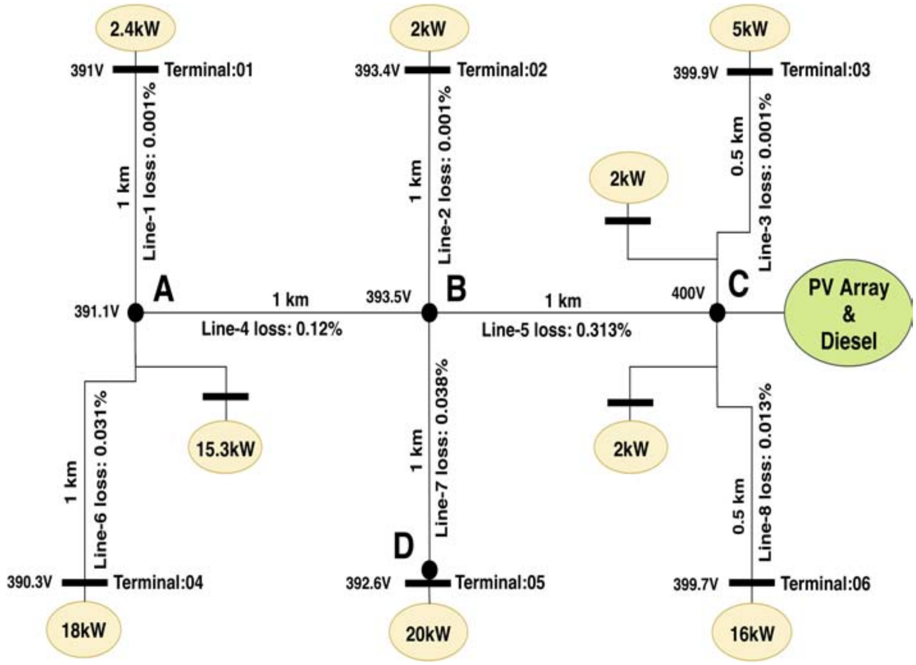


Fig. 4.13: PV array and diesel generator in location C.

Case IV : ***PV array and diesel generator connected in location D of mini-grid***

In this case, the mini-grid network was designed with some modifications after which the sources were connected in location D. In contrast to the previous three cases, the connections between the points A and B were removed, along with the connection between B and C. New connections were added from Terminal 4 to 5, and 5 to 6. Figure 4.14 shows the voltage at different points and line loss of different segments. In this case the minimum voltage recorded as 396.8V at Terminal 01, incurring a voltage drop of 3.2V and a total line loss of 0.219%.

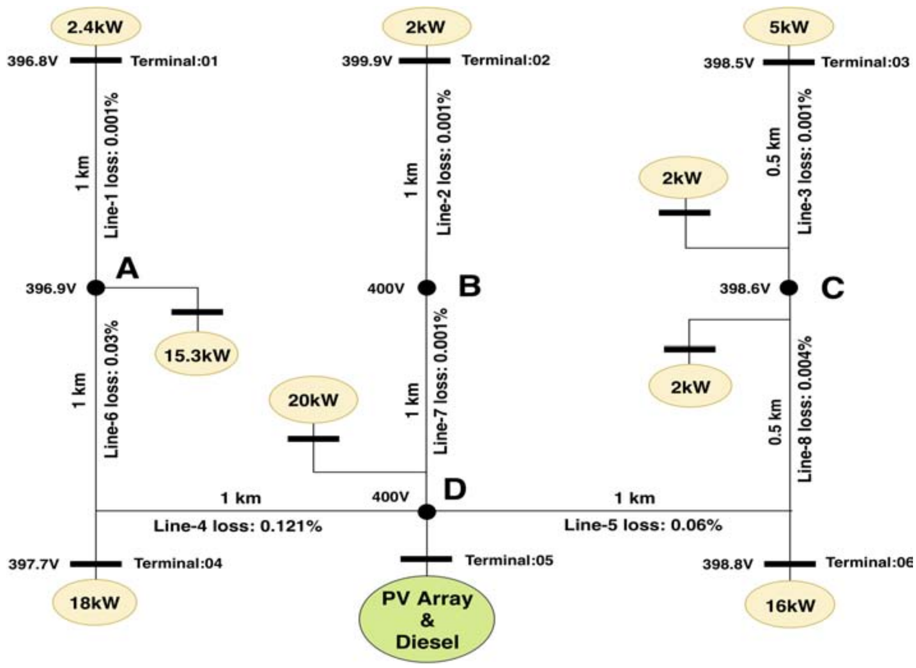


Fig. 4.14: PV array and diesel generator in location D.

Analysis of Source Location

From the results, it can be inferred that as far we go from the sources, the voltage drop increases because of line impedance and line loss increases with the flow of current. The PV array and diesel were connected in different locations and for each location, voltage and line loss have been calculated individually. The summary of voltage drop results are as shown in Table 4.1 and line loss results are shown in Table 4.2. From this summary table, it can be concluded that point D is the optimal position for source placement in the mini-grid because both the voltage drop and total line loss are minimum in this case. The maximum voltage drop recorded is 3.2V at Terminal 01 and the total line loss is 0.219% which is the minimum compared to the others. In general, the mid point of the network is thought to be the best location for sources to minimize line losses and voltage drop, but this is not true for all cases. It also depends on location with load density. This is because position D shows good results comparing other 3 locations because location D is closer to large loads than others. Location C is far from most of large loads, which is why this location shows the maximum voltage drop and line loss results.

Table 4.1: Voltage drop for different source positions.

Source location	Voltage at different locations of mini-grid								
	A	B	C	Terminal					
				01	02	03	04	05	06
A	400	395.5	394.1	399.9	395.4	394	399.2	394.6	393.6
B	397.6	400	398.7	397.5	400	398.6	396.8	399.1	398.4
C	391.1	393.5	400	391	393.4	399.9	390.3	390.6	399.7
D	396.9	400	398.6	396.8	399.9	398.5	397.7	400	398.8

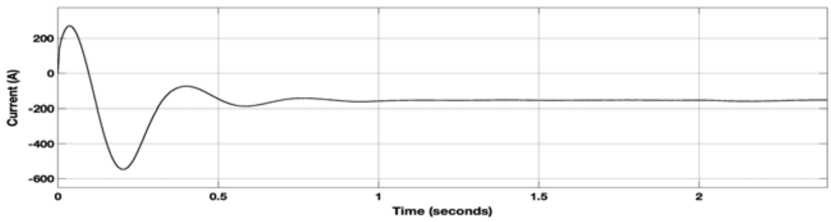
Table 4.2: Line loss for different source positions.

Source location	Line loss (%)								Total line loss(%)
	Line-1 (1km)	Line-2 (1km)	Line-3 (0.5km)	Line-4 (1km)	Line-5 (1km)	Line-6 (1km)	Line-7 (1km)	Line-8 (0.5km)	
A	0.001	0.001	0.001	0.209	0.059	0.031	0.038	0.012	0.352
B	0.001	0.001	0.001	0.122	0.060	0.031	0.039	0.012	0.267
C	0.001	0.001	0.001	0.120	0.313	0.031	0.038	0.013	0.518
D	0.001	0.001	0.001	0.121	0.06	0.03	0.001	0.004	0.219

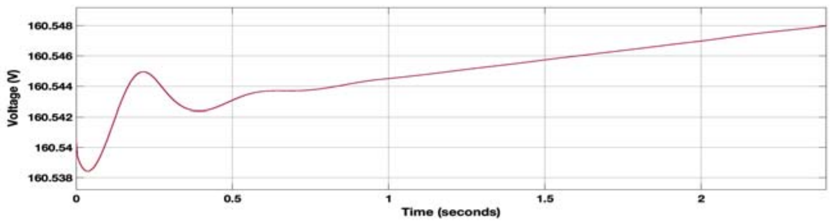
4.5 Battery Charging/Discharging

A lead acid battery bank has been used as the energy storage system, where the nominal voltage level is 160V and rated capacity is 6588Ah. When solar power is enough to supply load demand, a part of the solar power is used to charge the battery. According to design, the battery's operating region is 50% ≤ SoC ≤ 100%.

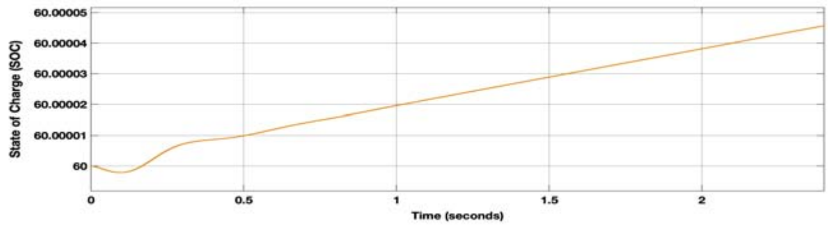
When the battery charges, its terminal voltage increases along with its SoC. Figure 4.15a shows the charging current of the battery, and Figure 4.15b shows its terminal voltage.



(a) Battery charging current

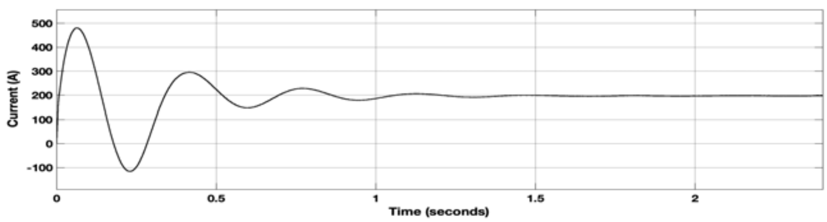


(b) Battery terminal voltage during charging

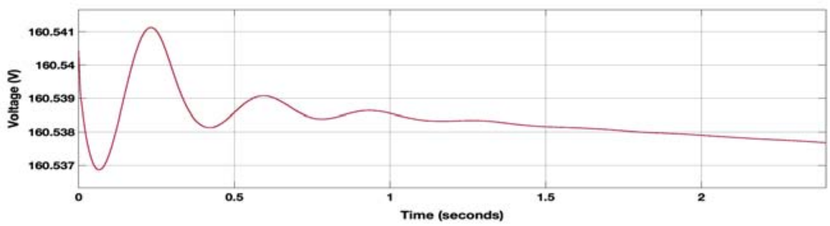


(c) Battery SoC during charging

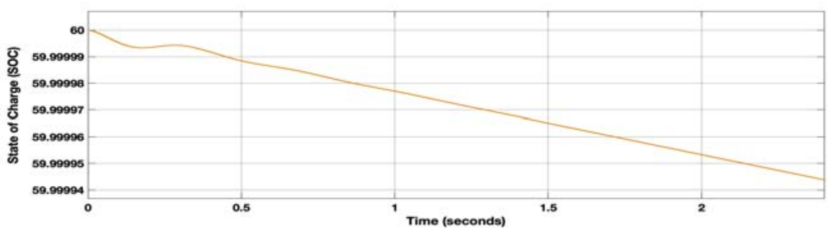
Fig. 4.15: Simulation results of battery characteristics- charging.



(a) Battery discharging current through resistive load



(b) Battery terminal voltage during discharging



(c) Battery SoC during discharging

Fig. 4.16: Simulation results of battery characteristics- discharging.

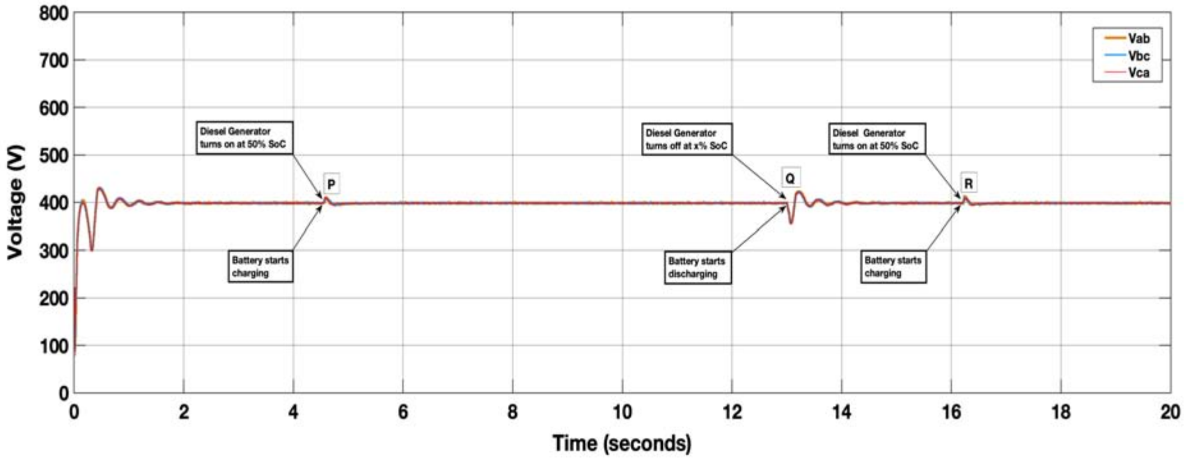
The terminal voltage rises with respect to time. In the the first 0.3 seconds represents the transient period. Figure 4.15c shows an increase in SoC from 60% to above. When load demand is above the generation from PV, the rest of the load demand is satisfied from battery power. During discharging of the battery, both the terminal voltage of the battery and its SoC decrease. Figure 4.16a shows the discharging current from the battery, where it remains to be a positive DC current of 200A to supply the loads. Figures 4.16b and 4.16c show the battery terminal voltage and SoC respectively, both with respect to time during discharging.

4.6 Simulation Results of Power Management

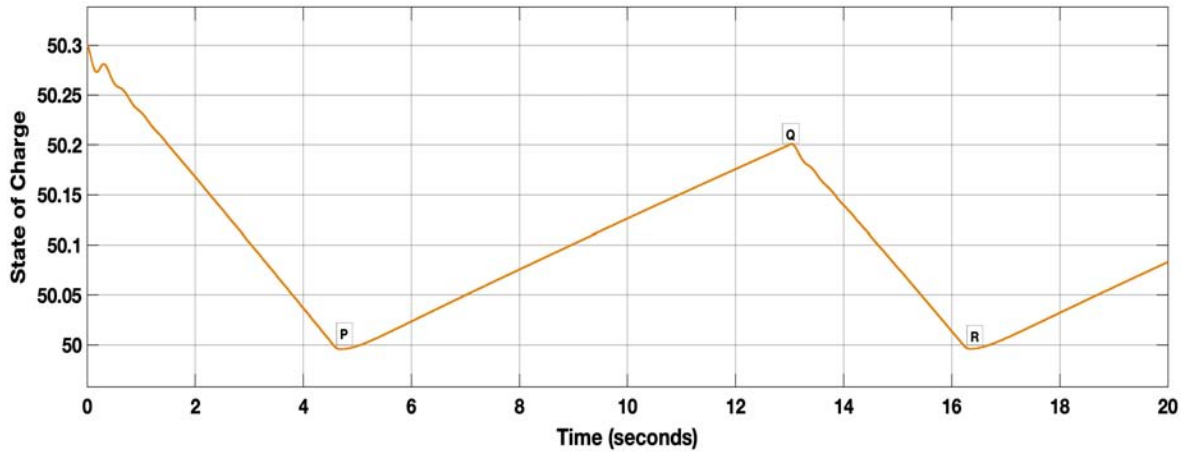
A power management algorithm is very important for operation and management of resources in a power system. For proper operation of the mini-grid model, a control system has been developed for power management based on battery SoC, solar power generation and connected loads which has been discussed in Chapter 3. The battery's operating range has been considered $50\% \leq SoC \leq 100\%$ which is carefully maintained to extend the lifespan of lead acid battery. To illustrate power management algorithm properly, simulation results are briefly discussed here case by case.

Case I: ***Battery SoC drops below 50%***

This scenario arises when solar power is not abundant to supply loads and battery SoC decreases below 50%. At night or low light condition, the battery starts supplying power to loads which decreases battery SoC. As soon as battery SoC drops below 50%, diesel generator starts to supply loads and charge the battery. Charging the battery by diesel is not economic, which is why diesel is operated to charge the battery to a certain battery SoC level which is defined as x in this thesis. In this mini-grid model, the value of x is set to 60%, which indicates that the diesel will operate until battery SoC reaches 60%. When battery SoC = 60% diesel generator turns off until battery SoC again drops below 50%. For the purpose of simulation, a low value of x (50.2) is selected because a high value of x will take long time to simulate. Figure 4.17 shows simulation results of switching between battery and diesel generator based on battery SoC. During simulation, solar radiation was kept $200W/m^2$ and battery's initial SoC was kept 50.3%. Initially, the battery starts discharging from 50.3% SoC which is shown in Figure 4.17b. Battery SoC drops below 50% at point P when diesel generator turns on which creates a small voltage fluctuation in grid voltage as shown in Figure 4.17a. Diesel generator charges battery and supplies power to loads, which results in increasing battery SoC from point P to Q. After battery SoC charges to 50.2% at point Q, diesel generator turns off and the battery starts to discharge towards 50% again, which creates another fluctuation in grid voltage. In general, the diesel generator's ON state indicates the battery will be in charging state. Whereas, the diesel generator's OFF state indicates that the battery will be in discharging state. This cycle will repeat until solar power is abundant to supply loads and charge battery.



(a) Grid voltage

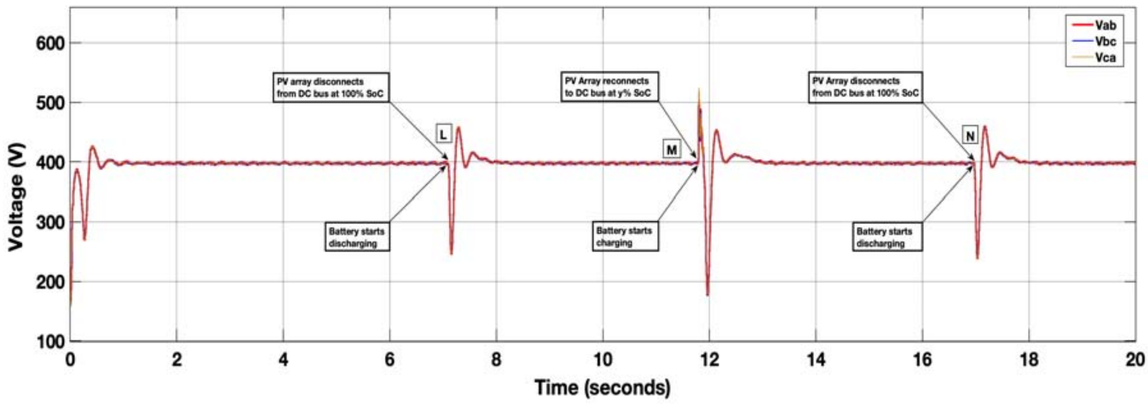


(b) Battery SoC

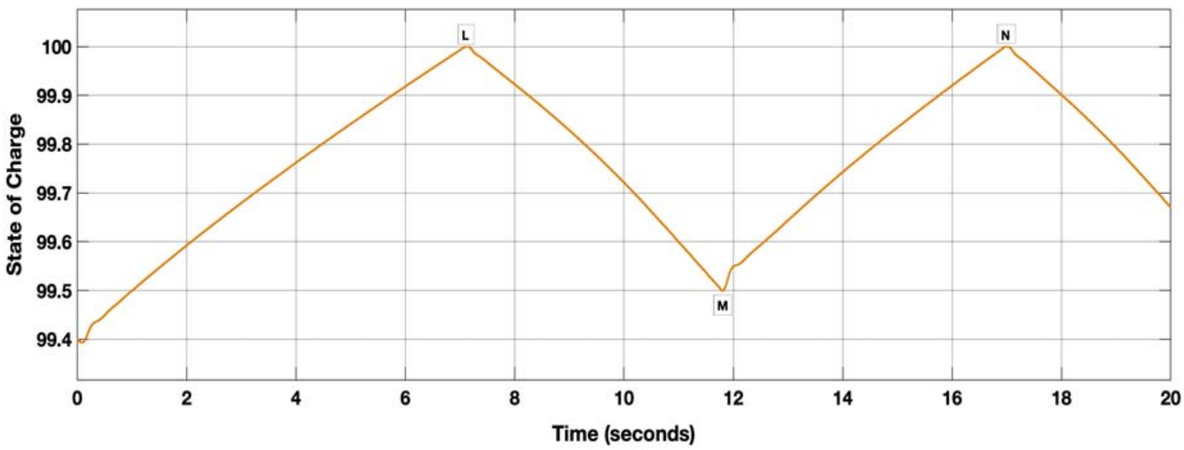
Fig. 4.17: Simulation results of switching between battery and diesel generator.

Case II: *Battery SoC reaches 100%*

This scenario arises when solar power is abundant to supply loads and battery SoC reaches 100%. During day time, PV array produces maximum power which is used to charge battery and supply to connected loads. In the designed model, the battery can not be disconnected from DC bus as it maintains a constant DC bus voltage and stabilization. In order to avoid overcharging, PV array is disconnected from DC bus when battery SoC reaches 100% and PV generation is more than load demand. At 100% SoC, battery starts discharging and PV array stops supplying power to DC bus and is connected to dump loads (e.g. water heater). Battery is not allowed to discharge to 50% when solar power is abundant. In this case, the battery SoC is allowed to drop to certain value of $y\%$ which is user-defined. When battery SoC hits $y\%$, the PV array will reconnect to DC bus and start charging the battery along with supplying loads. In the mini-grid model, value of y has been considered 90% which means PV array will be reconnected to DC bus at 90% SoC after disconnection. Case II has been illustrated in Figure 4.18. For simulation purpose like case I, we have chosen value of y, 99.5 which is close to 100%. Initial value of battery SoC has been set to 99.4% and solar radiation $1000W/m^2$. Simulation starts with battery charging from 99.4% SoC shown in Figure 4.18b. When battery SoC reaches 100% at point L, PV array disconnected from DC bus which create a voltage fluctuation shown in Figure 4.18a. From point L, battery SoC decreases because battery start to supply power to loads. When battery SoC hits 99.5% at point M, PV array reconnects to DC bus and starts supplying power to loads and charging battery which creates fluctuation in grid voltage. PV array's disconnection with battery's discharging and PV array's re-connection with battery charging cycle continue until low light condition occurs, e.g. night-time.



(a) Grid voltage

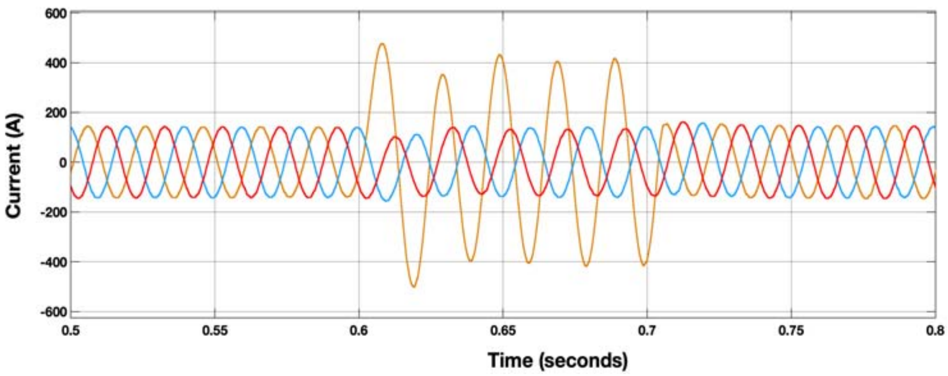


(b) Battery SoC

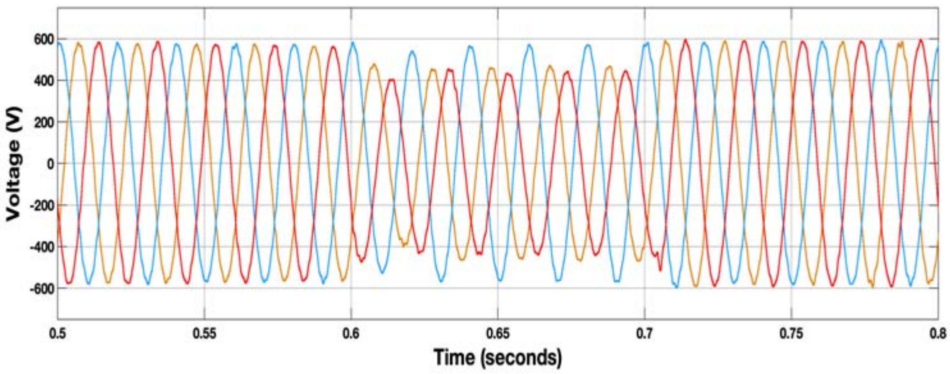
Fig. 4.18: Simulation results of switching between PV array and battery.

4.7 Fault Analysis

Fault analysis of a mini-grid is an important consideration for design and operation of mini-grid. Overcurrent, overvoltage and other impacts that arises from faults are needed to be studied to choose proper size of conductors, protection equipments such as switch gears, relays and analyze characteristics of faults with it's effects in mini-grid. It is crucially vital for overall system reliability assessment, so that equipments in the system can withstand the fault current, which usually flows in large quantities. Faults usually occur in a power system due to insulation failure, flash-over, physical damage or human error. These faults may either involve the three phases in a symmetrical nature, or in a asymmetrical manner where only one or two phases may be involved. The most common fault in a mini-grid is phase to ground fault, or single line to ground fault.



(a) Effect of single line-to-ground fault on grid current



(b) Effect of single line-to-ground fault on grid voltage

Fig. 4.19: Grid current and voltage during line-ground fault.

In general, a single line-to-ground fault on an electric line occurs when a conductor drops to the ground, coming to contact with the neutral conductor. This type of fault occurs in power systems due to several reasons, such as high speed winds, falling of a tree, lightning etc. In such situations, fault current level declines the further the fault is from the source because of the line impedance between the source and the fault. Single line-to-ground fault can be caused by a phase conductor breaking and falling down to earth. The system ground(s) would provide a return path for the fault current, completing the circuit. The effect of line-to-ground faults on grid current and voltage are shown in Figures 4.19a and 4.19b respectively.

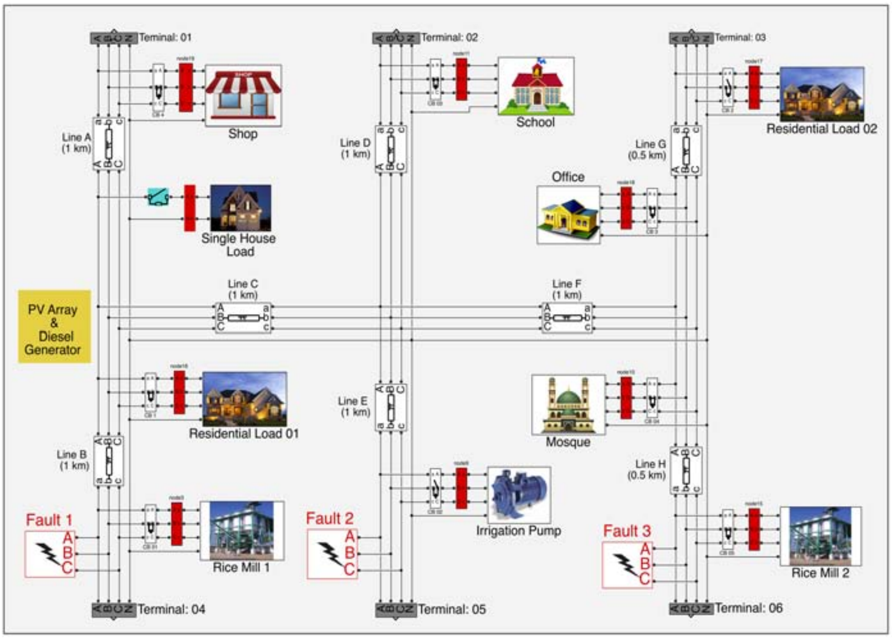


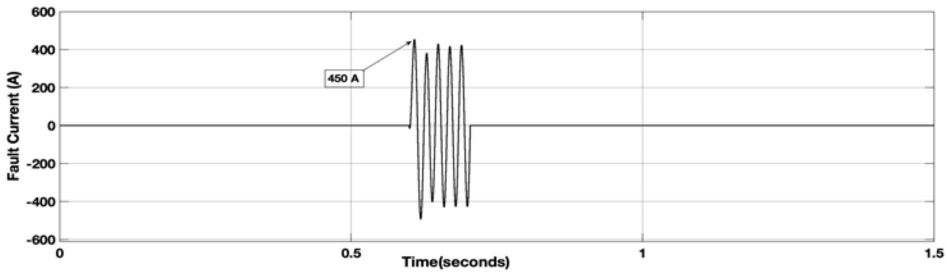
Fig. 4.20: Line-ground faults in three different locations.

To demonstrate the characteristics of single line-to-ground fault in a mini-grid, faults were injected in three different locations of the Simulink mini-grid model, as shown in Figure 4.20. The faults were placed in different distances from the source. As shown in the figure, Fault 1, 2 and 3 are 1km, 2km and 2.5km away, respectively from the source.

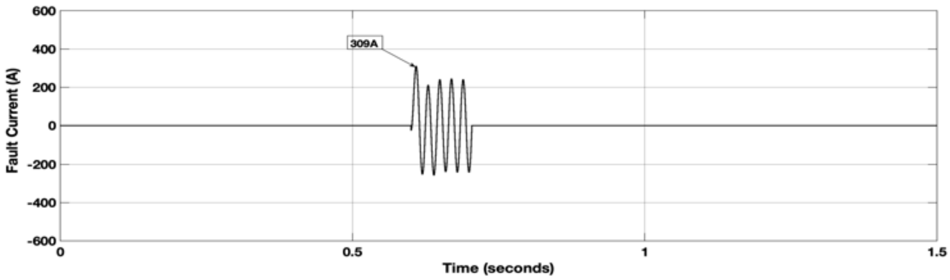
As the simulations were run after injection of faults in three different locations, the results were obtained based on the variations in fault current amplitude. The results for the three fault locations are shown in Figures 4.21a, 4.21b and 4.21c respectively. In Location 1, we obtained a fault current amplitude of 450A, with Location 2 giving 309A, and Location 3 giving 275A. By analyzing the results, it can be deduced that farther the fault is from the source, the lesser is the fault current amplitude.

When such a single-line-to-ground-fault occurs, it essentially means that a phase is coming to contact with the ground. The system we design in our Simulink model is a three-phase four-wire system. As a huge amount of this fault current is produced as a consequence, this actually flows through the fourth wire of the distribution system of the mini-grid - the neutral wire. This can be shown in the simulation results obtained from the neutral wire, as in Figure 4.22. This graph shows the huge fault current flowing through the neutral wire for a fault occurred in Location 1.

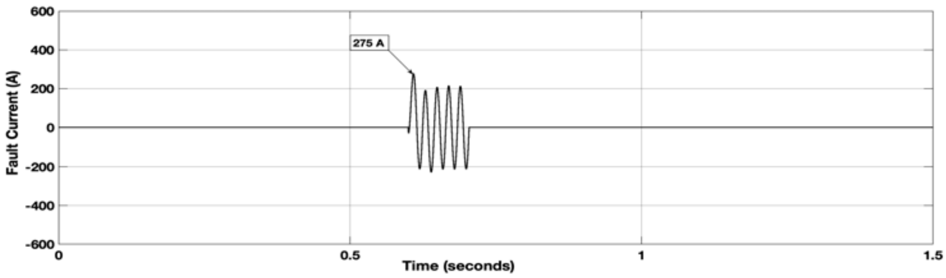
During the single-line-to-ground fault, the fault current is supplied from the source - comprising of either the battery, diesel generator or PV. In this model, as the PV, diesel and the battery are connected to a DC bus, they supply fault current. DC bus voltage also affected during faults. This has also been captured in our simulation results, as shown



(a) Fault current during line-ground fault in location 01



(b) Fault current during line-ground fault in location 02



(c) Fault current during line-ground fault in location 03

Fig. 4.21: Fault current during line-ground fault in three different locations.

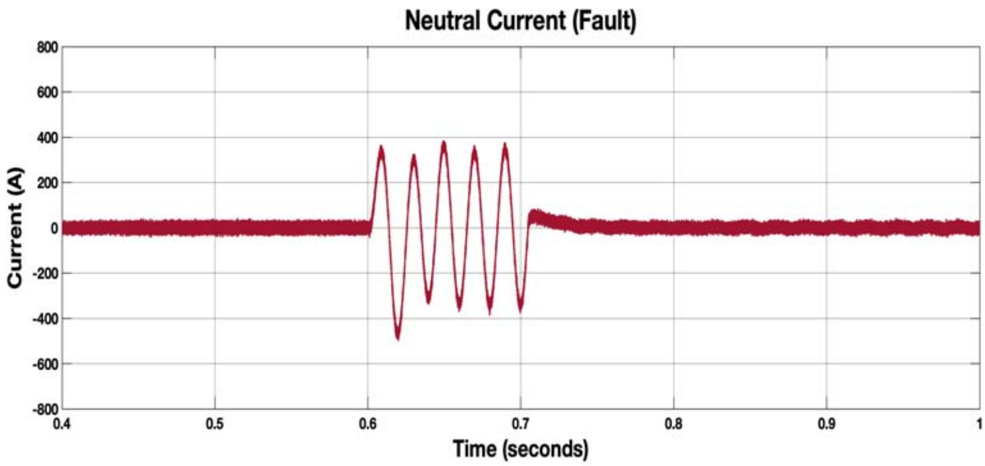


Fig. 4.22: Fault current flows through neutral.

in Figure 4.23. As shown in the results, the effect of this fault current has resulted in a fluctuation in the DC bus voltage, in the form of ripples, within the time frame of the fault occurrence.

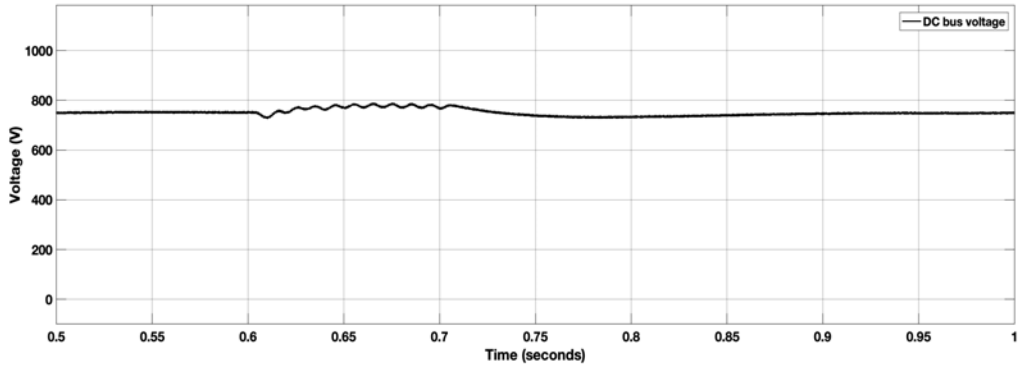


Fig. 4.23: Effect of line-ground fault on DC bus.

4.8 Discussion

The designed mini-grid model has been used to study and simulate many characteristics of a hybrid mini-grid. Grid voltage, current and frequency of network have been observed from simulation results and compared with expected grid voltage and frequency (400V 50Hz AC). This model can be used to select the best location for sources before implementation of mini-grid. The voltage at different node points along with the line loss of all segments of mini-grid have been measured placing PV array and diesel generator in different locations. Comparing these results from simulation, the optimal placement for PV array and diesel generator with minimum voltage drop and line loss has been chosen. The model was used to simulate and study daily load profile of mini-grid. Results from simulations have shown voltage fluctuations during abrupt changing of loads and impacts of considering line parameters in distribution network on voltage and current. Balanced/unbalanced and fixed variable loads were simulated to study its effects on the mini-grid. Household appliances like LED bulb, ceiling fan and mobile charger were designed and also simulated to study their characteristics. The developed power management algorithm was simulated here to observe controlled power flow from PV array and diesel based on battery SoC, solar radiation and connected loads. In this work, faults were simulated in different locations of the mini-grid to study the behaviours of faults and its impacts on grid network. This model can be used to study many characteristics of mini-grids along with analysis of several technical issues.

CHAPTER 5

CONCLUSION

5.1 Conclusion

Hybrid PV–diesel–battery mini-grids appear to be one of the most promising technological options for electrifying remote and rural areas. The mini-grid utilizes a mix of small-scale renewables and conventional fossil-fuel generation along with battery storage to reliably meet modest household, community service, agricultural, and in some cases light industrial, electrical loads. The hybrid PV–diesel–battery configuration has several advantages: meeting the system load demand in the optimal way; minimizing diesel usage and maintenance; optimal use of renewables etc. Though most of the research regarding mini-grids have been conducted for techno-economical analysis, none of the works represent a complete mini-grid model. Generally, a mini-grid based decision tool is implemented on Microsoft Excel spreadsheets or HOMER software to analyze comparative cost analysis between different operational scenarios, performance analysis, sensitivity analysis etc. But such models fail to address the challenges commonly faced in a mini-grid like smooth deployment of renewables, faults, harmonics, voltage drop, line loss, unbalanced loading condition etc. In contrast, a simplified model of hybrid mini-grid designed in MATLAB/Simulink environment can be used to simulate and analyse different characteristics of mini-grid in various scenario. An efficient Simulink based technical mini-grid model can significantly improve the analysis stage prior to the implementation.

This thesis aims to study and analyze the previously mentioned challenges by designing a hybrid PV-diesel-battery mini-grid model. In order for maximum power to be extracted from a PV module, the solar panel was connected to MPPT (INC) based boost converter. A bi-directional buck-boost converter was designed and simulated which has been used to charge and discharge battery and stabilize DC bus voltage. A power management algorithm has been developed to operate mini-grid with the best utilization of available energy with reliable and stable performance. A controller has been designed to operate the bidirectional converter in order to control power flow between the batteries and DC bus. A three-phase 4-wire inverter with controller and filter has been designed to generate a three phase 400V 50Hz AC supply. A diesel generator model has been used as a backup source. Different loads connected to the distribution network have been modeled and simulated with corresponding load profiles to analyze the mini-grid's load variation. The model has been used to determine the optimal placement for PV array and diesel with minimum voltage drop and line loss. Fault analysis has been performed to study the characteristics of fault.

This work also focuses on identifying and addressing some very important technical difficulties and can be used to study still relatively unexplored challenges of mini-grids implementation for remote island applications.

Finally, the study conducted in this thesis work will enrich the literature in rural electrification with specific attention given to Bangladesh and it is anticipated to contribute to the knowledge of hybrid mini-grid potentiality in Bangladesh.

5.2 Suggestions for Future Works

The contributions of this thesis indicate opportunities of not only extending this work in future to meet other goals, but also improve on the existing limitations of this work. The scope for future works are:

1. In a practical scenario, bidirectional inverters are used in mini-grids, but in our model we have designed a uni-directional inverter. Thus, this work has the scope of improving on the model by designing a bidirectional inverter.

2. The mini-grid model has been designed for simulation in discrete mode which takes longer to simulate long duration data. To solve this problem, model can be simplified or redesigned in phasor mode.

3. In our model, the battery is forced to discharge at 100% SoC in-spite of having abundant solar power. A battery should not be drained in the presence of sufficient solar power. To make this model realistic, the model will need to be redesigned.

4. The presence of intermittent loads, like arc welding, is a challenge for mini-grids. The equipments are prone to damage, thus these types of loads require to be modelled by examining their characteristics.

5. The mini-grid model has been designed using solar power, but it can also be designed for other renewable energy sources e.g. wind .

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Appendices

Appendix A

The detailed load profile of the mini-grid has been shown in Table A1. Loads are classified into 5 service types which include households, small shops, social institutions, office and rice mills. Under each service type, there are different number of appliances. Load data of each appliance has been shown in hourly intervals. The table also provides information of total energy consumption in a day with day load and night load.

Table A1: Detailed mini-grid load profile.

Package Type	Appliance Type	Hour of Day																								Total Load	Day load	Night load
		AM												PM														
a. Households		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	kWh	kWh	kWh
Package-1	LED light																		1.2	1.2	1.2	1.2	1.2	1.2		7	0	7
	Ceiling Fan	2.6	2.6	2.6	2.6	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	1.7	1.7	1.7	1.7	1.7	1.7	2.6	30	5	26
	TV					0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	3.5	3.5	3.5	3.5	3.5	3.5		30	6	24
																										67.4	**11.0**	**56.4**
Package-2	LED light																		1.0	1.0	1.0	1.0	1.0	1.0		6	0	6
	Ceiling Fan	3.4	3.4	3.4	3.4	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	2.3	2.3	2.3	2.3	2.3	2.3	3.4	40	6	33
	TV					0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	2.3	2.3	2.3	2.3	2.3	2.3		20	4	5
																										65.2	**10.2**	**55.0**
Package-3	LED light																		1.4	1.4	1.4	1.4	1.4	1.4		9	0	9
	Ceiling Fan	4.8	4.8	4.8	4.8	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	3.2	3.2	3.2	3.2	3.2	3.2	4.8	55	9	47
	TV					0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	2.1	2.1	2.1	2.1	2.1	2.1		18	4	14
																										81.9	**12.4**	**69.6**
Package-4	LED light																		0.2	0.2	0.2	0.2	0.2	0.2		1	0	1
	Ceiling fan	0.8	0.8	0.8	0.8	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.6	0.6	0.6	0.6	0.6	0.6	0.8	10	1	8
	TV					0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.4	0.4	0.4	0.4	0.4	0.4		3	1	3
	Refrigerator	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	11	4	7
b. Small Shops																									**24.8**	**6.2**	**18.6**	
Package-5	LED light																		0.1	0.1	0.1	0.1	0.1	0.1		0	0	0
	Ceiling fan					0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1		2	1	1
																										2.7	**1.1**	**1.6**
Package-6	LED light																		0.33	0.33	0.33	0.33	0.33	0.33		2.00	0.00	2.00
	Ceiling fan					0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.7	0.7	0.7	0.7	0.7	0.7		5.92	8.05	7.87
	TV					0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.6	0.6	0.6	0.6	0.6	0.6		8.2	3.2	5.0
																										26.1	**11.3**	**14.9**
Package-7	LED light																		0.07	0.07	0.07	0.07	0.07	0.07		0.43	0.00	0.43
	Ceiling fan					0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1		3.03	1.53	1.50
	TV					0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2		2.35	0.92	1.43
	Refrigerator	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	4.9	1.8	3.1
c. Social Institutions																									**10.7**	**4.3**	**6.4**	
Package-8	LED light																		0.05	0.05	0.05	0.05	0.05	0.05		0.3	0.0	0.3
	Ceiling fan					0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.07	0.07	0.07	0.07	0.07	0.07		1.8	1.0	0.9
d. Office																									**2.1**	**1.0**	**1.1**	
Package-9	LED light																		0.02	0.02	0.02	0.02	0.02	0.02		0.1	0.0	0.1
	Ceiling fan					0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.02	0.02	0.02	0.02	0.02	0.02		0.9	0.5	0.4
	Computer					0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09								1.2	0.8	0.4
																										2.2	**1.4**	**0.9**
e. Rice Mills																												
Package-10	Rice Mill (20 HP)									18	18	18	18			18	18									**107.4**	**107.4**	**0.0**
Package-10	Rice Mill (18 HP)									10	10	10	10			10	10									**60.4**	**60.4**	**0.0**
Package-10	Rice Mill (16 HP)									9	9	9	9			9.0	9.0									**53.7**	**53.7**	**0.0**
Sub Total		12	12	12	12	7	7	7	7	43	43	43	43	7	7	43	43	7	23	23	23	23	23	23	12	**504.8**	**280.4**	**224.4**
Total		**12**	**12**	**12**	**12**	**7**	**7**	**7**	**7**	**43**	**43**	**43**	**43**	**7**	**7**	**43**	**43**	**7**	**23**	**23**	**23**	**23**	**23**	**23**	**12**	**505**	**280**	**224**