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HYBRID SOLAR PV-GENSET-BATTERY STORAGE POWER SYSTEM FOR A REMOTE OFF-GRID APPLICATION: CASE STUDY IN ETHIOPIA

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Declaration

I [Solomon Gebremariam Fissaha], hereby declare that this thesis represents my personal work, realized to the best of my knowledge. I also declare that all information, material and results from other works presented here, have been fully cited and referenced in accordance with the academic rules and ethics.

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Abstract

A hybrid power system that consists of PV-array, diesel generator, battery bank (storage device) and convertors has been proposed and discussed to obtain an efficient topology, economic power management strategy (system), and efficient power system with less environmental effect for a typical rural area where electricity has not reached yet. The first work of this thesis was selection of the most efficient topology among the proposed configurations(DC-bus, AC-bus and Mixed-bus topologies) that are connected to different energy sources, DC source (PV-array), AC source (diesel generator) and storage device (battery bank) based on the power output efficiency which delivers to the load demand. Then, depending on the load demand and the solar irradiation considered for typical rural village, all components of the system are sized properly and three different power management strategies where the diesel generator is assisted from the renewable energy and battery bank are considered in order to investigate the best power management strategy by taking into account different criteria such as environmental impact, costs, power losses etc.

The selection of the most effective topology is conducted by taking every power source independently and the efficiencies of the system elements then after the output powers are compared by graphs. Depending up on, power balance between the two sides (supply and demand), Genset control and charging/discharging, mathematical modeling is generated for every power management strategy. This different mathematical modeling is modeled using MATLAB/Simulink blocks then, the Simulink models are simulated. Fuel consumption of the system by the generator for different power management strategies and the life-cycle costs of the systems are analyzed by using Microsoft Excel 2010. The cost analysis is analyzed by categorizing into three parties: the capital investment, variable and life-cycle costs.

After the output power is compared, it is found that the Mixed-bus configuration is the most efficient topology among the proposed layouts and it is selected for further study. Having Simulink models simulated, the simulation results (power shares of the different energy sources and battery bank, energy stored and power losses) are discussed and it is observed that the results are as per the mathematical modeling in addition to that the battery bank charges and discharges between the limits (lower limit and upper limit) and the demand is supplied from the energy sources and battery bank at each instant of time.

The environment effect is associated with fuel consumption of the diesel generator and it is found that the amount of fuel consumption of the system by the generator is different for different power management strategies so that the impact on the environment is also different. After the cost is investigated for each power management strategy, it is noticed that the capital, variable and life-life costs are different for different power management strategies. Even if the capital investment of the renewable energy system (OESPV) is the highest, it is found that OESPV is the most cost effective followed by GAPVB entire the lifetime of the system. Whereas, the Genset system (ODG)) is the most expensive overall the life time of the system due to the continuous fuel supply, replacement and operation and maintenance. In addition to that ODG has high negative impact on the environment.

Acknowledgement

This thesis paper work is on hybrid power system for off-grid remote areas application in Ethiopia which is part of MSc program study for two years in Energy Engineering at Pan Africa University Institute of Water and Energy Sciences (including Climate Change) PAUWES.

To start off with, I would like to express my deepest gratitude to PAUWES for offering me the scholarship and for my supervisor Dr. Mulu Bayray Kahsay for his supervision and helping throughout the duration of my thesis work. Next special gratitude goes for those who supported me my friends and my family for their kindness and generosity.

List of Abbreviations

Abbreviation	Description
AC	Alternating Current
BB	Battery Bank
BC	Battery capacity
CC	Capital cost
CC_{sys}	Total capital cost of the system
CC_{bb}	Total capital cost of the battery bank
CC_{con}	Total capital cost of the convertors
CC_g	Total capital cost of the Genset
CC_{pv}	Total capital cost of the PV-panel
DC	Direct Current
DG	Diesel Generator
DOD	Depth of discharge
Edg	Energy of Diesel generator
fc	Fuel Consumption
FC	Fuel costs
FC_g	Fuel costs of Genset
GAPVB	Genset supplies the average power whenever there is power demand
h	Hour
H_p	Number of peak hours
HPSs	Hybrid Power systems
kW	Killo Watt
kWh	Killo Watt hour
LCC	Life-cycle cost
LCC_{bb}	Life-cycle cost of battery bank

LCC_{conv}	Life-cycle cost of convertors
LCC_g	Life-cycle cost of Genset
LCC_{pv}	Life-cycle cost of PV
LCC_{sys}	Life-cycle cost of the system
M_s	Number of PV-modules in series
m	Meter
M_p	Number of PV-modules in parallel
N_{mod}	Total number of PV-modules
MW	Mega Watt
N_{pv}	Number of PV-arrays
ODG	Only the Diesel Generator supply the load demand
OESPV	The only Energy Source is PV-panels Supported by battery bank
OMC	Operational and maintenance cost
OMC_{bb}	Operational and Maintenance Cost of Battery Bank
OMC_{conv}	Operational and maintenance cost of convertor
OMC_g	Operational and maintenance cost of Genset
OMC_{pv}	Operational and Maintenance Cost of PV
P	Power
PAUWES	Pan Africa University Institute of Water and Energy Science
P_{dg}	Power Generator
P_{dg-nom}	Power Generator Nominal
P_{mod}	Power of Module
PMS	Power Management Strategy
PV	Photovoltaic
Pu	Per Unit Power
RC	Replacement Costs

RC_{bb}	Replacement Costs of Battery Bank
RC_g	Replacement Costs of Genset
RESs	Renewable Energy Sources
V_{batt}	Battery Voltage
VC	Costs of Variable
W	Watt

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Chapter 1

1 INTRODUCTION

Nowadays, according to World Energy Outlook, about 1.2 billion people which are 16% of the global population have no access to electricity and 80% of them live in rural areas (Bekele, 2015). More than 95% of those who are living without electricity are in sub-Saharan Africa and developing Asia countries (Bekele, 2015) (Lambe, 2013). A lot of countries have been trying to scale up the access to electricity and to reduce the entire their independence on traditional of energy systems and using of fossil fuels by innovating new power systems. Although good attention has been given towards rural electrification lasting about twenty years in developing countries, still it is at enfant age. People that live in rural areas use mainly biomass as sources of energy for cooking and another purposes in traditional ways. Consequently, serious social, environmental and economic problems have been faced.

1.1 Background of the Problem

Ethiopia is located in the horn of Africa and it is endowed with abundant renewable resources such as hydro, solar, wind, geothermal and biomass. Even if the country has high amount of renewable potential, very small portion of it has been used and most of the people do not have access to modern energy. There is sunshine entire of the year almost across the country. Approximately, most of part of the country have over 3000 hours of sunshine and the annual average daily solar energy in some part of the country is 5.0kWh/m2 and in the north part it can be 6.0 to 7.5kWh/m2 per day (Derbew, 2013) (Mazengia, 2010). The total amount exploitable solar energy of Ethiopia is approximately about one million GW with an average insulation of 5.0kWh/m2. Although the country is endowed with huge amount of solar energy, the amount utilized so far is so small only 450kW using photobiotic panels (Agency, 2011), (Md. Minarul Islam, 2013). Ethiopia is one of the least developed countries in the world; especially most of the population of the country has been suffering from energy poverty (Krishnan, 2014), (Eshete, 2015). At present, more than 73% population which is 73 million people in Ethiopia do not have access to electricity in their homes. Ethiopia Energy sector highly depends on oil import and about 96% of the population has been depending on biomass like crop waste, animal mature and fire wood in traditional way as a result there are environmental, social such as health problems via indoor air pollution (Köhlin, 2009), (Mazengia, 2010), (Md. Minarul Islam, 2013).Almost all of these people live in rural areas where electricity has not reached yet. There is huge amount of wood consumption that affects environment as it results in deforestation in rural areas. The deforestation has been causing loss of biodiversity and soil erosion consequently, the balance of ecosystem has been lost. This traditional way of using energy also has caused health problems and low income. The rural areas may be electrified either by extending the grids of the existing power systems or by introducing isolated hybrid power systems. Extension of the existing grids is not appropriate as the power is not affordable due to difficult landscapes of the areas so that it becomes complicated and unreliable. For remote areas where electricity has not reached yet, decentralized hybrid power systems which contain fossil fuel generator, renewable energy source and battery storage systems are preferable.

A system that depends entirely in either renewable energy resources or powered by diesel is possible but it is not reliable and affordable. The system which is dependent on diesel 100% has a negative impact on access to electricity due to fluctuations of prices and fuel supply of the fuel in addition to that it has negative environmental effect. The huge potential of renewable resources such as solar, hydro, wind can be harnessed and converted to electricity to supply clear energy to the people that live without electricity but these only could not be reliable as there is intermittency. Only renewable energy resource systems are not reliable since there is intermittency of energy resources from time to time and from season to season. For instance, solar energy is obtained only day time but during cloudy and night time there is no access to solar energy. In order to meet reliable, affordable and sustainable electricity integrated hybrid systems are recommended that involve renewable resources, diesel generator and battery storage.

1.2 Statement of the Problem

Renewable energy and non- renewable energy technologies have been recommended to solve electricity problem in rural areas where electricity has not reached yet. However, for effective and economical utilization, off-grid hybrid power systems provide different options. Such hybrid power systems have not been analyzed for different possible topologies and different power management strategies.

1.3 Research Question

i. Which technological configuration of hybrid power systems is the most efficient from the three topologies (AC-coupled hybrid power system, DC-coupled hybrid power system and Mixed-coupled hybrid power system)?

ii. Which power management strategy (scenario) of hybrid power systems is the most efficient, cost effective and that has less environment effect from the proposed scenarios to satisfy the energy demand to off-grid areas sustainably and efficiently?

1.4 Research Hypothesis

From the research question, the following hypotheses can be generated:

i.

Alternate Hypothesis (H1):

All the technological configurations of hybrid power systems have different total efficiency so that the power delivers to the load varies depends on the system topology.

Null Hypothesis (H0):

All the technological configurations of hybrid power systems have no different total efficiency so that the power delivers to the load does vary depends on the system topology.

ii.

Alternate Hypothesis (H1):

All proposed power management strategies of hybrid power system have different power shares, environment effect, total costs, and efficiencies.

Null Hypothesis (H0):

All proposed power management strategies of hybrid power system have no different power shares, environment effect, total costs, and efficiencies.

1.5 Objectives

General objective: Analyze hybrid solar pv-genset-battery storage power system for a remote off-grid application by considering different topologies and power management strategies to obtain an efficient topology, economic power management strategy and efficient power system with less environmental effect for a typical rural area.

Specific objectives:

- Analyze the proposed system topologies (AC-bus, DC-bus and Mixed bus) to select the most efficient topology
- Analyze the three proposed power management strategies to compare the hybrid power system, only renewable energy system(only PV-arrays with battery bank) and diesel generator system
- Analyze life-cycle cost comparison for the different cases of proposed power systems
- Investigate environment effect caused by fuel consumption of generators for different power management strategies

1.5 Methodology

1.5.1 Introduction

To succeed the objectives of this research project, different methodologies are carried out in this paper. To obtain detail information about the energy sources (PV-panel and Genset), battery bank and convertors literatures are studied. In the literature study, hybrid power system that involves solar arrays, battery bank, power converters and Genset are described detail. Under chapter-one, in the introduction part the overview of shortage of electricity in the world and particularly in Ethiopia is described. The renewable energy resource specially the solar potential is discussed and how the non-electrified remote areas can be electrified is also discussed. The negative impact of using biomass in traditional way and the objectives of this paper is mentioned. In chapter-two different literatures are discussed about hybrid power system that involves diesel generator set, PV-array and storage system. The proposed topologies of hybrid power system are presented under this chapter in order to get the most efficient layout for further study. Under chapter three (methodology), depending on the entire efficiencies of the systems, formula for the power deliver to the load are explained. In addition to that the proposed power management strategies and the formula for cost analysis are discussed to get the best energy management strategy. In chapter four the power output of the three topologies, load profile, solar irradiation, the results of simulated and life-cycle cost analysis are discussed for all power management strategy. Under chapter five conclusion and recommendation are presented.

1.5.2 Data collection

To conduct this thesis, different sorts of data are considered such as efficiencies of the system elements, total estimated daily load profile (kW), hourly average solar insolation/irradiation (kW/m^2) and life-cycle costs of the hybrid power systems. These data are obtained from literatures, Ethiopian Electric Utility and Universal Electricity Access Project (UEAP) in Ethiopia.

1.5.3 Data analysis

The possible topologies are investigated in detail in order to get the best layout (configuration) for further study as the first work of this thesis was to obtain the most efficient layout. The most efficient topology is selected based the total power (directly and/or via the battery bank) delivers to the load. This is conducted by taking the efficiencies of the battery bank, power electronic and storage devices to compare the power delivers to the load graphically by using Microsoft excel.

Total estimated daily load profile (kW) is considered for typical village remote area and all system elements are sized properly in order to synchronize the demand and the supply. For the selected layout, different types of energy management strategies (scenarios) are investigated to provide cost effective, sustainable and reliable energy. For each energy management strategy, mathematical models are generated for equations of energy balance, power balance, control Genset, charging/discharging battery bank and then, all these equations are modeled using MATLAB/Simulink blocks. The hourly average power demand and hourly average solar insolation/irradiation are taken as inputs for simulation of different scenarios of power management strategies. The Simulink model is simulated then after the results (power shares, energy stored and power losses) are discussed in detail. Life-cycle costs of the proposed scenarios of the hybrid system are analyzed in order to get the best efficient power management strategy, cost effective and less environmental effect. Based on the literatures, the cost analysis and the outputs of the simulation, some crucial points are discussed in the conclusion parts.

Chapter 2. LITERATURE REVIEW ON HYBRID POWER SYSTEMS

2.1 Introduction

Nowadays, in developing countries, especially the remote areas need affordable, reliable and efficient energy for their fast development. For remote areas where electricity has not reached yet, decentralized hybrid power systems which contain fossil fuel Gensent, renewable energy source and battery storage systems are preferable (Bekele, 2015), (Tazvinga, 2015), (Weldemariam, 2010). Reliable and affordable electricity is the most fundamental precondition for improving social, economic and environmental of human being. Currently many researchers have conducted researches and they have proven that hybrid power systems are the most suitable for rural areas as hybrid power systems are reliable and environmental friendly to supply electricity to the remote areas (Bekele, 2015), (M.S. Ismail). Increase energy security and reliability issues are the most benefit of using hybrid power systems (Marty, 2016), (Nayar, 2010), (Weldemariam, 2010). Standalone hybrid (decentralized) systems which is fed by renewable energy sources are capable of providing good quality, affordable and reliable electricity for lighting, water supply, communication and so on (Bekele, 2015), (Gorthi, 2011). An incorporation of storage devices with renewable energy resources play great role on solving problems such unpredictable, intermittent nature of the renewable energies and high consumption of fuel as well (Dylan Theunissen, 2013), (Tazvinga, 2015). Off-grid power systems solve energy poverty directly and eradicate the need of long distance power distribution. Hybrid power systems are able to provide steady community-level electricity, like rural electrification, providing also the possibility to be upgraded through grid connection in the future (Elbaset, 2014) (Weldemariam, 2010). Hybrid systems assisted by backup Genset that operate with minimal fuel consumption have many advantages as the Genset operates when there is high loads that exceed the supply or at low renewable energy. These systems result in huge amount of fuel consumption reduction as compared to Genset only powered to supply (Anayochukwu, 2013), (Othman, 2005). As a result it reduces climate change in addition to that it is cost effective as it decreases the cost of fuel transportation and energy distribution from grid.

The cost effectiveness of hybrid power system is better than the conventional energy resources in their overall life span even if its initial investment is costly. The life-cycle cost of a power system that involves only the conventional energy resources more expensive due to the supply of fuel continuously, many number of replacements and operation and maintenance (Léna, 2013), (Reddy, 1995).

There are many advantages of using renewable energy resources over non-renewable resources. The following advantages are some of them (Weldemariam, 2010):

- avoid climate change and energy poverty
- enhance economic productivity and create local job opportunities
- create a better use of local natural resources
- improve health care
- lower cost of fuels transportation
- reduce dependency on oil
- eliminate long time waits for grid extension
- gain fast access to reliable electricity

The main problem of standalone systems of renewable energy resources such as wind, solar is fluctuation of power at the load side as the variables of renewable energy resources such as wind turbines, solar irradiation vary with times and seasons. This can be solved by using backup, like diesel generator in order to supply power when the demand exceeds the supply. And another point is to use battery storage energy for future use. The battery bank stores/charges energy from renewable energy resources when supply exceeds the demand and supplies/discharges during energy is less or no available from renewable energy resources.

The hybrid power system, in this thesis paper consists of the following main components: renewable energy system (PV), battery storage system, genset and inverters. These different system components are explained one by one in the next sections.

2.2 Diesel Generator Set

Diesel generator is one of the fundamental components of hybrid power system. It has been used widely to provide power to remote areas where electricity has not reached yet. This system (Genset) can be operated without supportive systems (renewable energy technologies and battery storages) but it has negative environmental impact and it is not cost effective. Renewable energy sources and battery storages must be incorporated with it (diesel Generator) in order to reduce the fuel costs and negative environmental impact. In this thesis diesel generator is taken as backup to supply reliable, effective and continuous power to satisfy consumers' energy need. It supplies energy whenever the demand exceeds the supply and/or when there is no energy from renewable energy resources and battery bank. Diesel generator has diesel engine and electrical generator (alternator) to generate electric energy. The diesel engine converts chemical energy available in the fuel into mechanical energy then the generated mechanical energy rotates the engine shaft connected to the electrical generator.

The diesel generator set has the following disadvantages (Weldemariam, 2010).

- negative environmental impact
- noisy
- too heavy and so difficult to handle it
- low efficiency
- not cost effective

The figure below (Figure2.1) has shown the fuel consumption of the diesel generator and it depends up on the power output. As it is seen, although there is no power generated from the Genset, about 25% of the fuel amount is consumed (Patel, 2006) (Weldemariam, 2010). This type of diesel generator operates at efficiency of around 30% for nominal load and whenever it operates at lower value of nominal load its efficiency reduces (Anayochukwu, 2013).

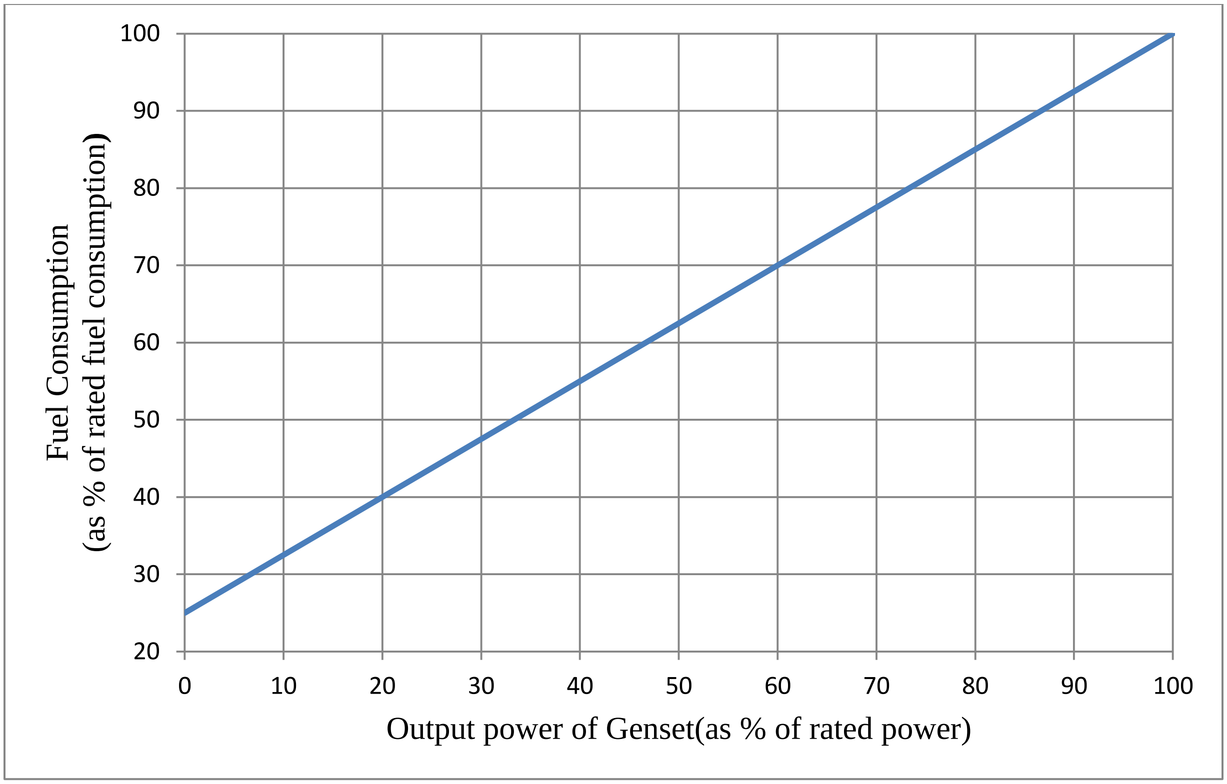

Figure 2.1: Relative fuel consumption versus output power of Genset (Patel, 2006) (Weldemariam, 2010)

The relative fuel consumption of the Genset is dependent on the output power of the Genset at any time ($P_{dg}(t)$) which is given as a function of nominal peak power of Genset($P_{g\_nom\_peak}$). And the relative fuel consumption ($fc_{relative}$) of the Genset is given as (Patel, 2006) (Weldemariam, 2010):

$$fc_{relative} = \frac{1}{4} + \frac{3}{4}\, Prelative(t) \tag{2.1}$$

Where, $P_{relative}(t) = \frac{Pdg(t)}{Pdg\_nom\_peak}$

2.3 PV-array System

Solar cell is the fundamental building blocks of PV energy system. For high generating of power, many cells are connected in series and in parallel circuit. PV-array is a combination of many modules electrically connected in series-parallel (Patel, 2006) to generate the required power. The PV-arrays absorb the solar light photons then the light energy is converted to electrical energy. The power generated from PV-array systems is DC power so that it can be utilized directly by DC appliances. For AC appliances, the power should be converted to AC power using convertors.

PV-array system is crucial in the standalone hybrid systems to supply sustainable power for the remote areas where electricity has not reached yet with support of diesel Genset and energy storage. Thus, an off-grid hybrid power system is needed for rural electrification when the following situations occur.

- It is far away from the main grid
- Grid extension is so expensive
- Power users so small
- It is difficult to electrify due to topography

The solar irradiation varies with time and season, this results in unreliable energy supply if it is not assisted by energy storage and diesel Genset.

PV-array has advantages and disadvantages (Patel, 2006) (Weldemariam, 2010) (Zeman, 203) as mentioned below:

Advantages

- Emission free and environmental friendly
- No need of fuel and water
- Needs minimum maintenance and low running cost
- Long lifetime
- No limit on harvesting if there is light

Disadvantages

- PV-array cannot generate energy if there is no light
- High initial cost
- No sustainable supply if it is not supported by battery bank and diesel Genset
- Large area is needed for installation

When PV-panel modules are sized, the following main factors should be taken into consideration (Magazines, 2008) (Weldemariam, 2010).

- Daily energy demand
- Efficiency of the PV-panel
- Solar irradiation of the site where the system is installed

The total numbers of PV-modules (number of PV-modules in series and in parallel) can be calculated as (Magazines, 2008) (Weldemariam, 2010)

Number of PV-modules in series, $M_s = (\frac{\text{Voltage of the load}}{\text{Voltage of a module}})$ and (2.2)

Number of PV-modules in parallel, $M_p = \frac{\text{Load(Ah)}*(\text{Voltage of module})}{(\text{Pmod})*(\text{Hp})(\text{Ah})}$ (2.3)

Where, P_{mod} = power of module

H_p =number of peak hours, the number of hours to convert the daily irradiation into standard irradiance

Therefore, the total number of PV-modules (N_{mod}) that form the PV-array is given as:

$$N_{mod} = M_s * M_p \tag{2.4}$$

2.4 Storage Systems

Energy storage is required to assist renewable energy technologies to provide sustainable energy, especially in standalone systems for rural areas where there is no access to electricity. The need of energy storage is to store energy from renewable energy technologies whenever there is excess energy and to supply the stored energy during the demand excesses the supply. In this thesis, the hybrid power system is PV-solar-Genset with battery bank. As the solar irradiation varies with tame and season, the energy storage assists to provide reliable energy.

The present and future energy storage technologies that are considered for standalone PV-solar systems are (Patel, 2006) (Tazvinga, 2015):

- Electromechanical battery
- Flywheel
- Compressed air

- Superconducting coil

Battery bank is an electrochemical device that stores energy in the form of electromechanical so that it is used for different applications. There are two types of electromechanical batteries (Patel, 2006) primary battery and secondary, rechargeable battery. The battery banks that are used with hybrid power systems are rechargeable/secondary batteries (Patel, 2006) (Weldemariam, 2010) so that they can store energy whenever excess energy from PV and discharge when there is less energy from PV.

Characteristics of battery

Battery capacity (BC):

This characteristic shows how much energy can be stored in the battery. The amount of energy that is able to be utilized from the battery depends on age of the battery, temperature, and battery type and discharge rate.

Battery voltage:

It is a voltage when the battery is fully charged. This amount of voltage depends on number of cells in the battery and voltages of cells.

Depth of cycle:

When the battery discharges fully, it can be damaged or destroyed before it gives services as it is supposed. Deep-cycle battery is able to discharge up to 15% to 20% of its capacity. This results in a depth of discharge (DOD) of 85%-80% (Reddy, 1995).

Autonomy: This refers to the maximum time in which the system can release energy continuously. This depends up on the application type and storage of the system and it can be defined as ratio of restorable energy capacity to maximum power discharge (Reddy, 1995).

$$a = \frac{\text{Erestore}}{\text{Pdiscarge}} \tag{2.5}$$

Cycling Capacity:

It refers to number of times that the storage of energy is able to release the energy level it has been designed to after every recharge and this is defined by number of cycles (N_{cycles}). The depth of discharge (DOD) highly affects the cycling capacity. The following figure, figure2.2 has shown the number of cycles versus the depth of discharge (DOD).

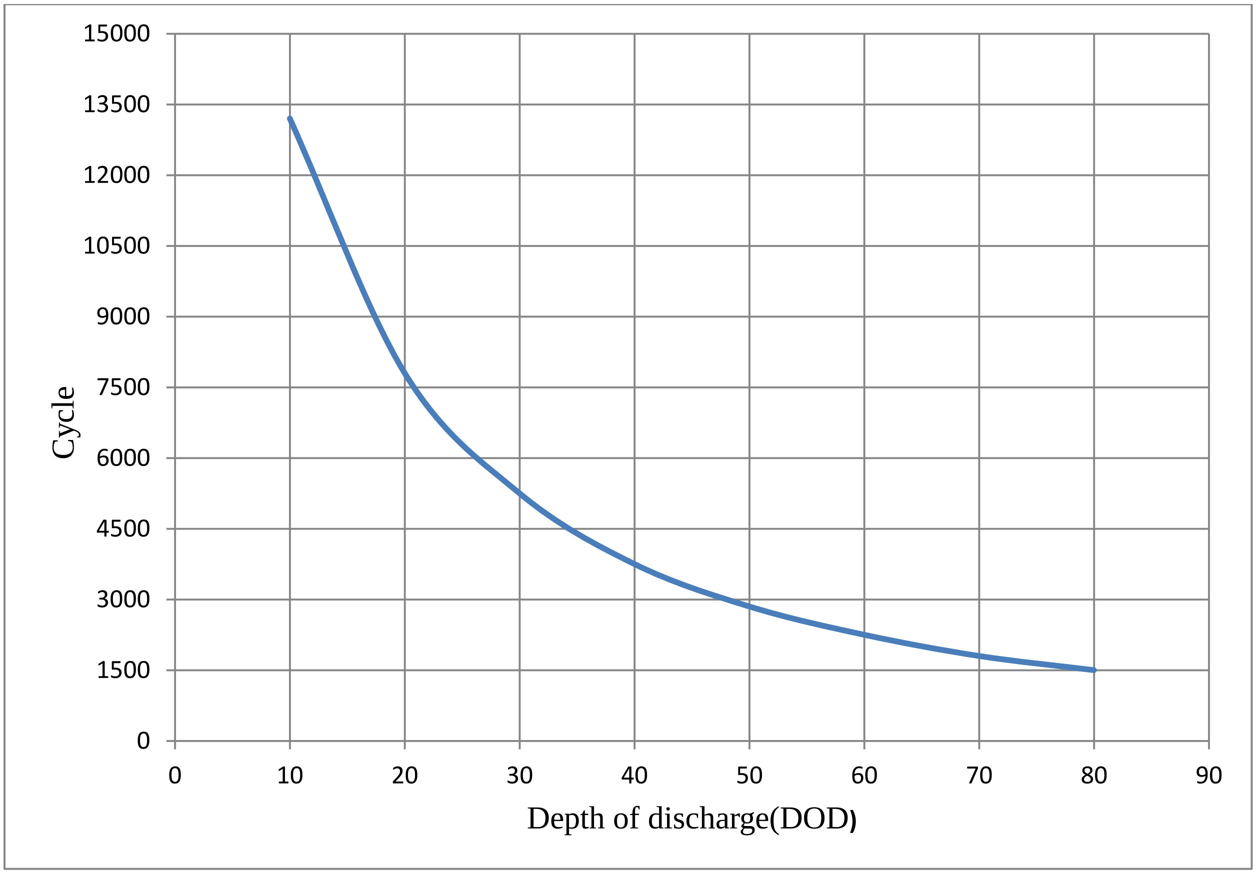

Figure 2.2: The number of cycling capacity versus the depth of discharge (DOD) for lead-acid battery (Magazines, 2008).

As it can be seen from the figure above, a battery with high depth of discharge (DOD) has low cycles so that its lifetime becomes short.

2.4.1 Sizing of battery

Battery is one of the main components of hybrid system in which energy is stored when there is excessive energy from the renewable energy resources that can be used at time the demand exceeds the supply. Maximum depth of discharge and daily energy demand are among the main factors that affect the sizing of battery (Tazvinga, 2015), (Weldemariam, 2010).

Battery voltage (V_{batt}) is defined as: it is a voltage when the battery is fully charged and it depends on the voltage of each cell and number of cells (C.O.C. Oko E.O. Diemuodeke, 2012)

(Weldemariam, 2010).

Battery voltage (V_{batt})= $N_{cells} V_{/ce}$ (2.6)

Where, N_{cells} = number of cells

$V_{/ce}$ = voltage per cell

When the capacity of the battery bank is sized, it is based on the energy consumption per day (kWh/day). The sizing of battery bank for the daily energy consumption for this thesis is given below (C.O.C. Oko E.O. Diemuodeke, 2012) (Weldemariam, 2010).

Battery capacity, $BC = \frac{Edaily-load-demand}{\eta b} \frac{DOA}{DOD}$ [Wh] (2.7)

Where,

$E_{daily\text{-}load\text{-}demand}$ = total daily energy demand (wh/day) (its value is given at appendix-B (B1))

DOD= battery depth of discharge (70% is the assumed value in this paper)

DOA=autonomous days (one day of autonomous is considered here)

η_b=efficiency of battery(.85 is assumed in this thesis)

Once the battery capacity is calculated as given above, the number of batteries in series and in parallel can be defined as (C.O.C. Oko E.O. Diemuodeke, 2012):

Number of batteries in parallel, $N_{bp} = \frac{Voltage\ of\ application}{Voltage\ of\ one\ battery}$ (2.8)

Number of batteries in series, $N_{bs} = \frac{Battery\ bank\ capacity\ in\ Ah}{Capacity\ of\ one\ battery\ in\ Ah}$ (2.9)

And the total number of batteries required in the system is:

$N_t = N_{bp} N_{bs}$ (2.10)

2.5 Configurations of Hybrid Power Systems

Hybrid power system can include different types of energy resources such as wind turbines, PV-panel, hydro power from renewable energy technologies and from non-renewable energy commonly diesel Genset are used. Besides, the system can also comprise storage device (battery bank) and convertors. Even if any combination of hybrid power system is possible, some of them might not be efficient, reliable and affordable (cost effective). Therefore, investigating the hybrid system is crucial in order to get the best appropriate system to a site where the hybrid system is installed by considering different factors such as geographical location of the place, nature of the power load, resources of energy, and efficiency of the components of the system.

Under this project of thesis, the hybrid power system is PV-Genset with battery bank. Here, in this system there are two different power generating systems. One of them (PV-solar) generates DC power directly and Diesel Genset generates AC power. As a result, these generating systems should be coupled at a point prior to the power is delivery to the load in order to convert the power to the desired form. In the next section, section 2.1.5.1, three different topologies are proposed and looked into. In order to differentiate the best layout for further study, the proposed configurations are discussed by considering the power efficiencies of the systems under section 3.2.

Under this thesis, three types of configurations are proposed and investigated to choose the most effective layout for further study, and then the hybrid power system is designed based on the selected topology. Hybrid system with effective layout supplies reliable and affordable energy so that the consumers are satisfied. The following types of hybrid power system technological configurations are looked into to find the best layout (Girma, 2013) (Weldemariam, 2010):

i. AC-bus hybrid power system (scenario-1)

ii. DC-bus hybrid power system (scenario-2)
iii. Mixed-bus hybrid power system (scenario-3)

2.5.1 AC-bus hybrid power system

In this type of configuration, all the energy conversion systems are connected to the main AC-bus with load. The configuration of this AC-coupled hybrid power system is given the figure below (Figure 2.3).

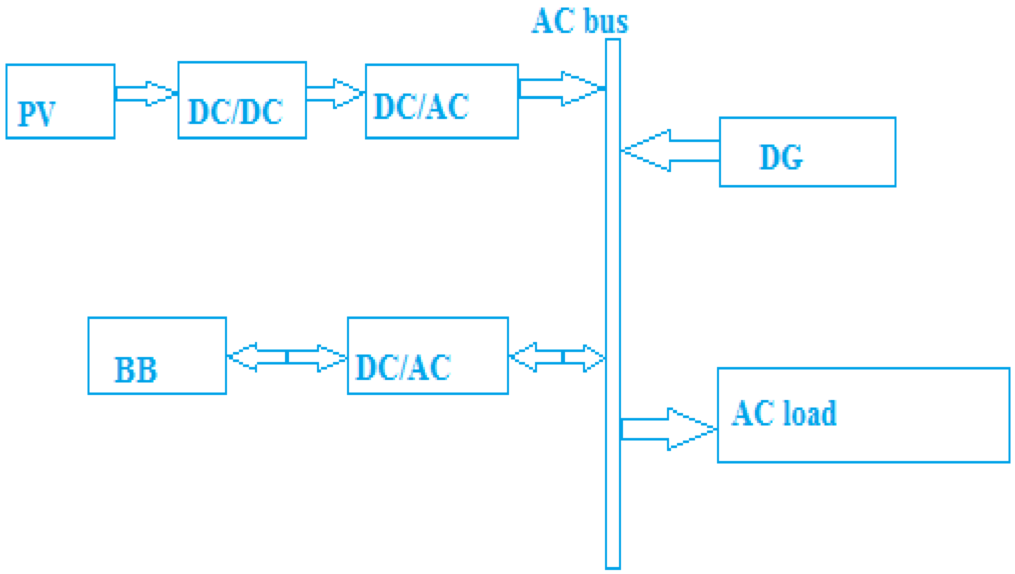

Figure 2.3: AC-coupled hybrid power systems (Girma, 2013) (Weldemariam, 2010).

As it can be seen from the figure, figure 2.3 above the diesel generator is connected directly to the main AC-bus as it produces AC power and there no loss associated with this diesel generator connection. An inverter is required before the PV-array and connected to the main AC-bus to convert the power to the desired form because the power from PV-panel is DC power. DC/DC converter needed here to stabilize the power generated from PV-panel. The battery bank needs bidirectional inverter for charging whenever there is excess supply and discharging during the less supply from the solar thus there is loss associated with this inverter.

2.5.2 DC-bus hybrid power system

This configuration, also known as centralized DC-bus topology, all the energy conversion systems are coupled onto a DC main bus prior to be being connected to the load. The configuration is given by the following figure, figure 2.4.

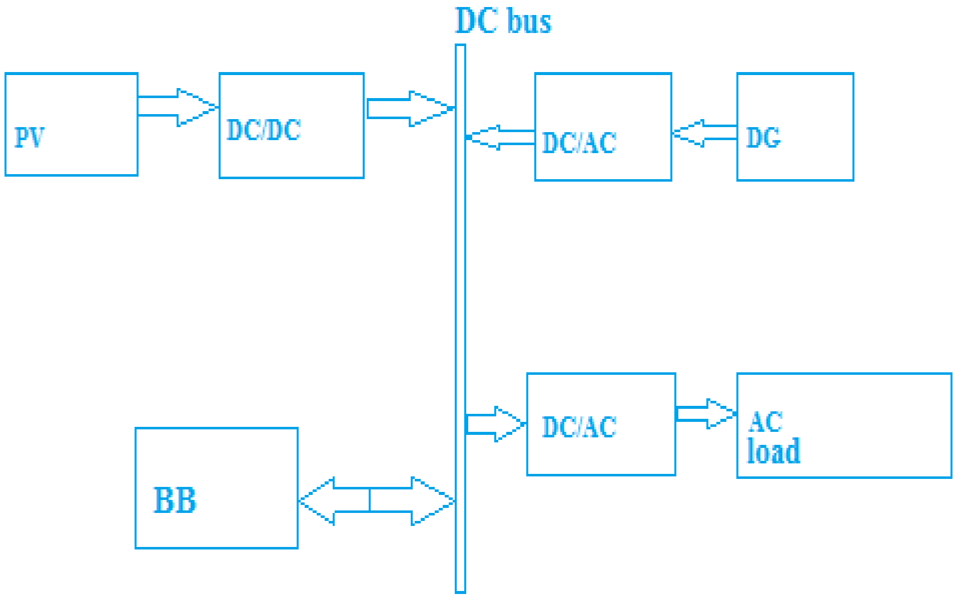

Figure 2.4: DC-coupled hybrid power systems (Guta, 2012) (Weldemariam, 2010).

As it can be observed from the figure above (figure 2.4), an inverter is needed to connect the load to DC-bus so as to convert the power to the desired form. The diesel Genset has connected to the DC-main bus through convertor (AC/DC converter) whereas PV-panel is connected via converter (DC/DC converter) to stabilize the power generated from it. Therefore, the loss associated with these convertors is taken into account. The battery bank is connected directly to the main DC-bus so that there is no loss associated with it.

2.5.3 Mixed-bus hybrid power system

This topology is a combination (mixed) of AC-coupled hybrid power system and DC-coupled hybrid power system. In this type of hybrid power system configuration, PV-array and battery bank are connected via DC/DC and directly to the DC-bus respectively whereas the diesel Genset and the load are coupled to the AC-bus without invertors. This Mixed-bus configuration is designed below.

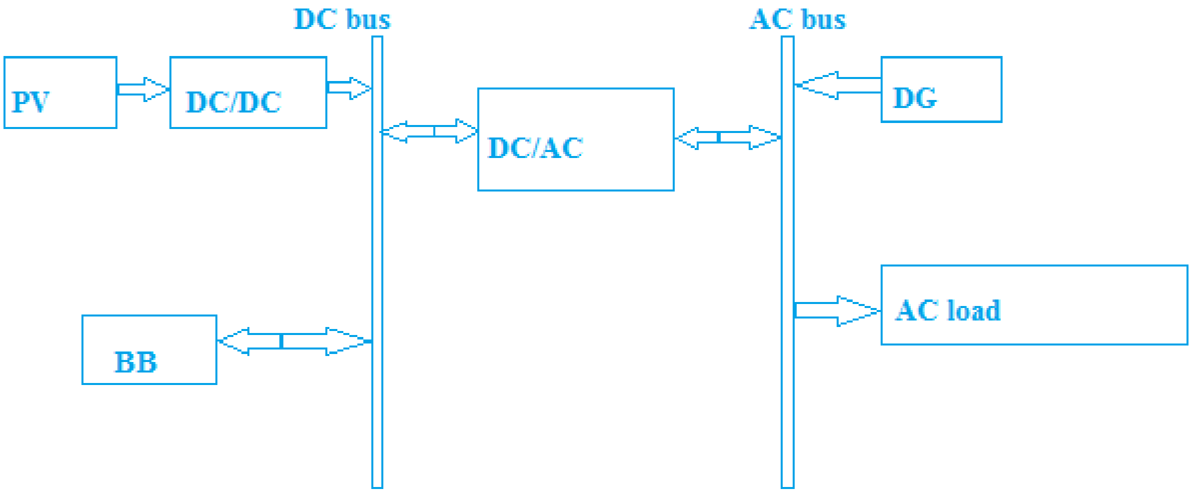

Figure2.5: Mixed-coupled hybrid power systems (Girma, 2013) (M.S. Ismail) (Weldemariam, 2010)

As can be seen from the figure above the diesel Genset is connected directly without convertor to the AC-bus with the load but the PV-panel is coupled to DC-bus only through DC/DC convertor to stabilize the power generated from the solar with battery bank. The two buses coupled via convertor (DC/AC or vice versa). Here, the losses of the convertors (DC/DC convertor and DC/AC or vice versa) are considered to investigate it.

Results of hybrid power systems that have been designed so far for remote areas where electricity has not reached yet are noticed from different literatures studied here. As per the literatures, electrification by introducing isolated hybrid power systems is appropriate when comparing to extending the grids of the existing power systems for off-grid areas which are far away from the existing national electric grids. Extension of the existing national gird to these areas is not feasible economically (Bekele, 2015) (Weldemariam, 2010) (M.S. Ismail).

When hybrid power systems consist of PV-array/wind/diesel generator with storage devices (battery bank) are compared to Diesel generator systems by considering some important criteria, hybrid power system are more preferable due to small storage device and low cost of energy according to the literature studied in this paper (Weldemariam, 2010) (BAE Batterien GmbH, 2008) (Nayar, 2010)

Many literatures have been written in different countries aiming at exploring economic analysis of electrifying rural areas that are far away from electric grids with different types of systems such as hybrid systems(include PV-arrays, diesel generators, storage devices and converters), only diesel generators etc. and it has been found that electrifying rural areas using hybrid power systems is so beneficial when compared to conventional source systems as they reduce air pollutants to the atmosphere (Girma, 2013), (Marty, 2016).

Many researchers, policymakers and customers have believed that solar-PV system is not feasible economically as it has high initial investment. As a result, customers in developing countries have not involved in solar-PV system. Therefore, they have recommended that for expansion of power generation in the developing countries to solve electricity problems, sola-PV system is not feasible option (Ondraczek, 2013) (Othman, 2005).

Design of different types of power system (hybrid system, only diesel generator, only renewable energy resource) is possible but their reliability and affordability of the energy matter the systems. Only diesel generator system is not reliable due to fluctuation of fuel price and availability of the fuel. Therefore, according to the literatures diesel generator is not recommended (Ana Rossello-Busquet, 2008) (Marty, 2016) (Othman, 2005).

CHAPTER 3. METHODOLOGY

3.1 Introduction

Under this project of thesis, the hybrid power system is PV-solar-Genset with battery bank. Here, in this system there are two different power generating systems. One of them (PV-solar) generates DC power directly and Diesel Genset generates AC power. As a result, these generating systems should be coupled at a point prior to the power is delivered to the load in order to convert the power to the desired form of power. These different elements of hybrid power system can be coupled using different topologies. Under this thesis, three types of configurations are proposed and investigated to choose the most effective layout for further study, and then the hybrid power system is designed based on the selected topology. Hybrid system with effective layout supplies reliable and affordable energy so that the consumers are satisfied.

To be more efficient, the hybrid power systems' elements should be sized properly in order to synchronize the demand and the supply. If the elements of the hybrid power system are oversized, the system cannot be economical and when they are undersized, shortage of power may occur. The proposed hybrid power system in this thesis project is PV-array-Genset with battery bank. Proper sizing of battery bank (storage device) lowers the fuel consumption, which in turn reduces the environmental pollution when compared to that of Genset is used alone. In addition to that the unwanted total cost for the system reduces so that the acceptance of the system increases. The load demand power and the available energy resource of the village area where the hybrid power system is installed should be studied before for proper design.

In this hybrid power system the energy sources (PV-arrays and Genset) and battery bank complement one another to provide reliable energy and the system becomes also cost effective. In other words, the Genset is assisted from the renewable energy source and battery bank in different methods. These different methods of assistances are called power management strategies.

Under this chapter, three different sorts of power management strategies are considered. Depending on the power/energy balance in both (supply and demand) sides, charging and discharging limits of battery bank mathematical modeling is designed as well as to the system elements sizing for every power management strategy. Then after, for all mathematical modeling of each power management strategy, MATLAB/Simulink models are generated after that the Simulink models are simulated for all power management strategies. Then the results of the simulation are discussed based on the power sharing results, energy stored in the battery bank and the losses associated with the convertors and charging/discharging battery bank under the next chapter.

Environmental effects, capital, lifetime costs and lifetime of each system components are the main requirements to select best power management strategy which is used for the hybrid system. Those criteria are discussed for every power management strategy to choose the most optimal power management strategy. The environmental effects are associated with the fuel consumptions and the comparison of the fuel consumption of each power management strategy is discussed under chapter-4 in section 4.31. In addition to the environmental effects, it is so important to analyze the costs of the system in order to choose the best system. Here, to choose the best cost effective power management strategy, the cost analysis is discussed under section 3.4.2. First the initial capital costs of each power management strategy is analyzed and compared. Then after, the costs of lifetime of each system is discussed and compared. Finally, sum of these costs are added and discussed, and then some important points are concluded.

In this thesis project, under chapter two three different topologies (scenarios) are proposed and discussed briefly. To select the most efficient, every topology is discussed for two cases (for PV power and Diesel Genset power) to determine each efficiency of the power being delivered from each energy sources. The consumed power may be delivered directly (without storing in the battery bank) and /or indirectly, through battery bank (after stored).

By referring to the figures (from Figure 2.3 to Figure 2.5), it can be seen that, the power from the sources that is consumed delivers to the AC-load directly and/or indirectly (after stored in the battery bank).

In all topologies, the power losses associated with battery bank and converter devices are considered. For topology one (Figure 2.3), the Genset is connected directly to the AC bus and therefore, it has no any loss associated with the power delivers directly to the AC-load whereas the power delivers to the load from the PV-panel has losses associated with DC/DC and DC/AC converters prior to connected to the AC-bus. In scenario-2 (Figure 2.4), both the energy sources (PV-array and Genset) are experienced power losses before they are connected to the main DC-bus. For scenario-3 (Figure 2.5), the Genset is connected directly to AC bus and thus there are no losses associated with converters for direct use of power, however, the PV-panel faces loss related to DC/DC. Therefore, the efficiencies of the DC/AC converter, AC/DC converter, DC/DC converter and battery bank are represented as η_{da}, η_{ad}, η_{dd} and η_{bb} respectively that help to compare the total power (directly and/or indirectly) delivered to the load.

The losses that are associated with wires are not taken into account for these topologies. The powers generated from the PV-panel and Genset are represented as P_{pv} and P_{dg} respectively. These power generated from the sources (PV-array and diesel generator) can be utilized directly and/or indirectly. If the power consumed directly is P_{dir}, then the remaining power that is stored in the battery is 1- P_{dir} (power indirect, P_{indid}) for both sources of energy. The total powers delivers to the loads for each topology are calculated by using the formula below to select the most efficient topology.

The following tables show equations for powers deliver to the load directly or indirectly for both energy sources (PV-array and Genset). Comparisons of powers consumptions/output of PV-panel and diesel generator delivers directly and or indirectly for scenarios1, 2 &3 are given by Figure 4.1 and Figure 4.2 respectively.

Table3.1: Formula for power delivered to the load directly or indirectly for topology-1

Topology-1:AC-bus hybrid power system			
Power source	Direct Power Consumption, P_{dir}	Indirect power Consumption, P_{indir}	Total power Consumption, P_{ctotal}
PV-array, P_{pv}	$P_{dir}\ \eta_{dd}\ \eta_{da}$	$(1-P_{dir})\ \eta_{dd}\ \eta_{da}\ \eta_{ad}\ \eta_{da}\ \eta_{b}$	$P_{dir}\ \eta_{dd}\ \eta_{da}\ +(1-P_{dir})\ \eta_{dd}\ \eta_{da}\ \eta_{ad}\ \eta_{da}\ \eta_{bb}$
Genset, P_{dg}	P_{dir}	$(1-P_{dir})\ \eta_{ad}\ \eta_{da}\ \eta_{bb}$	$P_{dir}\ +(1-P_{dir})\ \eta_{ad}\ \eta_{da}\ \eta_{bb}$

Table3.2: Formula for power delivered to the load directly or indirectly for topology-2

Topology-2: DC coupled hybrid power system			
Power source	Direct Power Consumption, P_{dir}	Indirect power Consumption, P_{indir}	Total power Consumption, P_{ctotal}
PV-array, P_{pv}	$P_{dir}\ \eta_{dd}\ \eta_{da}$	$(1-\ P_{dir})\ \eta_{dd}\ \eta_{da}\ \eta_{bb}$	$P_{dir}\ \eta_{dd}\ \eta_{da}\ +(1-\ P_{dir})\ \eta_{dd}\ \eta_{da}\ \eta_{bb}$
Genset, P_{dg}	$P_{dir}\ \eta_{ad}\ \eta_{da}$	$(1-\ P_{dir})\ \eta_{dd}\ \eta_{da}\ \eta_{bb}$	$P_{did}\ \eta_{ad}\ \eta_{da}\ +(1-\ P_{dir})\ \eta_{dd}\ \eta_{da}\ \eta_{bb}$

Table3.3: Formula for power delivered to the load directly or indirectly for topology-3

Topology-3:Mixed-coupled hybrid power system			
Power source	Direct Power Consumption, P_{dir}	Indirect power Consumption, P_{indir}	Total power Consumption, P_{ctotal}
PV-array, P_{pv}	$P_{dir}\,\eta_{dd}\,\eta_{da}$	$(1- P_{dir})\,\eta_{dd}\,\eta_{da}\,\eta_{bb}$	$P_{dir}\,\eta_{dd}\,\eta_{da} +(1- P_{dir})\,\eta_{dd}\,\eta_{da}\,\eta_{bb}$
Genset, P_{dg}	P_{dir}	$(1- P_{dir})\,\eta_{ad}\,\eta_{da}\,\eta_{bb}$	$P_{dir} +(1- P_{dir})\,\eta_{ad}\,\eta_{da}\,\eta_{bb}$

The results of Comparison of powers deliver (some part of it directly and/or indirectly) to AC load in the three configurations from the energy sources is discussed under the next chapter. Under that portion, the first work of this thesis should be finished as the next work is based on that result. In addition to that the first research question must be answered and the research hypothesis also be proved.

3.2 Management Strategies of Power, Modeling and Simulation

3.2.1 Battery bank sizing

The battery bank should be sized properly so as to store sufficient enough energy from renewable resource, PV-arrays whenever there is excessive energy supply. Once the surplus energy from the renewable energy resource is stored in the battery bank, then it supplies power when there is no/ less power from the renewable energy resource. This battery bank supplies demand during night time or cloudy time.

When the capacity of the battery bank is sized, it is based on the energy consumption per day (kWh/day). The sizing of battery bank for the daily energy consumption for this thesis is given below (Guta, 2012).

Battery capacity, $BC = \frac{Edaily-load-demand}{\eta bb} \frac{DOA}{DOD}$ [Wh] (3.1)

Where,

$E_{daily-load-demand}$ = total daily energy demand (wh/day) (its value is given at appendix-A)

DOD= battery depth of discharge (70% value is considered in this paper)

DOA=autonomous days (one day of autonomous is considered here)

η_{bb}=efficiency of battery(.85 value is considered in this thesis)

Based on the load profile considered here and parameters have been taken, the capacity of the battery is calculated and it is 2.08MWh. Battery charging or discharging within 30%-90% of peak capacity battery often brings high efficiency as a result designing of controls for the lower and upper limits of the battery is very important. To obtain the nominal capacity of the battery bank, the calculated value should be multiplied by 1.25 (BAE Batterien GmbH, 2008) (Weldemariam, 2010).

3.2.2 Controlling model of charging and discharging of the battery bank

The battery bank has minimum and maximum limit capacities in which it can be discharged and charged respectively. Thus, it is better to give an attention when it is sized. The controlling model of charging and discharging of the battery bank should be designed in such a way that it is used in a safe way in every power management strategy.

Figure3.1 shows model of equivalent circuit of battery bank which is connected to the DC-bus configuration. The battery has internal resistance (R_{int_bb}) and as it is seen in the equivalent circuit model, the current flows into or out the battery depending on the supply and the demand power.

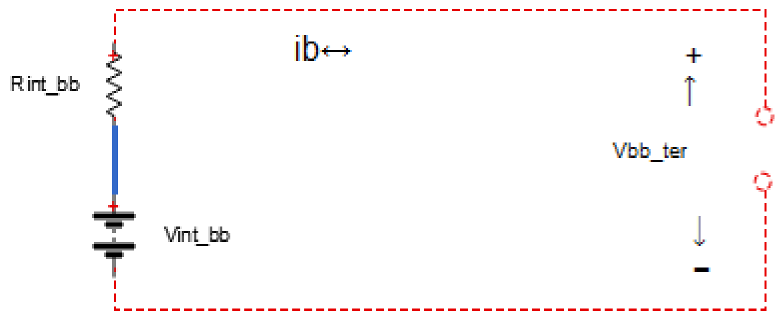

Figure 3.1: equivalent circuit model of battery bank

The voltage at DC-bus (battery terminal) can be expressed by using Kirchhoff's voltage law as:

$-V_{int\_bb} + i_b R_{int\_bb} + V_{bb\_ter} = 0$

$V_{bb\_ter} = V_{int\_bb} - i_b R_{int\_bb}$ (3.2)

Power can be drawn from the battery when the demand exceeds the supply and it flows to the battery when the supply is greater than the demand. This can be expressed by the product of the terminal voltage at battery and the current that flows through it and it is:

$P_{dfb}(t) = V_{bb\_ter} i_b(t)$ (3.3)

The energy that is available in the battery when the battery charges, discharges or neither charges nor discharges is given as:

$e_{ava}(t) = e_{bb\_ini}(t) + \int P_{dfb}(t)dt$ (3.4)

Where, $e_{ava}(t)$= energy available in the battery

$e_{bb-ini}(t)$=battery initial energy

$P_{dfb}(t)$=power drawn from battery or flow to the battery

V_{bb_ter}= battery terminal voltage at DC-bus connection

V_{bb_int} =internal voltage of battery bank

i_{bf}= current flows into or out of the battery

Note: the current that flows out is negative (convention)

R_{int_bb}=battery bank internal resistance

If there is flow of current, there is charging or discharging of battery bank. But when the battery stops charging and discharging, there is no flow of current. To identify either the battery charges or discharges, it is taken the conventional sign of the current flow. As per the convention considered here, negative current flow (current flows out) shows discharging of the battery and positive current tells charging.

To model the equivalent circuit of battery bank, the following states should be considered in addition to the above conditions.

A. When energy of the battery bank is between the minimum and the maximum values:

$$E_{bb\_min} < E_{bb}(t) < E_{bb\_max} \tag{3.5}$$

When the state of the energy is greater than the minimum and less than the maximum values of the battery bank energy, it is able to charging and discharging depending on the supply and the demand. If the supply exceeds the demand, it charges and discharges when the demand is greater than the supply.

B. When Energy of the battery bank has reached at its peak value and power is delivered from it.

In this state, the battery has fully charged and it starts discharging if there is load demand.

$P_{pv(t)} + P_{g(t)} < P_{load(t)}$

$P_{pv(t)} + P_{g(t)} - P_{load(t)} < 0$ and (3.6)

$E_{bb}(t) = E_{bb\_max}$

According to the convention of the current flow and direction in this paper, the current and the power have negative and positive sign respectively.

C. When Energy of the battery bank has reached at its minimum value and it starts charging.

Under this condition, the battery bank has discharged to its minimum condition and the supply exceeds the demand so that it starts charging. The state can be expressed as:

$P_{pv(t)} + P_{dg(t)} > P_{load(t)}$

$P_{pv(t)} + P_{dg(t)} - P_{load(t)} > 0$ and (3.7)

$E_{bb\_min} = E_{bb}(t)$

According to the convention of the current flow and direction in this paper, the current and the power become positive and negative respectively.

To charge or discharge the battery bank, one of the three above conditions must happen. If there is no charging and discharging condition, there is no flow of current, as a result, the power becomes zero and this shows that battery energy is constant.

Taking the three conditions above of the energy battery bank and the power conditions, the control mechanism of battery charging and discharging is designed and shown by the following figure:

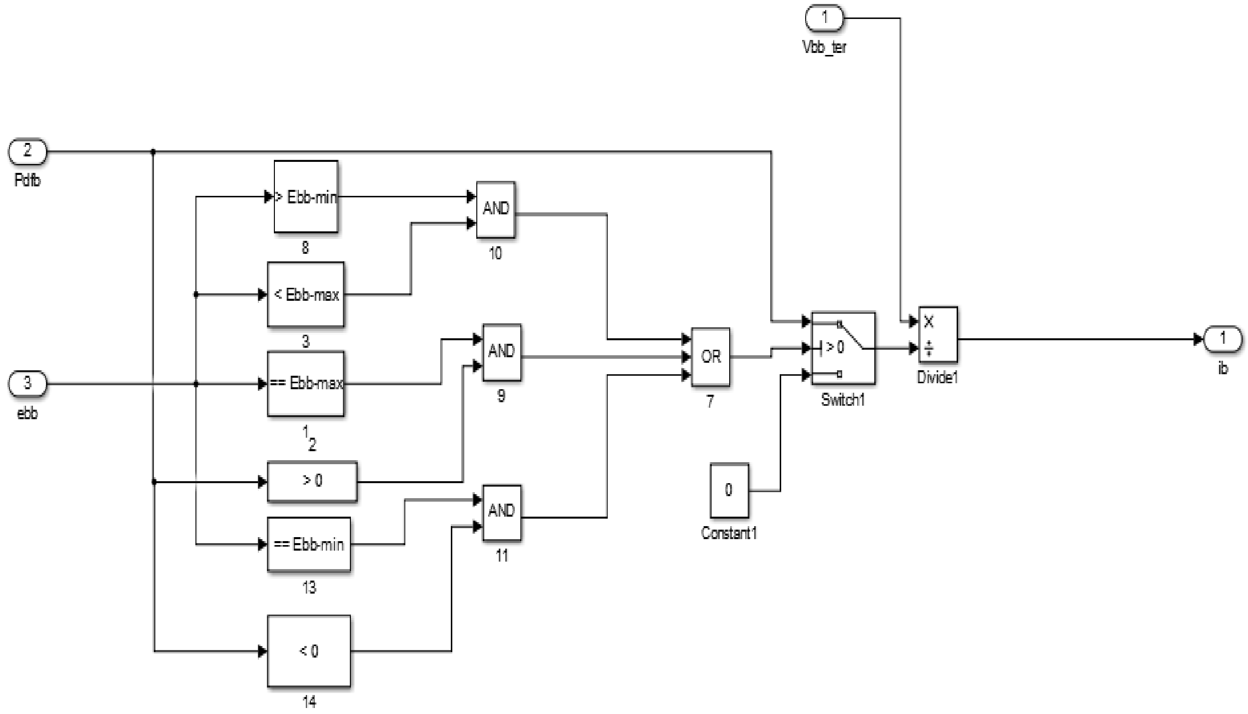

Figure 3.2: control mechanism of battery charging and discharging

Considering the electrical circuit model given by figure 3.1 and the above control mechanism of battery charging and discharging, the simulation model of the rechargeable battery designed by MATLAB Simulink blocks is given by the figure below:

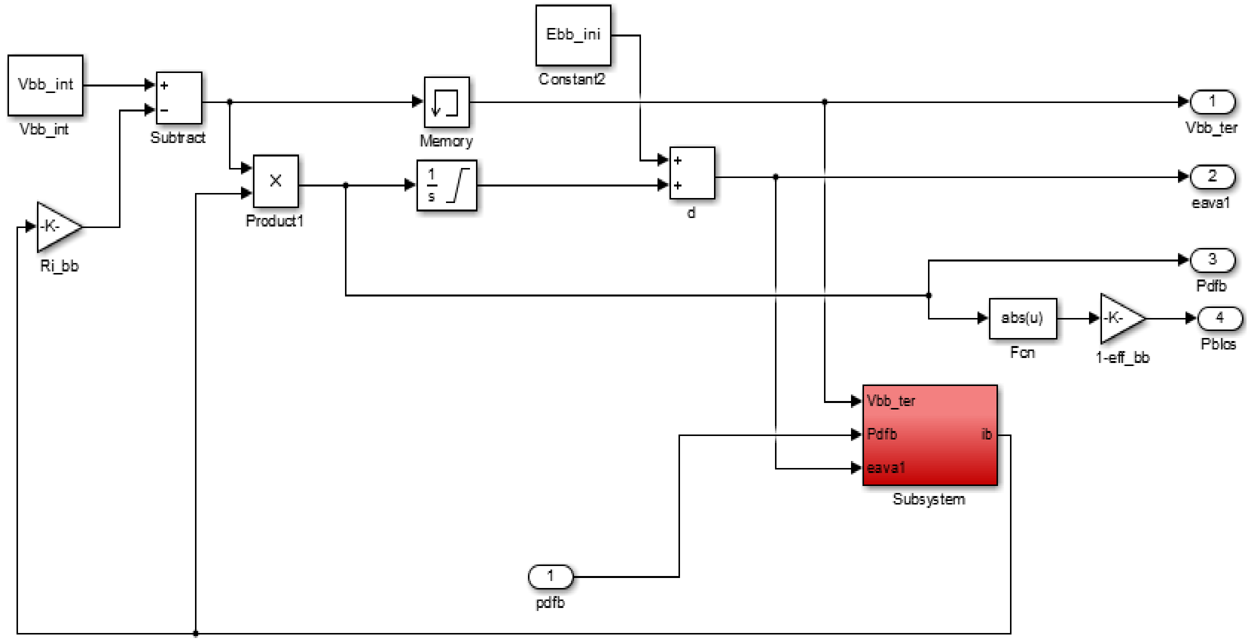

Figure 3.3: Battery bank MATLAB Simulink model

3.3 Management Strategies of Power and Modeling

For the proposed hybrid power system the energy sources (PV-arrays and Genset) and battery bank assist one another to provide sustainable energy. In other hands, the Genset is assisted from the renewable energy source and battery bank in different methods. These different methods of assistance are called power management strategies. Under this portion, different sorts of power management strategies are presented and for every power management strategy, mathematical modeling, sizing of system elements, Simulink modeling are generated. Then after, the Simulink model is simulated and the result is discussed for each power management strategy.

The following power management strategies are considered for this thesis project:

1. The only Energy Source is PV-panels Supported by battery bank (OESPV)

2. Only the Diesel Generator supply the load demand (ODG)

3. Genset supplies the average power whenever there is power demand (GAPVB)

3.3.1 PV-panels supply the load with battery bank (OESPV)

In this power management strategy scenario, Genset does not contribute any supply, the only power source is PV-arrays. The battery bank charges or discharges depending on the supply from the PV-arrays and the demand. The battery bank is supposed to charge when supply power from the energy resource is greater than the demand and discharges whenever the load demand exceeds the supply within the limit capacity.

3.3.2 Mathematical Modeling of OESPV power management strategy

Under this power management strategy scenario, PV-panels supply the power and the battery bank charges or discharges depends on the supply power and the demand load. Here, the mathematical equation includes power balance between the two sides (supply and demand), limits of energy storing, charging power and discharging power. The power balance and the limits of energy storing of battery bank are given as:

$P_{pv(t)} + P_{bb(t)} = P_{load(t)}$ and

$E_{bb\_min} < E_{bb(t)} < E_{bb\_max}$ (3.8)

When the supply exceeds the demand, the battery bank is charged by the surplus power from the energy source, PV-panels and the battery bank should not be charged beyond the upper limit capacity of the battery. The charging power (P_{char}) can be defined as:

$P_{pv(t)} > P_{load(t)}$

$P_{pv(t)} = P_{char} + P_{load(t)}$

$P_{pv(t)} - P_{load(t)} = P_{char}$ and (3.9)

$E_{bb\ (t)} < E_{bb\_max}$

In this condition, the battery bank charges and thus, the energy that is stored ($E_{bb\_stor}(t)$) in the battery bank is defined as:

$E_{bb\_stor}(t)=E_{bb\_ini}(t)-E_{bb}(t)$ and (3.10)

$E_{bb\_stor}(t)=\int P_{bb\_stor}(t)dt$

During the power demand is greater than the supply, the battery bank discharges so as to support the energy source, PV-panels and the battery bank is expected not to discharge below the low limit capacity. The discharge power can be defined as:

$P_{pv(t)} < P_{load(t)}$

$P_{pv(t)} + P_{bb(t)} = P_{load(t)}$

$P_{bb(t)} = P_{load(t)} - P_{pv(t)}$ and (3.11)

$E_{bb(t)} > E_{bb\_min}$

In this situation, the storage device discharges and it supplies energy to the load. This drawn energy from the battery can be given as:

$E_{bb\_sup}(t)=E_{bb\_ini}(t)-E_{bb}(t)$ and (3.12)

$E_{bb\_sup}(t)=\int P_{bb}(t)dt$

There are losses associated with convertor (DC/DC) ($P_{dd\_loss}(t)$)and internal resistance of battery bank $P_{blos}(t)$ that are considered when the power is referred to DC-bus. These losses are given as:

$P_{blos}(t)=P_{dfb}(t)(1-\eta_{bb})$ and (3.13)

$P_{dd\_loss}(t)=N_{pv}Irr(t)A_{pv}\eta_{pv}(1-\eta_{dd})$

3.3.3 System elements sizing of OESPV power management strategy

Under this scenario, the PV-arrays and the battery bank should supply the required power demand, the peak power as well as the instantaneous power. The elements that are expected to be sized in this power management strategy are PV-arrays and battery bank. The battery bank is sized in section 3.3 based on the load profile taken in this paper and its capacity is 2.08MW. When the PV-arrays are sized, it must meet the daily energy demand. Therefore, to determine the number of PV-arrays those supply at least the daily energy demand; we take the daily energy demand equal to the daily energy obtained from PV-arrays. This can be determined as:

$N_{pv}E_{pv\_panel} = E_{daily\_load}$ and

$$Npv = \frac{\int_0^T Pload(t)dt}{\int_0^T Ppv\_panel(t)dt} \qquad (3.14)$$

In the last sections, the total power load per day and the power generated from a PV-panel are given how to be calculated and their values are given at appendix. Therefore, the numbers of PV-panels that can meet the daily energy demand are calculated using the above equation, the daily load demands and the power obtained from one PV-panel. Thus, the numbers of the PV-panels in this power management strategy are 637 for the load considered in this paper.

The capacity of battery bank is discussed in previous section and it is given below as.

$$\text{Battery capacity, BC}=\frac{\text{Edaily\_load\_demand}}{\eta\text{bb}}\frac{\text{DOA}}{\text{DOD}}\quad[\text{Wh}] \qquad (3.15)$$

3.3.4 Simulink modeling of OESPV power management strategy

Depending on the equations (3.8), (3.9), (3.10), (3.11), (3.12), (3.13), (3.14) discussed above and the battery bank Simulink discussed in section 3.2.1, the simulation model of OESPV power management strategy is designed in Figure 3.4 below which includes the Simulink model of battery bank discussed by Figure 3.2 and Figure 3.3.

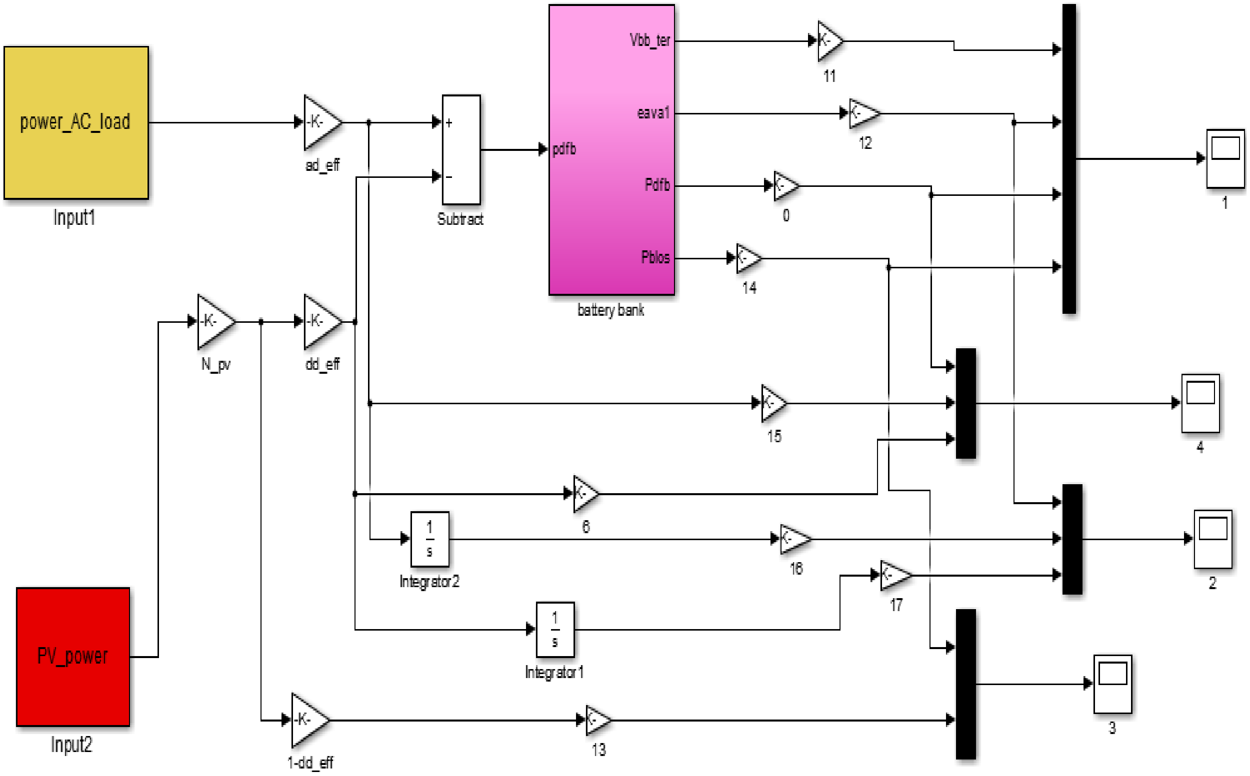

Figure 3.4: Simulink model of OESPV power management strategy

As it is observed from the Figure 3.4, the data inputs (power demand and the power obtained from PV-panel) are referred to DC-bus. The power demand is multiplied by AC/DC convertor efficiency and the solar power is multiplied by DC/DC convertor efficiency. The input power obtained from solar irradiation is multiplied by N-pv panels to meet the load demand. Since there are losses when the input powers are referred to DC-bus, the DC/DC and AC/DC losses are considered in addition to the battery loss.

3.3.5 Only the diesel generator supply the load demand (ODG) power management strategy

In this power management strategy scenario, the only one energy source is Genset. Here, the PV-arrays are not supposed to assist the diesel generator. The Genset supplies the load demand according to the means of the control model. If the load demand is less than or equal to the peak power of the Genset, the diesel generator supplies the demand. However, if the load demand exceeds the peak power of the generator, the entire load demands can't be supplied via the Genset, only it supplies the peak power. Under this power management strategy scenario, battery bank is required for starting and stopping times of the Genset. Since the Genset has a delay to supply energy during its staring time and it also delays when it stops. Thus, if there is battery bank, it can provide the load demand at initial time and stores the energy at stopping time.

3.3.6 Mathematical modeling of ODG power management strategy

The Genset supplies the load demand if the load demand is within limits of the genset power. Here, the mathematical modeling comprises the power balance between the supply and the demand, and the Genset control limits.

The power balance is defined as:

$$P_{supply} = P_{demand} \quad \text{and} \tag{3.16}$$

$$P_{dg(t)} = P_{load(t)}$$

The Genset control can be given as:

$$P_{dg(t)} = \begin{cases} \mathrm{Pload(t)}, 0 < \mathrm{Pload(t)} < \mathrm{Pl-max} \\ \mathrm{Pdg-max}, \mathrm{Pload(t)} > \mathrm{Pl-max} \\ 0, \mathrm{otherwise} \end{cases} \tag{3.17}$$

3.3.7 System elements sizing of ODG power management strategy

In this condition, the diesel generator is only supposed to supply the load. The Genset sizing is based on the maximum load power in such a way that the only Genset is able to meet the load demand. The sizing of the Generator set is defined as:

$$P_{dg\_max} = P_{l\_max} \tag{3.18}$$

As it can be observed from load profile Figure, the peak power value of the load demand profile is 105.3kW so that the Genset should meet this power, 105.3kW.

3.3.8 Simulink modeling of ODG power management strategy

Based on the detail Simulink of battery bank discussed in section 3.2.1, Simulink model of Genset control given in Figure 3.5, Simulink model of fuel consumption of Genset given in Figure 3.6, equations of mathematical and sizing, the Simulation Model of ODG power management strategy is shown in Figure 3.7.

Under this power management strategy scenario, the battery bank is used only at starting and stopping time of the Genset since the Genset has a delay in both time (starting and stopping). During starting time the battery bank supplies until the Genset starts supplying and at stopping time the battery bank stores energy.

Based on the mathematical modeling of Genset control discussed in this section (equation 3.17), its Simulink block is given below in figure3.5.

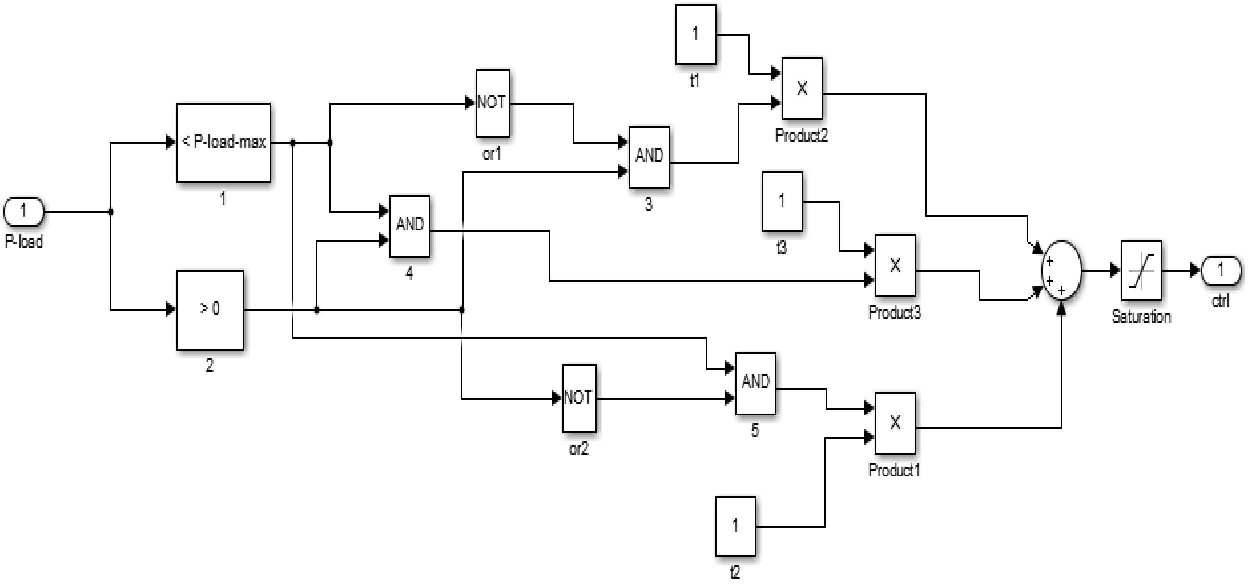

Figure 3.5: Simulink model of Genset control for ODG power management strategy

The fuel consumption of Genset given in Figure 3.6, gives the fuel consumed at every time whenever the Genset delivers power to the load and it sums up all the consumed fuel at the end of the day to give the total daily utilized fuel.

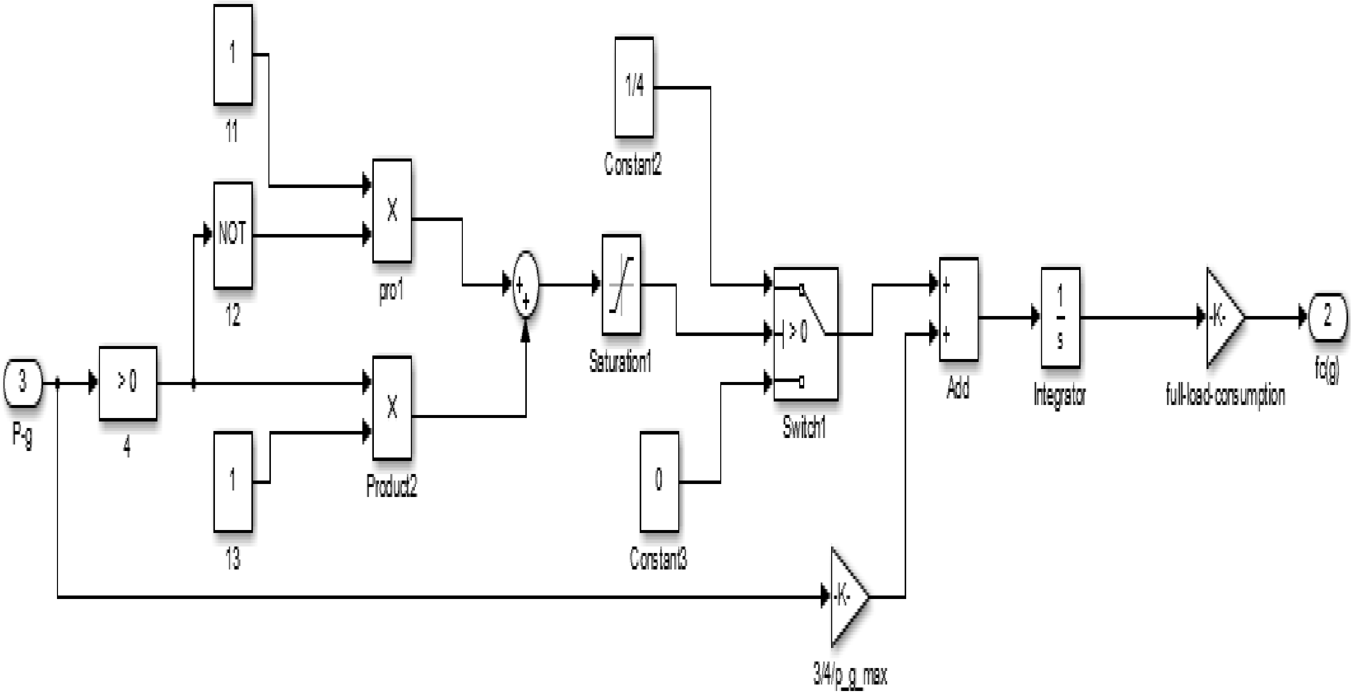

Figure 3.6: Simulink model of fuel consumption of Genset for ODG power management strategy

The Simulation Model of ODG power management strategy is shown in Figure 3.7 below. As it is seen from the figure, the system has three sub-systems: fuel consumption of Genset, Genset control and battery bank sub-systems.

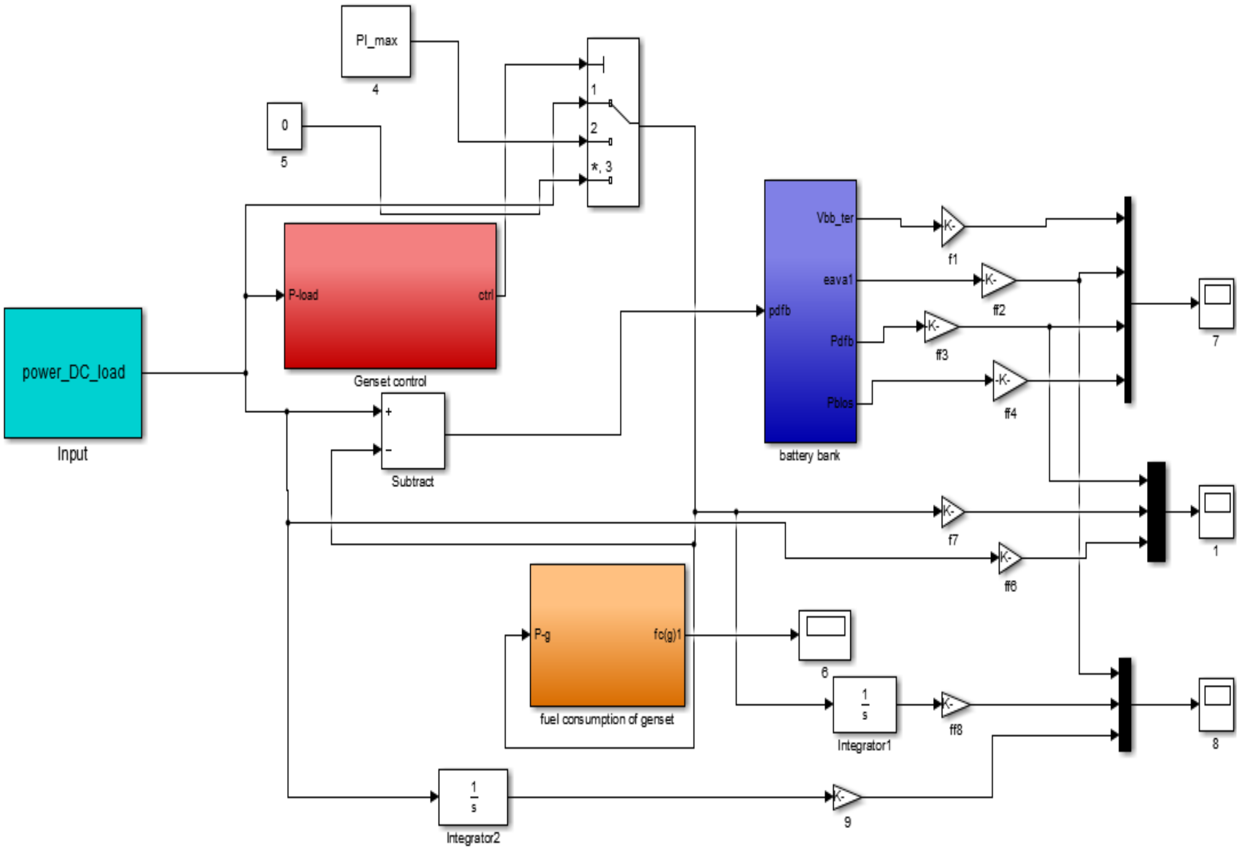

Figure 3.7: MATLAB/Simulink Model of ODG power management strategy

3.3.9 Genset supplies the average power whenever there is power demand (GAPVB)

In this power management strategy, the Genset is supposed to supply the average power of the demand whenever there is load and the remaining portion of the demand is provided by PV-panel and battery bank. The battery bank charges/discharges depends on the supply and the demand power, that is, whenever the supply exceeds the demand it charges from either the PV-panel or Genset or from both of them and it supplies/discharges when the demand is greater than the supply.

3.3.10 Mathematical modeling of GAPVB

In this power management strategy of the hybrid power system, the Genset is expected to provide the average power of the load whenever there is a demand and the remaining part of the load is supplied by PV-panel and battery bank. Here, the mathematical modeling comprises different equations that show power balance (between supply and demand), battery charging and discharging and control of Genset. Power balance, Genset control and energy equation for battery charging/ discharging equations are given below.

$P_{pv(t)} + P_{dg(t)} + P_{bb(t)} = P\_{load(t)}$

$$P_{dg(t)} = \begin{cases} P\_load\_ave \;, P\_load(t) > 0 \\ 0, otherwise \end{cases} \quad \text{and} \qquad (3.19)$$

$E_{bb\_min} < E_{bb(t)} < E_{bb\_max}$

Within the limit capacity, minimum and maximum the battery charges or discharges depending up on the supply and demand power. When the supply power exceeds the demand power, the battery charges and the energy stored in the battery is less than the maximum/peak capacity of the battery. The equation which describes for these conditions is given bellow.

$P_{supply} > P_{demand}$

$P_{pv(t)} + P_{dg(t)} = P\_{load(t)} + P_{bb(t)}$

$P_{char(t)} = P_{pv(t)} + P_{dg(t)} - P\_{load(t)}$ and (3.20)

$E_{bb(t)} < E_{bb\_max}$

When the power demand exceeds the power supply, the battery discharges its stored energy and the energy stored in the battery is greater than the minimum energy capacity of the battery.

$P_{supply} < P_{demand}$

$P_{pv(t)} + P_{dg(t)} + P_{bb(t)} = P\_{load(t)}$

$P_{bb(t)} = P\_{load(t)} - (P_{pv(t)} + P_{g(t)})$ and (3.21)

$E_{bb(t)} > E_{bbmin}$

3.3.11 System elements sizing of GAPVB power management strategy

The battery bank is already discussed in detail and sized in section 3.2.1. The value of battery bank capacity, obtained based on the load demand considered in this paper is 2.08MW. Under this energy management strategy, the Genset is supposed to supply average load demand. For this power management strategy, GAPVB, Size of the Genset is calculated based on the equation (3.19) and the Genset peak nominal power size is given by:

$$P_{\_dg\_max} = P_{\_dg\_aver} \qquad (3.22)$$

The numbers of the PV-panels are sized properly based on the daily energy balance equation and it is defined as:

$$N_{pv}E_{pv\text{-}panel} + E_{dg} = E_{daily\text{-}load} \qquad \text{and} \qquad (3.23)$$

$$N_{pv} = \frac{\int_0^T P\_load(t)dt - \int_0^T Pg(t)dt}{\int_0^T Ppv\_panel(t)\,dt}$$

Based on the above equations given for sizing, the numbers of the PV-panels for this power management strategy are 240.

3.3.12 Simulink modeling of GAPVB power management strategy

Taking the three sub-systems (fuel consumption of Genset, Genset control and battery bank sub-systems), equations of mathematical and sizing (3.12), (3.13), (3.19), (3.20), (3.21), (3.22) and (3.23), the Simulink Model of GAPVB power management strategy is shown below in Figure 3.9.

Detail of sub-system of Genset control for GAPVB power management strategy is given below by Figure 3.8.

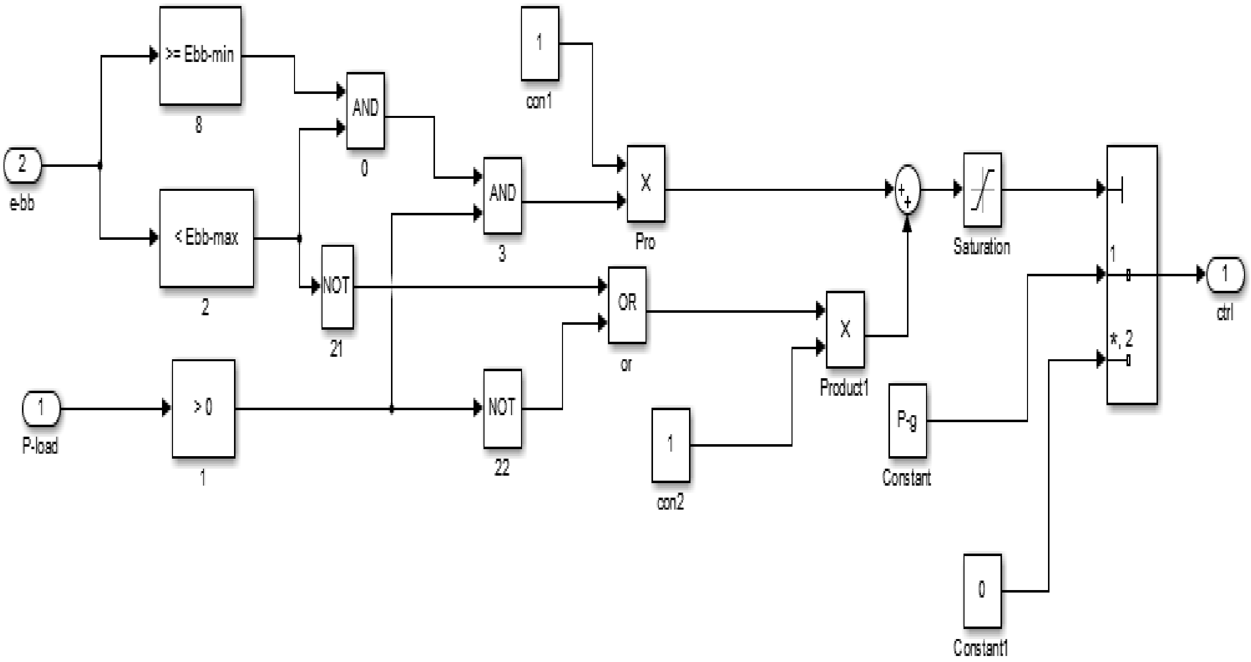

Figure 3.8: Simulink Model of Genset control for GAPVB power management strategy

Here, the Genset is expected to supply average power demand when there is power demand and the battery bank capacity becomes within its limits. The power genset becomes zero when the there is no load demand and the energy of battery bank is at its peak value.

The Simulink Model of GAPVB power management strategy is shown below in Figure 3.9.

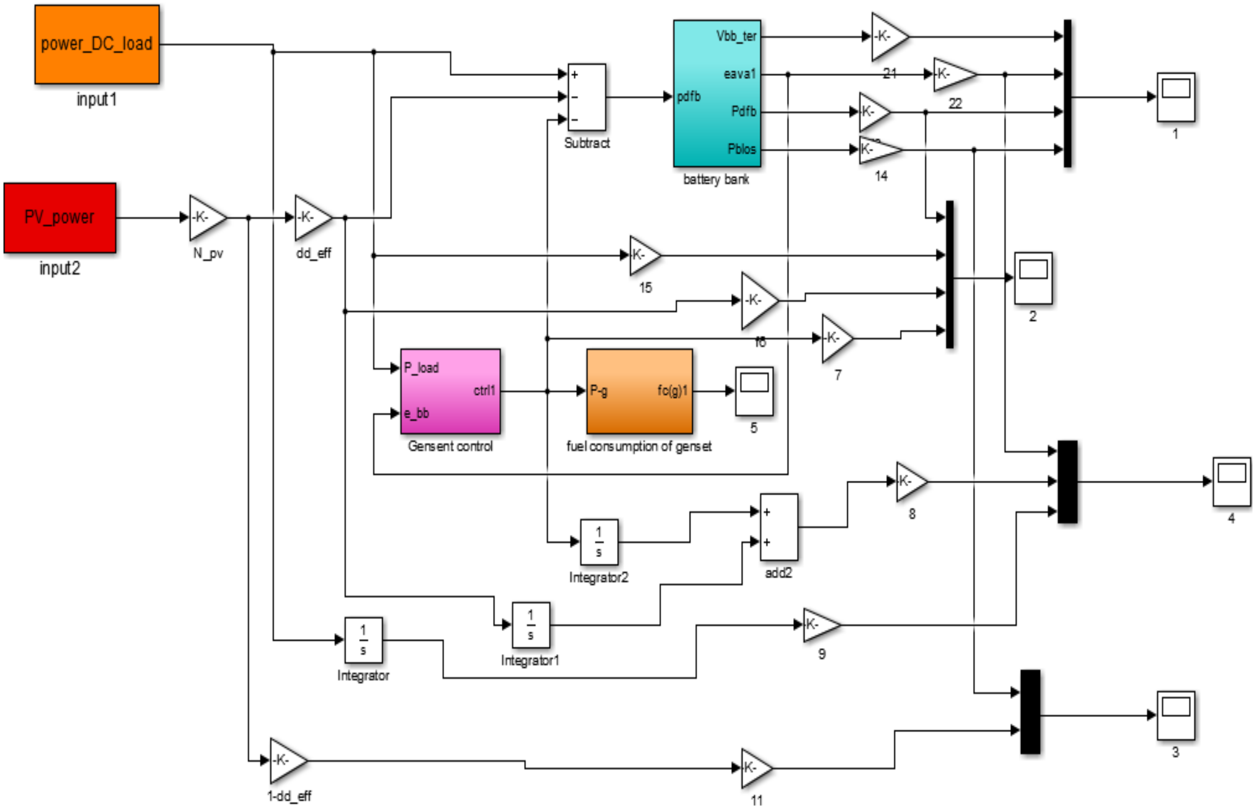

Figure 3.9: Simulink Model of GAPVB power management strategy

As it is observed from the figure above, the system has two inputs from solar irradiation and load demand. The losses of the convertors (DC/DC and AC/DC) and battery bank are taken into account.

3.4 Optimization of System

From the proposed topologies, the best configuration has been selected in section 3.2.1 depending on the power delivered to the load. Besides, for the different sorts of power management strategies considered in this paper, sizing of the system elements, mathematical modeling, Simulink modeling are discussed for each power management under section 3.3. To select the best optimal system, environmental effects, capital and lifetime costs and lifetime of each system components are taken in consideration. Those criteria are discussed for every power management strategy to select the most optimal power management strategy. The environmental effects are associated with the fuel consumptions and the comparison of the fuel consumption of each power management strategy is discussed under chapter-4 in section 4.31. In addition to the environmental effects, it is better to analyze the costs of the system so that the cost analysis is discussed under section 3.4.2 First the initial capital costs of each power management strategy are analyzed and compared using graph. Then after, the costs of lifetime of each system is also discussed and compared. Finally, total summation of these costs are taken and discussed, and then some important points are concluded.

3.4.1 Issues related to environmental effects

Nowadays, environmental issues are the main concern as the greenhouse gasses are warming our earth. The main pollutants such as carbon dioxide, methane are emitted when fossil fuels are burnt. At remote areas where electricity has not reached yet, diesel generator is a main source of electricity. As a result, it has a negative impact on the environment. This can be reduced by using hybrid power systems that comprises Genset, renewable energy resources and battery bank. During daytime the Genset can be replaced by renewable energy resources and during nighttime the battery can assist it. Therefore, hybrid systems have more advantages over conventional power system.

3.4.2 Fuel consumption

As it can be seen from Simulink results, the power shares Gensent, battery bank and PV-panel are different for each power management strategies at every instant of time. Thus, the fuel consumption of each system is different at each cycle as the power delivers to the load from the diesel generator is different. The diesel generator supplies power based on the genset control design for each system so that the fuel consumption of the systems is different.

As it has been discussed under chapter-2, the fuel consumption of the diesel generator is dependent on power output. The relationship between the fuel consumption of the diesel generator and the output power has been discussed under chapter two and it is given by Figure2.1. Although there is no power generated from the Genset, about 25% of the fuel amount is consumed, as it can be observed from that figure (Patel, 2006) (Weldemariam, 2010) .

The relative fuel consumption of the Genset is dependent on the output power of the Genset at any time ($P_{dg}(t)$) which is given as a function of nominal peak power of Genset($_{Pdg\text{-}nom\text{-}peak}$). And the relative fuel consumption ($fc_{relative}$) of the Genset is given as (Patel, 2006):

$$fc_{relative} = \frac{1}{4} + \frac{3}{4}\ Prelative(t) \tag{3.24}$$

Where, $P_{relative}(t) = \frac{Pdg(t)}{Pdg-nom-peak}$

The nominal peak power of Genset is different for each power management strategy and it is defined for every system power management strategy. As a result, the fuel consumption is different for all system power management strategy since it depends up on the output power. The relative fuel consumption is obtained by above equation, equation3.24.

The fuel consumption at every instant of time and daily fuel consumption can be calculated by using the following formula (Patel, 2006):

When the relative fuel consumption is multiplied by fuel consumption consumed at nominal peak power of Generator (fuel consumption of nominal) gives fuel consumption at every instant of time. This can be expressed mathematically as:

$$fc(t) = f_{c\text{-full load}} \times fc_{relative,}\ \text{(liter/hours)} \tag{3.25}$$

The daily fuel consumption (fuel consumption/ every cycle) can be obtained by combining the above two equations (3.24 and 3.25).

$$\text{fc-daily} = \frac{1}{T}\int_0^T fc(t)dt$$

$$\text{fc-daily} = \frac{fc-full\ load}{T}\int_0^T (1/4 + 3/4\ \ (Pg(t))/(Pg - nom - peak))\ dt, (Litere) \tag{3.26}$$

The fuel consumption becomes high when the Genset source considered the only energy source to the load demand. The relative fuel consumption at every instant of time and daily fuel consumption of each power management strategy is obtained by the above equations and it is discussed in detail under chapter four.

3.4.3 Cost analysis

Different sorts of hybrid power systems can be designed for remote areas where there is no access to electricity irrespective of their expenses but costs matter the acceptance of the systems for the consumers. To be cost effective, the system should be sized properly so that it becomes acceptable. Generally, the lifetime costs of the system comprises capital costs (CC), operational and maintenance costs (OMC), fuel costs (FC) and replacement costs (RC). These lifetime costs of the systems can be different from system to system. Some of them can have high initial costs or operational and maintenance costs (OMC), fuel costs (FC) and replacement costs (RC) depending on the type of the system.

The lifetime costs of the system considered here are investigated into two sections. The first section has dealt with capital costs which consist of sum of the investments of each component of the system, packaging, transportation, installation etc. The second portion has included lifetime costs of the systems and components of the system which is named as costs of variable (VC). These costs that are categorized into two parts are analyzed separately in detail then after they are compared for different systems (power management strategies). To differentiate the best cost effective system, sum of both costs calculated in two parts are taken. Therefore, this summation of costs gives the lifetime cost of the system and it enables for selection of the most effective cost system.

The analyses of the two parts of costs are discussed in detail below:

3.4.4 Capital costs of the system

It is once expenses (or fixed) that includes sum of the investments of each component of the system, packaging, transportation, installation etc. that considered single fee at the initial of the project.

For different systems that involve PV-panel, fueled generator, wind generator etc., the lifecycle costs (initial costs, operation and maintenance costs, replacement costs and fuel costs) are different. For some systems the initial costs can be more whereas for other systems it could be less and the same to operation and maintenance costs, replacement costs and fuel costs.

The total initial/capital cost of the proposed system in this paper is given as:

$$CC = CC_{pv} + CC_{g} + CC_{bb} + CC_{con} \qquad (3.27)$$

Where, CC= total cost of the system

CC_{pv} = total cost of the PV-panel

CC_{dg} = total cost of the Genset

CC_{bb} = total cost of the battery bank

CC_{con}= total cost of the convertors

3.4.5 Capital costs each subsystem of the system

Capital cost of PV-array:

This cost includes costs of the total numbers of PV-panels, engineering, packaging, transportation, installation, balance etc.

This cost can be calculated using the following formula (Kolhe, Kolhe, & Joshi, 2002) (Weldemariam, 2010).

$CC_{pv} = (1+K_{pv})N_{pv}C$

Where,

C= cost of a single PV-panel

K_{pv}=costs related to engineering, packaging, transportation, installation, balance etc. (additional costs) N_{pv} = number of PV-arrays

This formula can be defined/ simplified as:

$$CC_{pv} = (1+K_{pv})N_{pv}\frac{price}{watt}(\mathrm{Wp/panel}) \qquad (3.28)$$

This price per watt is the investment cost of the PV-array that depends on the peak power rated of the PV-panel.

By the same way the capital costs of the battery bank, power convertors and Genset can be defined as:

$$CC_{dg} = (1+K_g)N_{dg}\frac{price}{Genset} \qquad (3.29)$$

$$CC_{bb} = (1+K_{bb})\frac{price}{Ah}\frac{BC}{Vsys} \qquad (3.30)$$

$$CC_{con} = (1+K_{conv})\frac{price}{watt}(\mathrm{Wp/conv}) \qquad (3.31)$$

Where,

K_{dg}, K_{bb}, K_{conv} stand for costs related to engineering, packaging, transportation, installation, balance etc. (additional costs) of genset, battery bank and convertors respectively.

N_{dg}= the numbers of Genset with selected capacity

BC= battery capacity in Wh

Wp/conv= peak watt of convertor

Therefore, the total capital costs of the system can be obtained by adding the costs of the subsystems. By combining the above equations (3.30 to 3.33), the total cost becomes:

$$\begin{aligned} CC_{sys} = \; & (1+K_{pv})N_{pv}\frac{price}{watt}(Wp/panel) \; + \\ & (1+K_{dg})N_{dg}\frac{price}{Genset} \; + \\ & (1+K_{bb})\,\frac{price}{Ah}\,\frac{BC}{Vsys} \; + \\ & (1+K_{conv})\,\frac{price}{watt}(Wp/conv) \end{aligned} \qquad (3.32)$$

Based on this formula the total initial investment costs of the different power management strategies are calculated and have been compared to select the most cost effective system and main points are discussed. The detail values of these capital costs are given in Appendix-C (C4).

3.4.2.2 Variable costs of the system (VC)

These costs include the expense after the initial costs in overall the lifetime span of the system and components of the system. These expenses are: costs of present value of operation and maintenance (OMC), costs of fuel (FC), and costs of present value of replacement costs (RC) (Kolhe, Kolhe, & Joshi, 2002) (Weldemariam, 2010). And this can be calculated as:

$$VC=OMC+FC+RC \qquad (3.33)$$

Operation and maintenance (OMC) includes the sum of the expenses timely scheduled for operation and maintenance such as insurance, salary of operators, maintenance, inspections, taxes, recurring costs etc. This cost can be expressed as a percentage (say p %) of the initial capital cost.

The hybrid power system includes generators that are diesel fueled so that there is annual expense for the consumed fuel. This total annual cost of fuel is termed as costs of fuel (FC).

All components have different lifetimes so that for those which have short lifetime replacement of equipment and/or components is crucial. For instance, battery bank and generators may not last 20 years, lifetime of the system. These subsystems can be replaced one or twice within the lifetime of the system. The total cost of these replacements and repairs within the life of the hybrid power system is called replacement costs.

Formula that relate present, annual, and future values of money:

The value of money at present and futures cannot have the same worth so that it is important to relate them. The money at present has more worth than at futures. The future value of the money discounts at annual interest rate (i).

To relate the present and the future values at annual interest rate (i), life span of the system (N), amount present value (p) and amount future value, the equation is given as (Francis M. Vanek, 2008) (Kolhe, Kolhe, & Joshi, 2002):

$$\mathrm{P}=\frac{F}{(1+i)^{N}} \qquad (3.34)$$

The present (uniform present worth) value can also be calculated by using the following formula, given that annuity of equal size (A) over a life span of the system (N) (Kolhe, Kolhe, & Joshi, 2002) (Francis M. Vanek, 2008).

$$\mathrm{P}=\frac{A(1+i)^{N}-1}{i(1+i)^{N}} \qquad (3.35)$$

The modified formula for the present (uniform present worth) value can be expressed as at annuity of equal size (A) with escalation rate (e_r) over a life span of the system (N) at discount rate (i) (Kolhe, Kolhe, & Joshi, 2002) (Weldemariam, 2010).

$$\mathrm{P}=\mathrm{A}\left(\frac{1+er}{i-er}\right)\left[1-\left(\frac{1+er}{1+i}\right)^{N}\right] \qquad (3.36)$$

This equation (3.36) is used to calculate the lifetime costs of each subsystem so that it is used below for all subsystems.

i.PV-array subsystem

The initial cost of PV-panel already discussed it includes costs of the total numbers of PV-panels, engineering, packaging, transportation, installation, balance etc. PV-array does not need any replacement within the system lifetime (20 years) so that the variable cost of this subsystem comprises only the operation and maintenance costs (OMC). This cost is expressed as a percentage (say p %) of the initial capital cost (Kolhe, Kolhe, & Joshi, 2002).

When every operating cost is escalated at a rate of e_r and at discount rate (i), then the variable cost of the subsystem (VC), PV-array at life span of the system (N) is given as:

$$VC_{pv} = OMC_{pv} = \begin{cases} OMC0pv((1+re)/(i-er))[1-((1+er)/(1+i))^{\wedge}N\ ] \\ OMC0\mathrm{pv} * \mathrm{N}, \mathrm{i} = \mathrm{er} \end{cases}, \ i \neq e_r \qquad (3.37)$$

Where, OMC_{0pv} is considered as P% of the initial cost.

ii.Genset subsystem

The total cost of Genset subsystem includes fuel costs (FC), operation and maintenance costs (OMC) and replacement costs (RC) in addition to the capital costs discussed in the last section. The variable cost of the Genset subsystem can be given as (Kolhe, Kolhe, & Joshi, 2002) (Weldemariam, 2010):

$$VC_{dg} = OMC_{dg} + RC_{dg} + FC_{dg} \qquad (3.38)$$

$$OMC_{dg} = OMC_{annual}\left(\frac{1+er}{i-er}\right)\left[1-\left(\frac{1+er}{1+i}\right)^{N}\right], \qquad i \neq e_r \qquad (3.39)$$

$$RC_g = \sum_{i=1}^{x} IC\left(\frac{1+er}{1+i}\right)^{ia}, \quad a = \frac{N}{x+1} \qquad (3.40)$$

$$FC_{dg} = FC_{annual}\left[\left(\frac{1+fer}{i-fer}\right)\left(1-\left(\frac{1+fer}{1+i}\right)^{N}\right)\right], \quad f_{er} \neq i \qquad (3.41)$$

Where,

x and a = stand for number of replacements of the lifetime of the whole system and lifetime of every replacement

f_{er} = stand for fuel escalation rate

IC= is the present day cost of item

OMC_{annual} is cost of the operation and maintenance of the Genset system at escalate rate r_e at annual discount rate (i) which is calculated as p% of the capital cost (Kolhe, Kolhe, & Joshi, 2002) (Otasowie, 2014).

The fuel annual cost, FC_{annual} is summation of the daily fuel consumption cost and it can be given as:

$$FC_{annual} = D_{year} * fc_{daily} * fuel_{price} \tag{3.42}$$

Where, D_{year} = number of days in a year that the Genset runs

fc_{daily} = daily fuel consumption in liter/day

$fuel_{price}$= fuel price in dollar/liter

iii) Variable costs of battery bank (VC)

The variable cost of the battery bank consists of only the replacement costs (RC) and operation and maintenance costs (OMC)whereas the total (lifetime) costs of the battery bank is the summation of the initial investment costs (CC), maintenance costs (OMC) and the variable costs (VC). The replacement cost of battery bank subsystem depends on the number of replacements of the battery bank which occurs within the lifetime of the entire system. The variable costs (VC) (the replacement costs (RC) and operation and maintenance costs (OMC)) of the battery bank subsystem can be calculated by the following formula over the lifetime of the system (N), escalate rate (r_e) , and annual discount rate (i) (Kolhe, Kolhe, & Joshi, 2002), (Weldemariam, 2010).

$$OMC_{bb} = OMC_{annual}\left[\left(\frac{1+re}{i-re}\right)\left(1-\left(\frac{1+re}{1+i}\right)^{N}\right)\right], \quad r_e \neq i \tag{3.43}$$

$$RC_{bb} = \sum_{i}^{k} CCbb\left(\frac{1+re}{i+1}\right)^{ib}, \; b=\frac{N}{k+1} \tag{3.44}$$

Where, k = represents for the number of replacements

b= represents for lifetime of every replacement

And the annual maintenance and operation cost (OMC_{annual}) of the battery bank subsystem is calculated as percentage (say p %) of the initial cost value.

iv) Variable costs of power convertors

The lifetime of the power convertors is as the same as the life time of the system so that the variable cost comprises only the operation and maintenance cost (OMC). This can be calculated as:

$$OMC_{con} = OMC_{annual}\left[\left(\frac{1+re}{i-re}\right)\left(1-\left(\frac{1+re}{1+i}\right)^{N}\right)\right], \quad r_e \neq i \tag{3.45}$$

The variable costs are calculated using the given above equations then the values are taken to compare the power management strategies using graph and the values are given at appendix-C (C5). From the graph results points are discussed and core ideas are taken that help to select the best system.

3.4.2.3 Life-cycle Costs of the system

Cost analysis of the system is used to determining the best cost effective system and comparing different sorts of energy management strategies so that it enables to select the most cost effective system. Life-cycle cost analysis (LCC) of hybrid power system comprises the initial investment costs (CC) and variable costs (VC) (costs of present value of operation and maintenance (OMC), costs of fuel (FC), and costs of present value of replacement costs).

Generally this Life-cycle cost analysis (LCC) of hybrid power system can be expressed as:

$$LCC_{sys} = CC_{sys} + OMC+FC+RC \tag{3.46}$$

For every subsystem the Life-cycle cost analysis (LCC) is given as:

PV-array subsystem:

$$LCC_{pv} = CC_{pv} + OMC_{pv} \tag{3.47}$$

Gensent subsystem:

$$LCC_{dg} = CC_{dg} + OMC_{dg} + RC_{dg} + FC_{dg} \tag{3.48}$$

Battery Bank:

$LCC_{bb}= CC_{bb}+OMC_{bb}+RC_{bb}$ (3.49)

Power Convertors:

$CC_{conv}=CC_{conv}+OMC_{conv}$ (3.50)

The total life-cycle costs are obtained using the above equations and the values are used to compare the different types of power management strategies considered in this paper. The comparison is given by Figure 4.18 at section 4.5.4. The result is discussed in detail and some points are concluded that enable to choose the most cost effective system.

CHAPTER 4. RESULTS AND DISCUSSION

4.1 Introduction

Under chapter-3, three different sorts of power management strategies (the only Energy Source is PV-panels Supported by battery bank (OESPV), only the Diesel Generator supply the load demand (ODG) and Genset supplies the average power whenever there is power demand (GAPVB)) are considered and discussed. Mathematical modeling is designed for every power management strategy based on the power balance in both sides (supply and demand), charging and discharging limits of battery bank and system elements sizing is considered as well. Then after, for all mathematical modeling of each power management strategy, MATLAB/Simulink models are designed. After that the Simulink models are simulated for all power management strategies. Then the simulation results are discussed in detail under this chapter based on the power sharing results, energy stored in the battery bank and the losses associated with the convertors and charging/discharging battery bank.

Environmental effects, capital cost and lifetime cost and lifetime of each system components are discussed under chapter-3 so as to select the best optimal system. The environmental effects are associated with the fuel consumption and the comparison of the fuel consumption of each power management strategy is presented under this chapter in section 4.3.1. In addition to that the life-cycle costs of the systems are discussed under section 3.4.2 and compared in this chapter to choose the best power management strategy. First the initial capital costs of each power management strategy are analyzed and compared using graph. Then after, costs of lifetime of each system are discussed and compared. Finally, summation of both costs are taken and discussed, and then some important points are concluded.

4.2 Comparison of Power Delivers of the Topologies

Here, two cases are taken into account to investigate the efficiencies (to determine power delivers to AC-load) of the three configurations (AC bus, DC bus and Mixed bus) in order to select the best topology. The powers deliver to the AC load directly (the power reaches to the load without be stored in the battery bank) and indirectly (after stored in the energy storage) from the three configurations are compared using graphs. The power outputs have been given by the figures below are calculated using the formula given by tables (Table 3.1 to Table 3.3). At the end, some points are discussed based on the comparison graphs then the best configuration is selected for the further study.

i)Case-a: Comparison of PV Power Consumption in the three Topologies

As it can be observed from Figure 2.3 to Figure 2.5, the losses of direct power consumption from PV-array are associated with DC/DC and DC/AC converters in the three topologies. But for indirect power consumption from PV-panel depends on the DC/DC converter, battery bank and DC/AC converter for DC bus and Mixed bus whereas for AC bus the power consumption loss is associated with DC/DC, DC/AC, AC/DC converters and energy storage.

The figure below, Figure4.1 shows the comparison of the power consumption (output) of PV-array for the three topologies (scenarios). The x-axis shows the power utilized directly from the PV-panel whereas the y-axis tells the total power consumed (directly and indirectly used) from the PV-array for the three scenarios. Here, the sum of the percentage of the power used directly and the power utilized indirectly is 100% that is if the power utilized directly is 20%, then the remaining part of the power (80%) is used indirectly. Efficiency values of the converters and battery bank considered in this thesis paper are given at Appendix-A (Guta, 2012) (Weldemariam, 2010) (M.S. Ismail).

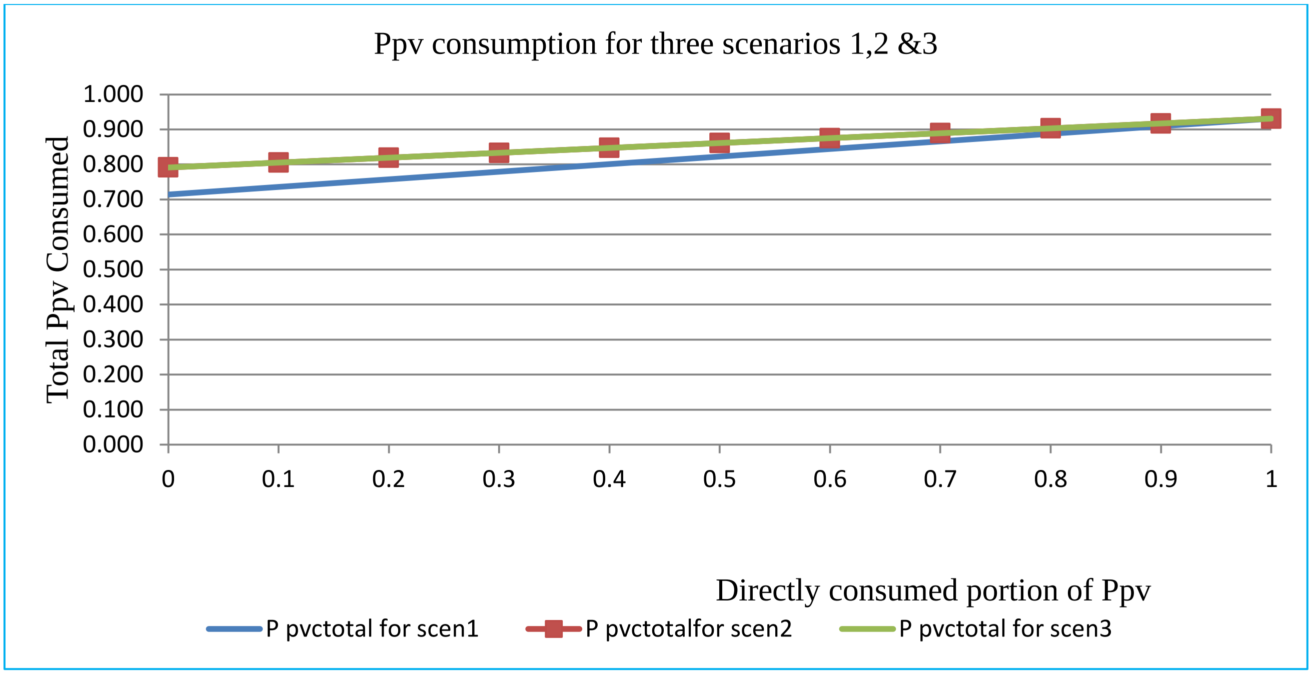

Figure 4.1: Comparison of power consumption of PV-panel directly and/or indirectly for scenarios1, 2 &3

As it can observed from the figure above, powers of topologies two and three are at the same level and the following points can be concluded

a) When the entire power generated from the PV-array is utilized indirectly (via the energy storage), topologies (scenarios two and three) have higher energy efficiency than that of topology one. Thus, scenarios two and three are preferable when the load demand is in the night time by storing the energy using energy storage to supply enough energy in the night time.

b) Some portion of the power generated is used directly and the remaining is indirectly (from small portion to less than 90% of the power from PV-array), still the output powers of the scenarios two and three have higher efficiency than that of scenario one. However, when the power is used directly is from around 90% to 100%, all topologies have almost the same energy efficiency.

c) Solar energy varies with times and seasons as a result storage energy is required in order to provide energy during the energy utilized directly from sun is not enough. Most of the energy demand in the rural areas is in the night time, therefore, when the sun is the only source of energy, energy storage is needed. Thus, from these three topologies, scenarios two and tree are preferable as topology one has low efficiency especially less than 90% of the generated power.

ii)Case-b: Comparison of Genset Power Consumption in the three Topologies.

The Genset supplies power when there is no enough power from PV-array and/or battery bank. Referring to Figure 2.3 to Figure 2.5, there are no direct power consumption losses from Genset source in AC bus and mixed bus configurations as the power losses associated with wires are ignored in this thesis but for DC bus layout there is power loss that depends on AC/DC and DC/AC converters. However, the indirect power consumption losses from Genset power source are associated with power electronic devices (AC/DC and DC/AC converters and energy storage) in the three configurations.

The graph below, Figure4.2 shows the comparison of the overall power (delivers directly and/or via the energy storage to AC load) consumed from the proposed scenarios. The x-axis shows the power used directly from the Genset whereas the y-axis tells the total power consumed (directly and indirectly used) from the Genset for the three scenarios.

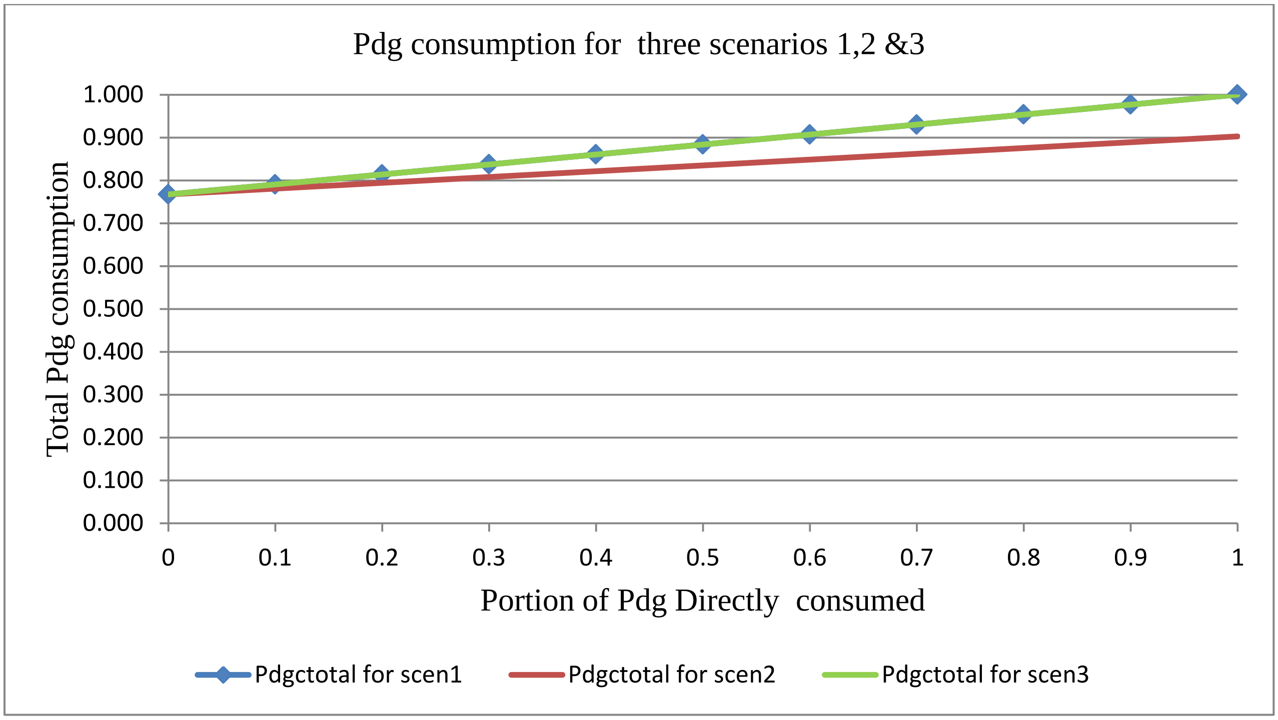

Figure 4.2: Comparison of power consumption of Genset directly and/or indirectly for scenarios1, 2 &3

As it can be observed from the graph above, the output powers of the generator at topologies one and three are at the same level and the following points can be deduced from the Figure: 4.2:

a) When all the power generated from the Genset is utilized indirectly (after it is stored in the battery), all the scenarios have the same efficiency but while some portion of the power is directly used and the remaining is utilized indirectly, scenarios one and three have the same and better efficiency than scenario two.

b) At a time all power generated from the Genset is directly utilized, the efficiency of power consumption of the scenario one and the scenario three still becomes the same and much better than that of scenario two. Since Genset is used as backup for PV-array and it can generate in the day time and night time, it is better when most of the portion of its power is consumed directly in order to reduce the size of the energy storage. As it can be observed from the above graph, Figure 4.2, scenario one and scenario three are preferable since they have better power efficiency.

The following main points could be concluded from the above results, discussion and the most efficient topology selected based on the results.

Depending on the above comparison of power consumption from the different energy sources when considered independently, best topologies are selected. For the PV-array when it is considered alone, scenarios two and scenarios three (DC bus and mixed bus) are preferable from the three proposed topologies (AC bus, DC bus and mixed bus). When Genset is only supposed to supply the required power to meet the load demand, scenarios one and scenarios three (AC bus and mixed bus) are preferable. As it is seen, scenario three is included in both cases. Thus, Mixed-coupled hybrid power system (mixed bus) has better power consumption efficiency in both cases so that it is selected for further study.

From these results and discussion, the first null hypothesis is rejected since all the proposed topologies have different efficiency.

4.3 Load Profile and Solar Irradiation

The load demand and the solar irradiation characters considered here are presented in sections 4.3.1 and 4.3.2 respectively. The output power that obtained from renewable resource, solar PV-panel is calculated using irradiation data; area of PV-panel and overall efficiency of the PV-panel in section 4.3.3 and the system elements are sized based on the management strategies of power considered in this paper as well as the supply and demand.

4.3.1 Load Profile

In rural areas in Ethiopia, the lighting load accounts for large portion of the load demand. Most of the appliances that the people always use take AC-power so that AC-load profile is considered in this study. The load demand in this paper is for typical rural village in remote area located in Tsegede Wereda, Tigray region, Ethiopia which is called Ketema Niguss. It is located far away from Addis Ababa by 15554km via Mekelle Town. The number of population at this place is 7355 and the households are 2782. Even if the load demand of household takes high portion of the total daily demand in this area, the daily demand includes commercial load, service centers (health centers, schools, church, and mosque) and deferrable loads and their values are given at appendix-B (B1). The daily demand curve at AC-bus is given in the figure below, Figure 4.3 and this daily demand is for 24 hours and averaged into hourly values.

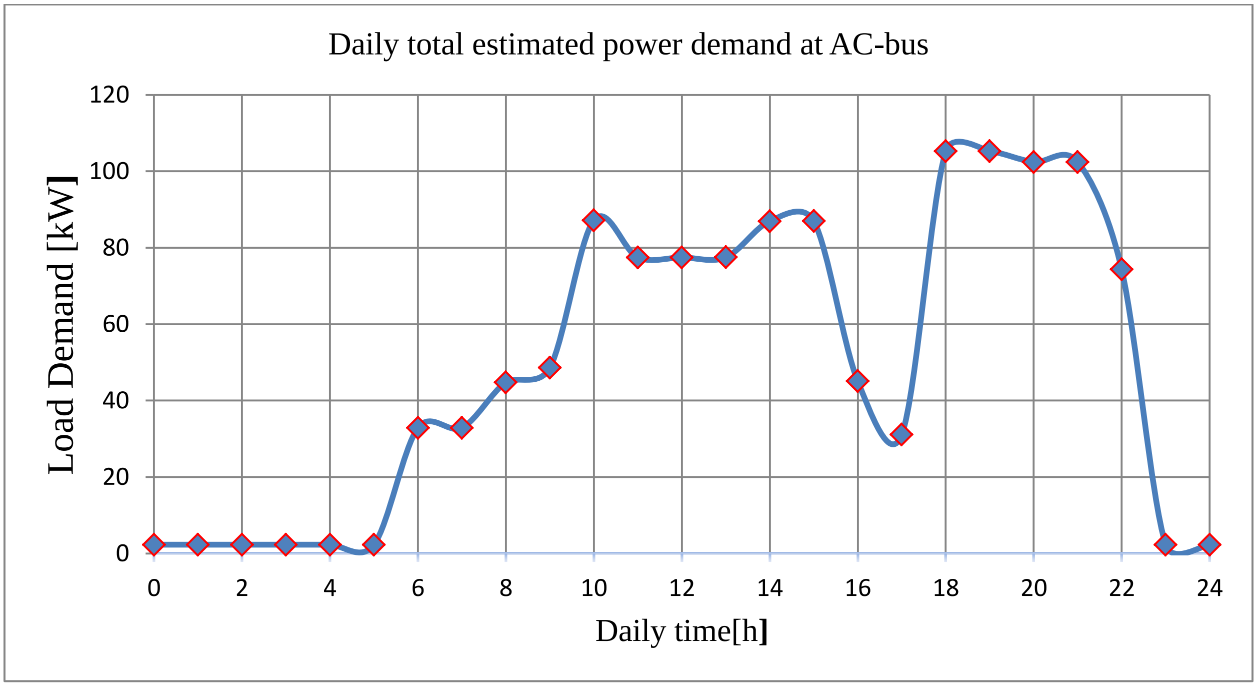

Figure 4.3: Daily total estimated load profile at AC-bus (Department, 2016)

For simplistic, the AC-load profile considered above is transferred to DC-load profile by taking into account the losses associated with power conversion and it is given in Figure 4.4.

The load demand transferred to DC-bus from AC-bus is given as: $Pl_{DC\text{-}bus}(t)=\frac{PlAC-bus(t)}{\eta ad}$

Where, $Pl_{DC\text{-}bus}(t)$= power load at DC-bus

$Pl_{AC\text{-}bus}(t)$=power load at AC-bus

η_{ad} =AC/DC convertors

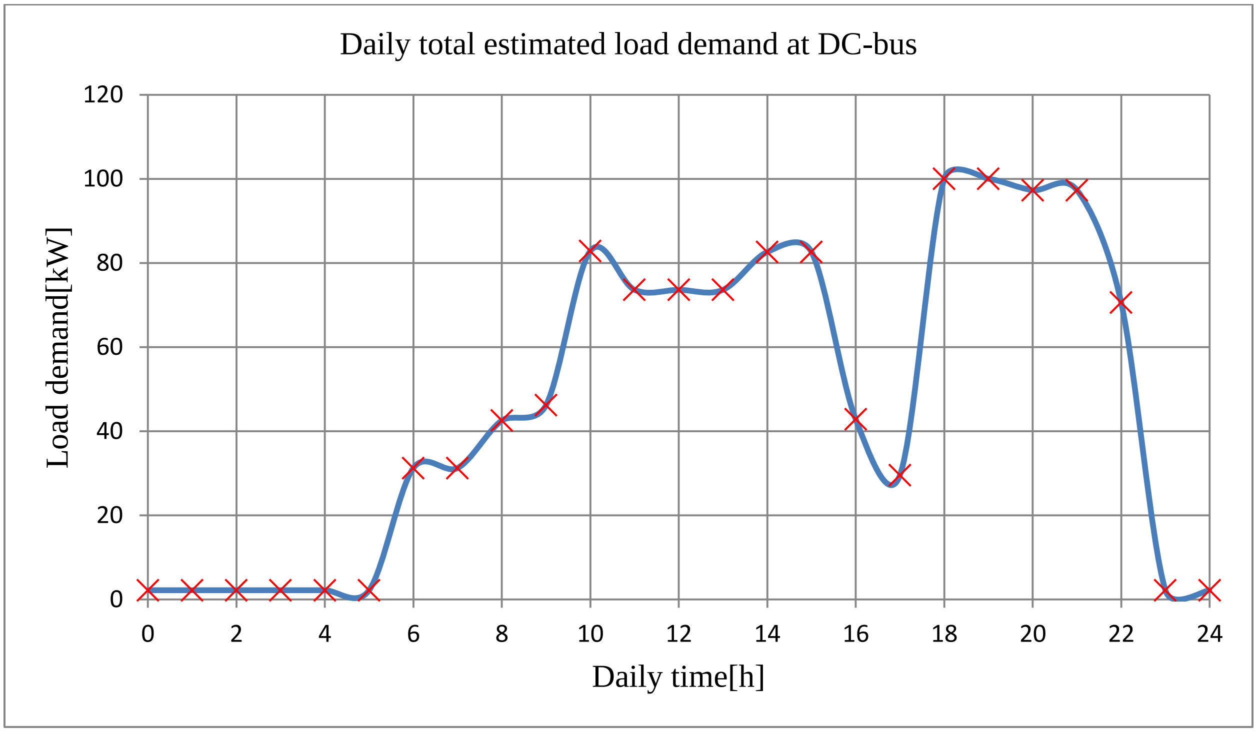

Figure 4.4: Daily total estimated load profile at DC-bus

The load profile includes load for households, commercials, service centers (health centers, schools, church, and mosque) and deferrable. The commercials and the service centers (health centers, schools among others) demand high power during working time and low power during night time on the corridors for lighting for their security except health centers. But health centers always require power as clinics work 24 hours. The households need power during evening and in the early morning for lighting as well as for other activities.

As it can be observed from the load profiles above, the load demand at daytime has high value in interval around 7:00 to 16:00hrs. This shows that the commercials and the service centers require high energy during this time (office time) for different activities and they can also need small amount of power from 18:00 to 6:00hrs for lighting on the corridors.

High load demand occurs in 18:00 to 22:00 hours interval when villages require more power. This high power consumption is for residential where power is required for lighting and other activities. In early morning the demand also appears for breakfast activities.

To design and model hybrid power system that includes solar-PV and Generator set with storage device so as to get the most reliable, efficient and cost effective for this sort of load demand profile, the best efficient topology is selected in the last section (section 4.2) which is Mixed Bus.

4.3.2 Solar irradiation

Ethiopia is endowed abundant solar energy resource in the entire year and approximately, most of parts of the country have over 3000 hours of sunshine and the annual average daily solar energy in some part of the country is 5.0kWh/m2 and in the north part it can be 6.0 to 7.5kWh/m2 per day (Mazengia, 2010) (Derbew, 2013).

The renewable energy resource has been used in this study is solar energy and its solar irradiation is averaged hourly. The solar irradiation is collected from the place where the hybrid power system is installed. Even if the renewable resource varies from time to time and season to season, the solar irradiation taken in this paper is considered as a constant in each hour. The irradiation is given the figure below, Figure 4.5 and the value of the solar irradiation is given at appendix-B (B2).

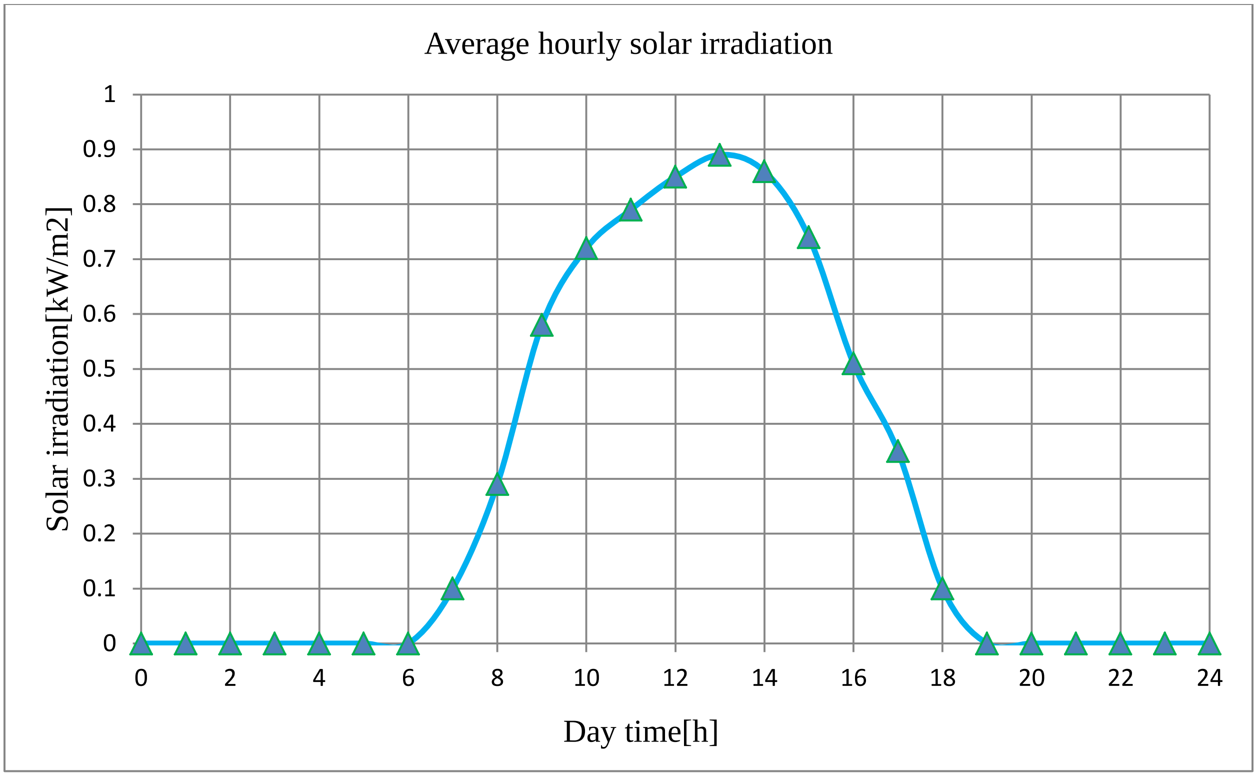

Figure 4.5: Hourly averaged solar irradiation (Department, 2016)

The figure shows the hourly average irradiation in which the maximum value occurs at daytime around 9:30 to 15:45 hours. It can be observed from the figure, the place has high solar potential energy. In order to utilize the energy efficiently, the system elements (PV-panel, Genset and battery) are sized properly so that the power demand defined met. The output power from single PV-panel is calculated below in section 4.3.3.

4.3.3 PV-panel power output

Once we have the renewable resource (insolation in kW/m^2) data as shown in the figure 4.5, the output power from renewable energy resource is possible to calculate. The output power is calculated using irradiation data, area of PV-panel and overall efficiency of the PV-panel. Therefore, the insolation that is taken in by single PV-array can be changed into output power using the following equation (Weldemariam, 2010).

$$P_{pv}(t) = Irr(t) A_{pv} \eta_{pv} \tag{4.1}$$

When the output power is referred to the DC-bus, it is calculated by multiplying the output power of the PV-panel by the efficiency of the DC/DC converter as it is given below.

$$P_{pvDC\text{-}bus}(t)=Irr(t)A_{pv}\eta_{pv}\eta_{dd} \qquad (4.2)$$

Where,

$P_{pv}(t)$ = PV-panel output power in watt (w)

$P_{pvDC\text{-}bus}(t)$= PV-panel output power after it referred to DC-bus

$Irr(t)$=irradiation data at time t in W/m^2

A_{pv}=area of a single PV-panel in m^2

η_{pv}=overall efficiency of the PV-panel

η_{dd} = efficiency of the DC/DC converter

The calculated output power from a single PV-panel using the above equation, the selected parameters (Francis M. Vanek, 2008) and insolation data is shown by the following figure (Figure 4.6). The value of the calculated output of a single PV-panel and the selected values are given at appendix-B (B2).

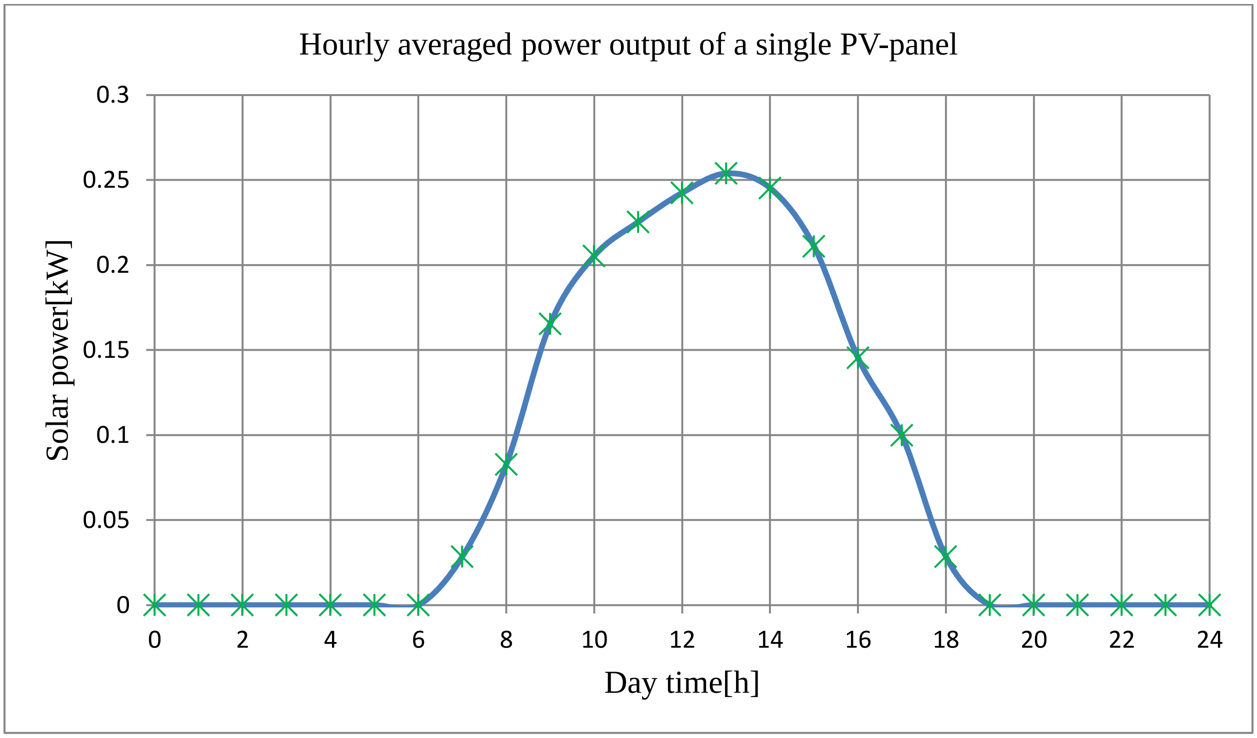

Figure 4.6: Hourly averaged power output of a single PV-panel

As it is observed from the figure above, Figure 4.6 the maximum output power that is obtained from a single PV-panel is around 0.253kW. Undoubtedly fluctuation of irradiation occurs so that it is better to take into account this fluctuation when the overall system of the hybrid designed for reliable energy supply. Therefore, the PV-panel which is taken here for further designing has higher capacity than that of used for calculation in order to minimize the problem that occurs due to the fluctuation of the insolation, to get reliable energy supply. Thus, the selected PV-panel for the next study has 0.603kW maximum power.

From the load demand and power output of a single figures, it is noted that the load demand is higher than the output power from the single PV-panel so that the system requires additional PV-panels in order to meet the load. In addition to that storage device is needed to store whenever there is excess energy from solar and supplies when there is less/no energy from the renewable energy for sustainable energy supply. Some service centers like hospital need always power so that for reliable energy supply backup Generator, Genset is required to supply whenever the power from PV-panel directly or indirectly does not meet the load demand.

4.4 Simulation Results and Discussion of the Power Management Strategies

4.4.1 Simulation results and discussion of OESPV power management strategy

For this proposed power management strategy, appropriate sizing of system elements is done based on the load considered in this paper. As proper sizing of the system is crucial, mathematical equation of power balance between the two sides (supply and demand), limits of energy storing, charging power and discharging power are considered. Then, mathematical equations are modeled using MATLAB/Simulink, after that the simulation model shown by Figure 3.4 is simulated. Depending on the proper sizing of the PV-panel element of the system, the numbers of solar modules that form PV-panel for this power management strategy (OESPV) are 637. These numbers of solar modules meet the load demand considered in this paper.

The simulation results of this power management strategy are indicated in the figures below. The simulation result has three different types of results: power shares of the renewable energy and battery bank, energy available in the battery bank (contribution) and power losses due to convertors and battery bank. Figure4.7, Figure4.8 and Figure4.9 have shown power shares of the renewable energy and battery bank, energy stored in the battery bank (energy contribution of the battery) and power losses respectively.

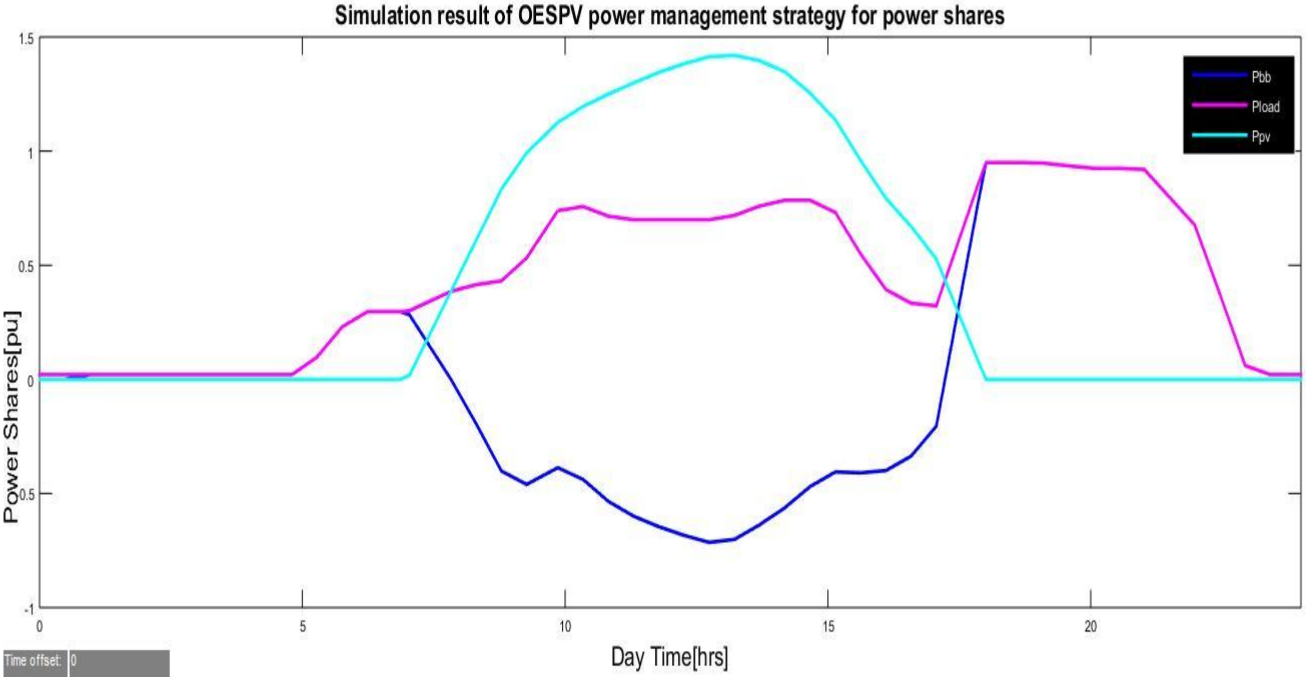

Figure 4.7: Simulation result of OESPV power management strategy for power shares

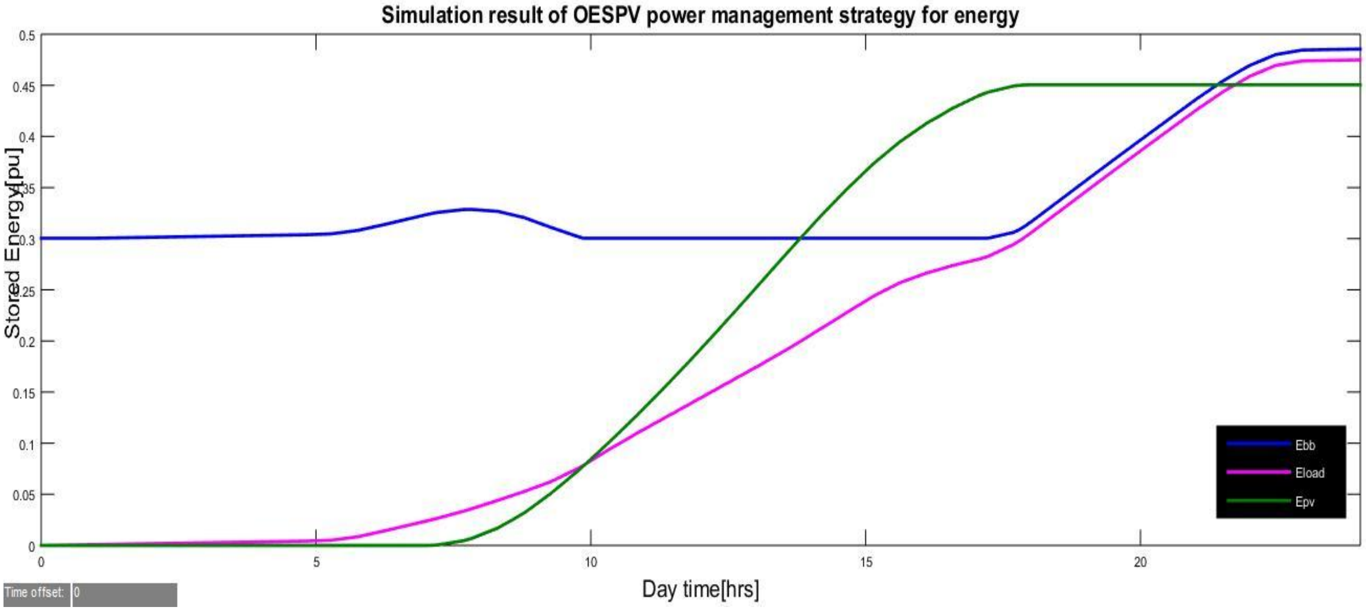

Figure 4.8: Simulation result of OESPV power management strategy for energy

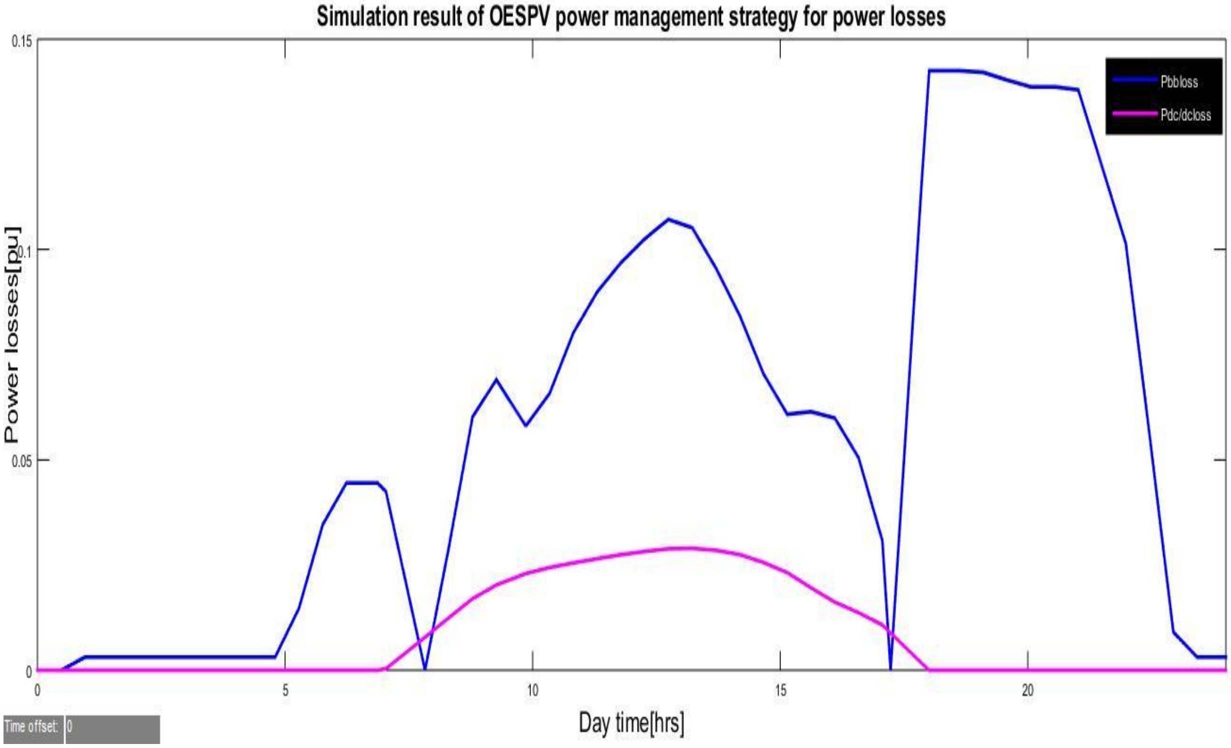

Figure 4.9: Simulation result of OESPV power management strategy for power losses

As it is observed from the figures above (Figure4.7 and Figure4.8), the power demand is supplied by the renewable energy (solar PV-panels) with support of the battery bank. Depending on the supply and demand the battery bank either charges or discharges at any time during a day. This always holds true for the whole day (cycle) to meet the load demand. The total supply power comes from solar PV-panel directly and/or indirectly without diesel generator’s support. The value of the power shares in both (solar-panel and battery bank) is different in the whole cycle and the maximum power share values are about 1.41Pu and 0.91Pu for solar-panel and battery bank respectively.

The battery bank includes two situations, charging and discharging.

Note: the current that flows out is negative (convention) throughout this paper and the general formula for energy condition at battery bank is given as: $e_{ava}(t) = e_{bb\_ini}(t) + \int P_{dfb}(t)dt$. And as it can be seen from Figure 4.7, the load profile and battery bank have the same magnitude at interval 0:00 hrs -6:40hrs and 19:00hrs-24:00hrs.

The charging and discharging conditions (cycles) of the battery bank are discussed below.

i) Charging section of the period

Under this section, the power supply from the solar PV-panel is greater than the load demand so that the battery bank charges. Thus, the stored energy during this interval is used for another section where the demand exceeds the supply. As it is seen from the graphs above (Figure4.7 and figure4.8) the negative power of the battery bank indicates that the battery bank charges where the power from the renewable energy is greater than the demand power. In addition to that since current flow out is considered as negative in this paper, at intervals where the battery bank charges the magnitude of the energy in the battery bank decreases as per the expectation. This can be observed from Figure4.8. This section is around from 7:40 to 17:20 hours interval. Therefore, during this interval the negative power and the reduction of energy magnitude of the battery bank show the charging condition. The maximum energy of the battery bank that can be stored is around 0.45pu (0.45*2.08MW=0.936MW) which is less than the maximum energy battery bank. This shows that the battery bank does not charge beyond its maximum capacity, 2.08Mw.

ii) Discharging section of the period

When the load demand exceeds the supply which is obtained from the renewable energy source, the battery bank supports the solar PV-panel in order to meet the load power demand. As it is seen by the Figure4.7, at time interval 17:20 to 7:40 hours the load profile is greater than the supply from the solar PV-panel. During this time interval the power of the battery bank is positive that shows discharging of the battery bank. In addition to that, the available energy in the battery bank in the same interval shown by Figure4.8 increases its magnitude according to the convention (the flow of current out is considered as negative). The minimum energy available or stored in the battery bank when it discharges becomes around0.3005pu (0.3005*2.08MW=0.625MW) which is greater than the lower limit of the energy battery bank (Ebb_min= 0.3Ebb_max=0.28MW).

Note: the minimum energy battery bank (Ebb_min) considered in this paper for simulation is maximum energy battery bank multiplied by 0.3 (0.3Ebb_max), Ebb_min= 0.3Ebb_max.

Important points that are noticed from these results are: the energy battery bank is between lower limit and the upper limit according to the Simulink design which means that the battery bank is not able to discharge below its lower limit and charges beyond its upper level limit. The values of battery capacity designed when the battery bank is sized (2.08MW) and the maximum value (0.936MW) obtained under this power management strategy have big difference. Thus, resizing of battery bank is recommended in order to charge to the maximum value and to become economical. The demand is met directly from the solar PV-panel during sunny time at daytime and the PV-panel is supported from the battery bank during the supply from the solar PV-panel becomes less than the demand especially in the night time.

The power losses associated with the converter and battery bank are shown in Figure4.9. These two losses are from DC/DC convertor and charging/discharging of the battery bank. As it can be observed from the figure above both losses are not the same entire the cycle. The losses associated with battery bank is high when maximum power is obtained from battery bank and high power loss of DC/DC convertor occurs whenever the PV-panel supplies maximum power. When the two power losses are compared in the whole cycle (day), power loss of battery bank is greater than that of DC/DC convertor.

Lifetime of battery is highly affected by the depth of discharge of it and depth of discharge depends on the stored energy state (lower level and upper level). In other words, battery number of cycles (life cycle) depends on the depth of discharge in every cycle. A battery that discharges deeply has small number of cycles so that its life cycle becomes short.

Therefore, the depth of discharge (DOD) of battery can be obtained using the upper and the lower energy levels as:

$$DOD = \frac{Ebb\_max - Ebb\_min}{Ebb\_max}$$

Thus, taking the values obtained above (upper value=0.45pu and lower value=0.3005pu), DOD of this power management strategy can be calculated as:

DOD = $\frac{0.45-0.3005}{0.45}$ ≈ 0.3322 ≈ 33.22%

Number of cycles approximately becomes 490 by referring to curve of VRLA batteries of depth of discharge (BAE Batterien GmbH, 2008) (Reddy, 1995). This shows that the battery has no the same lifetime as the system. This system needs replacements of batteries within the lifetime (20 years) of the system considered here. As it is observed from the calculated values and referring to curve of VRLA batteries of depth of discharge the numbers of replacement could be two times within the life of system. Therefore, this may not be cost effective.

4.4.2 Simulation results and discussion of ODG power management strategy

Under this power management strategy, the only energy source is generator set that supplies the load power demand. The PV-panel and the battery bank do not assist the Genset, but the battery bank contributes only at starting and stopping time since the Genset has a delay during these times.

The MATLAB/Simulink Model of ODG power management strategy is shown by figure 3.7 is simulated and the results are given by the Figure4.10 and Figure4.11. Figure4.10 and Figure4.11 have shown the natures of powers and the energies respectively.

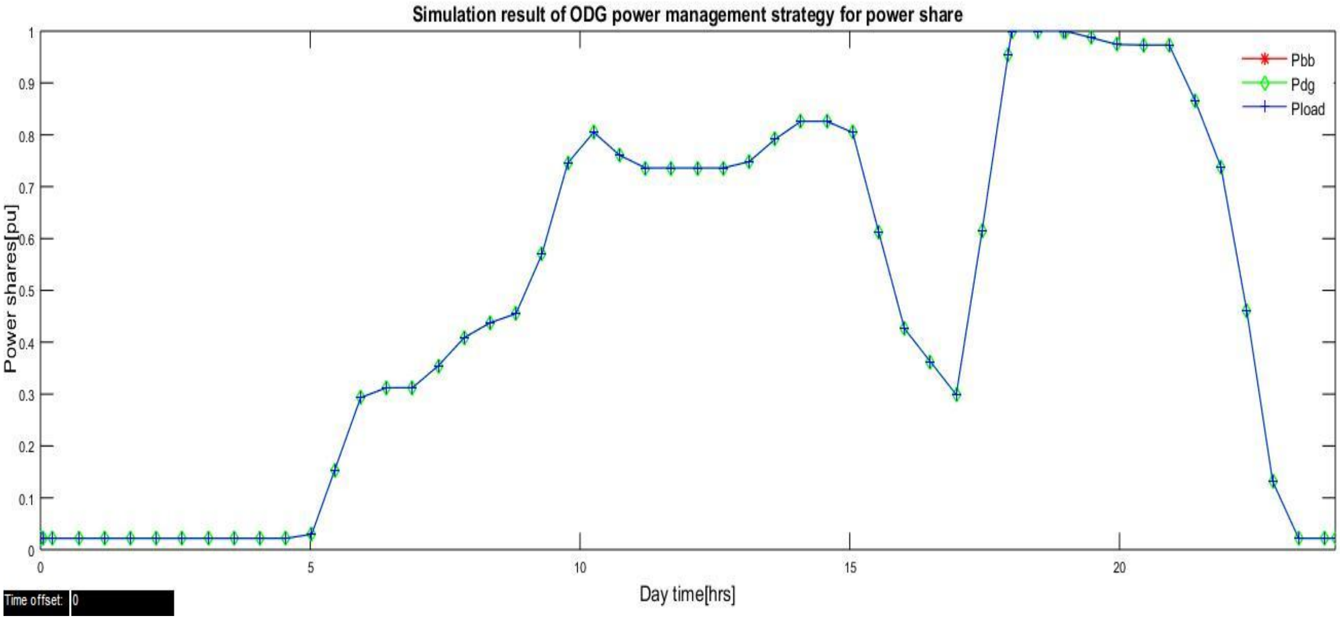

Figure 4.10: Simulation result of ODG power management strategy for power share

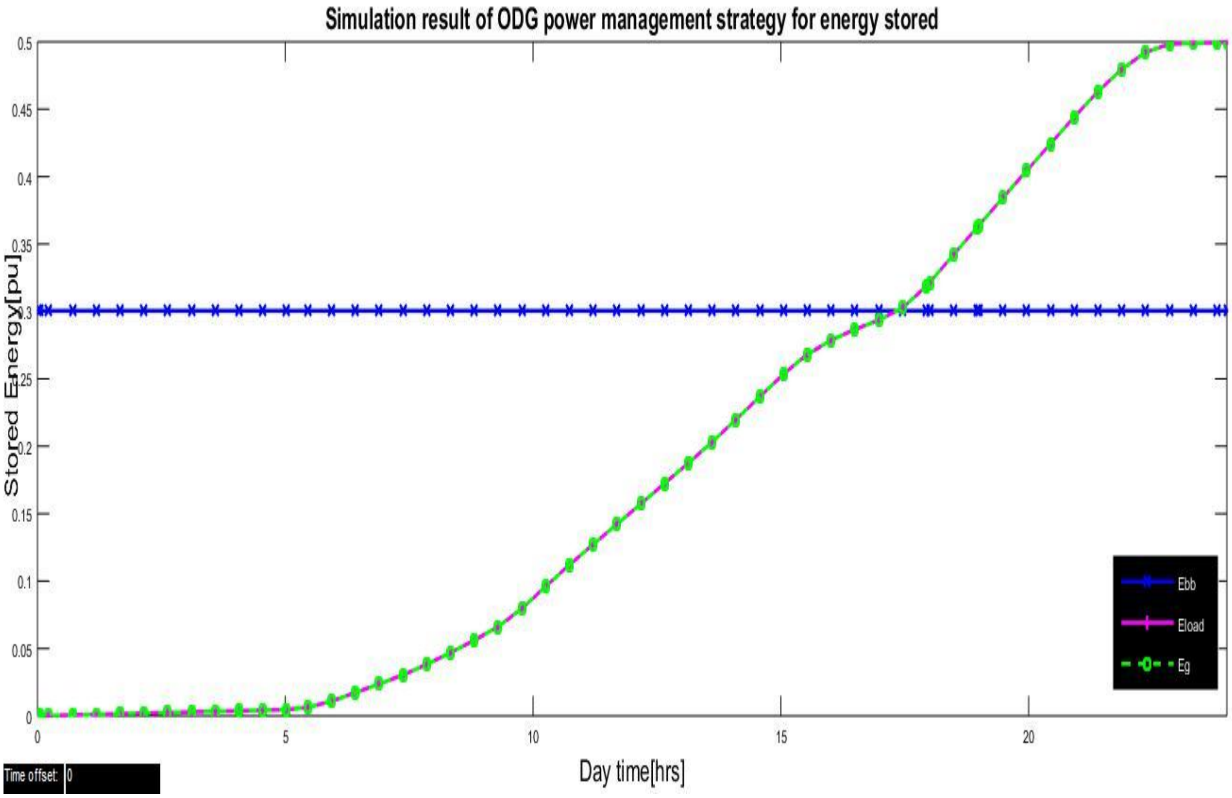

Figure 4.11: Simulation result of ODG power management strategy for energy stored

As it is seen from the Figure4.10, the result is exactly according to the designed Simulink. The only power source under this power management strategy is Genset so that it is supposed to supply power exactly as the load power demand. From the result above the Genset supplies power the same as the load demand in entire the cycle. The powers from the Genset and the load demand have the same magnitude. The power of the battery bank is zero as shown by the figure above since the current/power flow is zero. This shows that the battery bank neither charge nor discharge in this power management strategy, it is non-significant.

Figure4.11 has shown the energy result and from this figure the energy from the Genset is exactly the same as the load demand energy but the energy that is available in the battery bank is constant which is initial energy stored. This constant energy also shows no flow of current.

4.4.3 Simulation results and discussion of GAPVB power management strategy

In this power management strategy (GAPVB), the Genset is supposed to supply the average power demand load whenever there is demand and the remaining power demand is met by PV-panel with battery bank. The battery bank charges or discharges depending on the load demand and the supply. Based on the mathematical modeling, the Simulink model is shown by Figure3.21, and then this Simulink model is simulated. The results of the simulated model are given in Figure4.12, Figure4.13 and Figure4.14. Figure4.12, Figure4.13 and Figure4.14 have shown the nature of power shares from (Genset, battery bank and PV-panel), energy stored in the battery and power losses associated with charging/discharging and converters respectively.

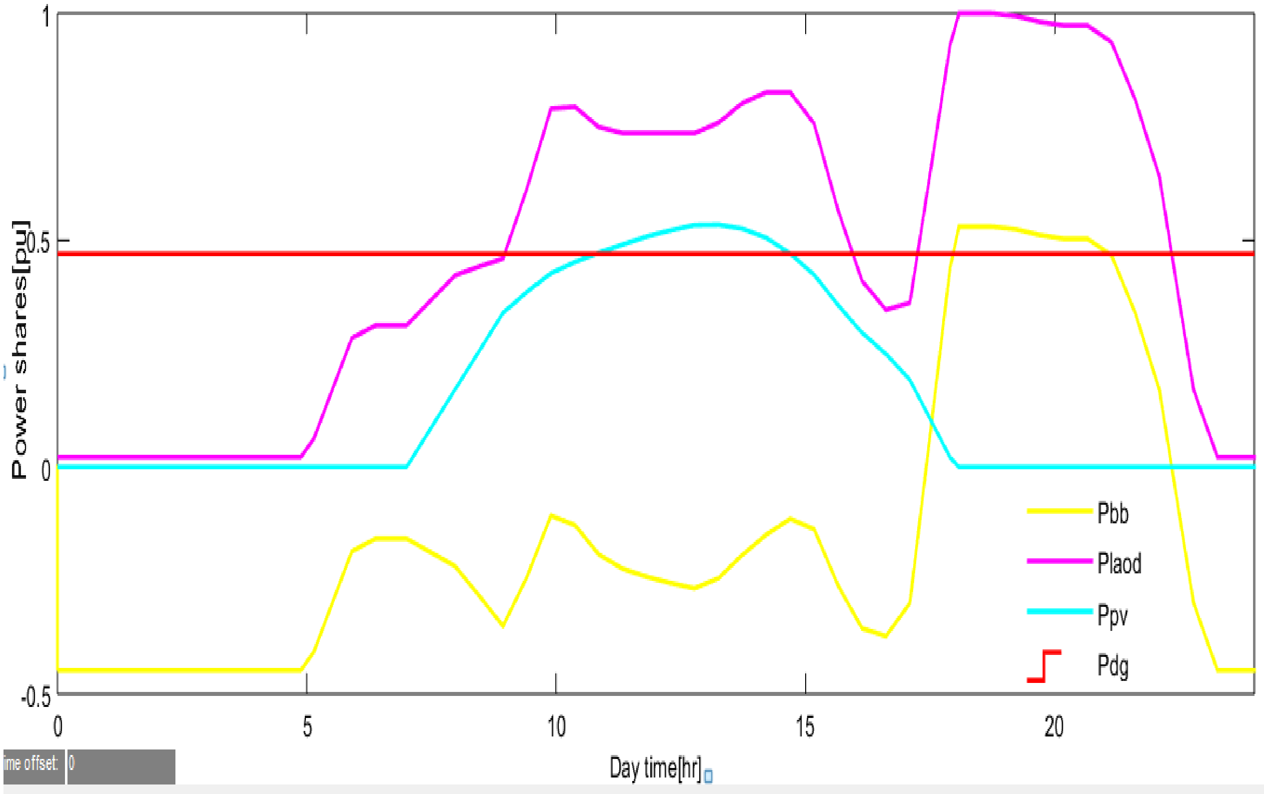

Figure 4.12: Simulation result of GAPVB power management strategy for power shares

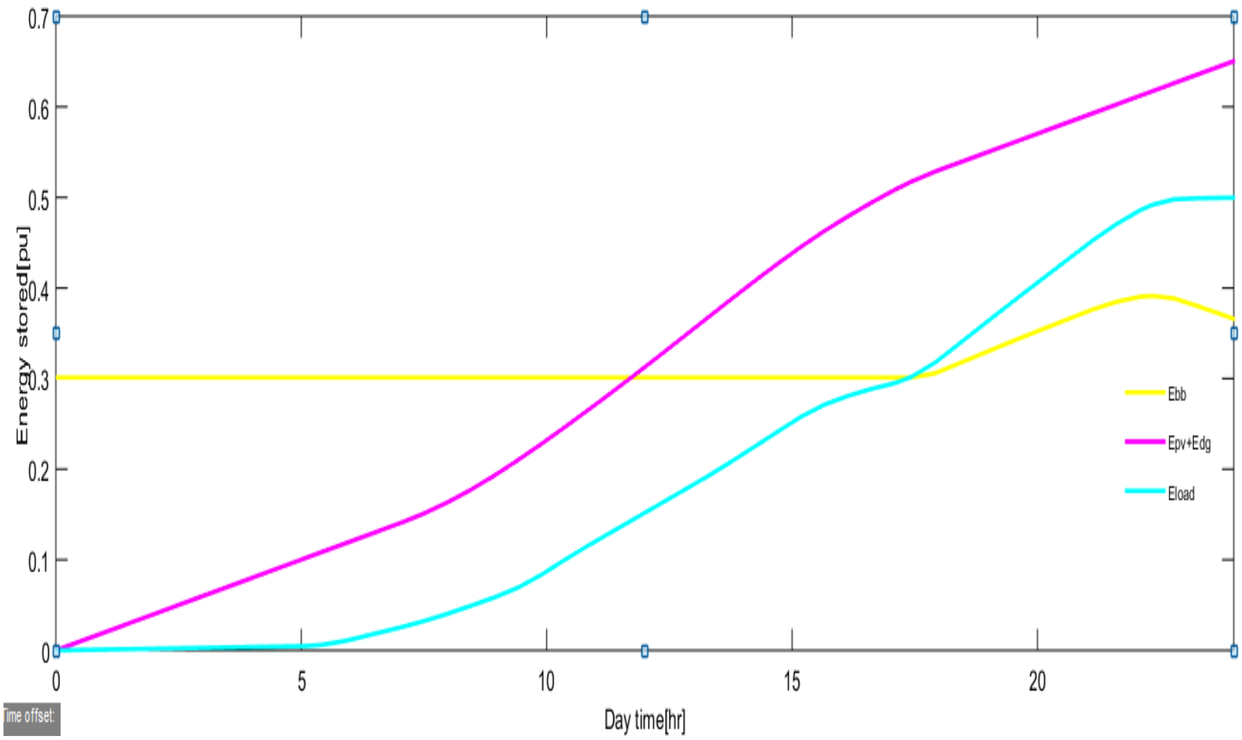

Figure 4.13: Simulation result of GAPVB power management strategy for energy

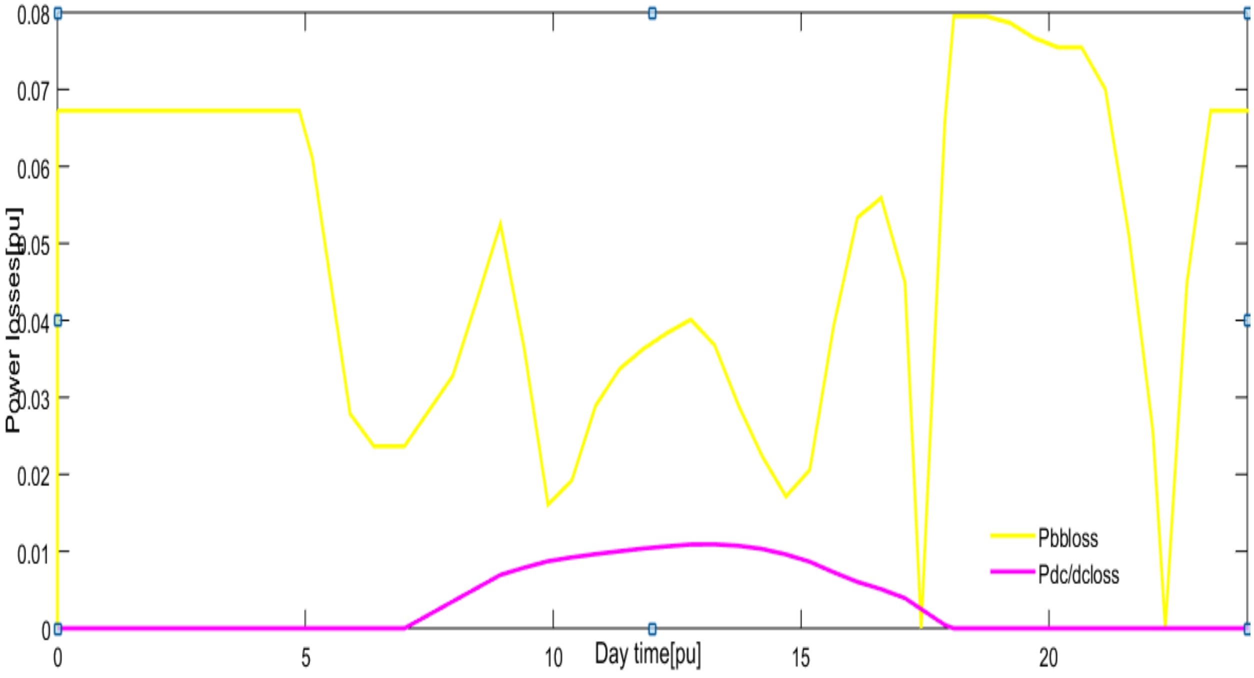

Figure 4.14: Simulation result of GAPVB power management strategy for power losses

As shown from the Figure4.12 above, the Gensent has supplied the average load power in the entire cycle since there is always load demand as per the Simulink design. Even if the power from Genset is constant (average load demand power) throughout the cycle, power shares from PV-panel and battery bank is different in the cycle. Therefore, the result of power shares can be discussed taking into two sections.

i) Charging section of the period

In this section power management strategy, the power of Genset alone or with the solar power is greater than the load demand so that the battery bank charges. Thus, energy is stored in the battery which is utilized when the power from Genset and solar is less than the demand. As it is seen from the result, the battery bank charges at time interval where the value of the battery bank power is negative as per the convention considered in this paper. This time interval is from around 22:30 to 17:30 hours where the battery has negative value and the power demand is less than the power sum of Genset and from solar. In this time interval the energy battery bank decreases according the convention of flow of power/current. The maximum energy in the battery is 0.387pu (0.387pu*2.08MW=0.805MW) which is less than the upper limit power of the battery. Thus, it shows that the battery bank contributes small in amount energy and is not able to charge beyond its upper limit.

ii) Discharging section of the period

Under this condition, the load demand is greater than the sum of the power of Genset and solar PV-panel so that the battery bank supplies power to assist Genset and PV-panel. As it can be observed from the Figure4.12, the battery bank has positive power in the time interval from around 17:30 to 22:30. This shows that the load power is greater than the power sum of Genset and PV-panel powers. In this interval the battery delivers power to the load according to the mathematical modeling even if the battery bank’s energy seems constant which is shown by Figure 4.13. This shows that although energy contribution of the battery bank is so small, it charges and discharges to meet the load demand and not reaches to the battery limits (lower and upper limits). In addition to that, the energy level increases in this interval according to the convention of the power/current flow even if the contribution is small. Therefore, the positive power and the increment of energy level tell discharge of battery bank in this paper context. The minimum energy in the battery bank at this interval is 0.3005pu (0.3005* 2.08MW= 0.624258MW) which is greater than the minimum energy where the battery bank can discharge to.

Important points that can be noticed from these two portions are: contribution of the battery bank is very small and it cannot charge or discharge to its upper limit and lower limit respectively. As it can be observed the power from the battery bank is small. This indicates that almost the load demand is met by PV-arrays and Genset and the contribution of the battery bank is small. Therefore, it is recommended that the battery bank should be resized to reduce the size of the battery bank which in turn decreases the cost of the battery or in order to charge to its maximum limit. In addition to that, the power obtained from the Genset can be minimized this can reduce the environmental effect. The load demand is met in the entire cycle directly (from PV-panel and Genset) or directly (via battery bank) according to the mathematical model.

Figure4.14 has shown the power losses associated to the convertors and battery bank charging/discharging. As it is observed from that figure, the loss associated with DC/DC is high when the power from the solar PV-panel is more. And the power loss due to charging or discharging battery bank has become high whenever the battery bank has contributed high power level.

As it is described on OESPV power management strategy, battery lifetime is affected by the depth of discharge which in turn depends on the stored energy state (lower level and upper level). In other words, the battery number of cycles (life cycle) is dependent on the depth of discharge in every cycle. A battery that discharges deeply has small number of cycles and its life cycle does not last for entire the life time of the system.

Therefore, the depth of discharge (DOD) of battery can be obtained using the upper and the lower energy levels as:

$$DOD = \frac{Ebb\_max - Ebb\_min}{Ebb\_max}$$

Thus, taking the values above (upper value=0.387pu and lower value=0.3005pu), it can be calculated as:

$$\text{DOD} = \frac{0.387-0.3005}{0.387} \approx 0.2213 = 22.13\%$$

This low DOD value shows that the battery has good lifetime. Number of cycles approximately becomes 9500 by referring to curve of VRLA batteries of depth of discharge (Köhlin, 2009) (BAE Batterien GmbH, 2008).This system may not need any replacement of batteries within the lifetime (20 years) of the system considered here. Since the battery replacement matters the life-cycle cost of the system, this hybrid power system may be cost effective. In the next chapter, cost analysis of the system is analyzed and under the conclusion part some important points are mentioned.

Generally, the results that have been discussed under section4.4 (Simulation Results and discussion of the power management strategies) can be summarized as: three different sort power management strategies are considered. For all power management strategies mathematical modeling is done based the power balance, energy balance between the two sides (supply and demand), Genset control, battery bank charging/discharging, power losses, elements sizing. The system elements are sized properly based on the supply and the demand so as to synchronize them. Then, for each power management strategies Simulink blocks are designed then after these Simulink blocks are simulated. The results of every power management strategies, power shares of the sources, stored energies and power losses are discussed in detail. In each power management strategy, the power shares, the energy stored and power losses are compared.

The comparison of maximum power shares of the sources, the power losses of the battery bank and convertors are summarized in the following tables. Table 4.1 shows maximum power comparison of the sources for each power management strategy. As it is observed from the table below, the maximum power contribution of every power source is different for different power management strategies to meet the load demand.

Table4.1: Comparison of Maximum power shares of the power sources for every power management strategy

Comparison of Maximum power shares of the power sources for every power management strategy										
Maximum power shares of the power sources for OESPV(%)				Maximum power shares of the power sources for ODG(%)				Maximum power shares of the power sources for GAPVE (%)		
Ppv	Pbb	Pdg		Ppv	Pbb	Pdg		Ppv	Pbb	Pdg
58	42	0		0	0	100		34	34	32

Table 4.2 shows the maximum power losses of battery bank and converters. As it can be seen from the table below, the power loss of DC/DC convertor for OESPV power management strategy is greater than that of GAPVB power management strategy which indicates that the power share from PV-panel for GAPVB power management strategy is less than that of OESPV power management strategy. The power losses of the battery bank are higher than the convertor's power losses for every power management strategy. Based on the maximum power losses given below, losses of both (battery bank and DC/DC) for OESPV are higher than that of GAPVB.

Table4.2: Comparison of maximum power losses of battery bank and convertors for the proposed power management strategies

Comparison of maximum power losses of battery bank and convertors for the proposed power management strategies								
Maximum power losses of battery bank and DC/DC for OESPV					Maximum power losses of battery bank and DC/DC convertor for GAPVB			
$P_{DC/Dcloss}$		Pbbloss			$P_{DC/Dcloss}$		Pbbloss	
Value	%	value	%		Value	%	value	%
0.03	17	0.144	83		0.011	12	0.08	88

As it has been discussed under the Simulation Results of the power management strategies regarding to the depth of discharge of batteries, it has been found that the values of DOD are different for different power management strategies. Therefore, the batteries will have different lifetime in the different systems. As it is observed from the calculated values of DOD and the numbers of cycles, the batteries may need replacements for OESPV power management strategy about two years whereas may not need any replacement for GAPVE power management strategy for the lifetime cycle (20 years) of the system considered here.

The cost analysis of the systems is analyzed under section 4.5 (Results and discussion of fuel consumption and Life-cycle costs).

From the above results (power shares and power losses) and discussion, the second null hypothesis of the research question is rejected as all proposed power management strategies of hybrid power systems have different power shares, and efficiencies.

4.5 Results and Discussion of Fuel Consumption and Life-cycle Costs

4.5.1 Results and discussion for fuel consumption of the Genset for the different power management strategies

The three different power management strategies (OESPV, ODG and GAPVB) proposed in this thesis paper are discussed in detail in the last sections based on their power shares, energy stored and power losses associated with storage devices, convertors to select the best system. As it has been seen from the power shares figures (Figure 4.7, Figure 4.10 and Figure 4.12), the power obtained from Genset is different for different power management strategies. As the power contribution from Genset is different for the different power management strategies, the fuel consumption is different too. Investigating the environment effect is one of the criteria to select the best system (power management strategy) in this paper by considering the amount of fuel consumption in lifetime of the system.

The first power management strategy (the only Energy Source is PV-panels Supported by battery bank (OESPV)) is not assisted by Gensent so that there is no expense for fuel.

The comparison of fuel consumption of the Genset for the proposed power management strategies in this paper is given by the Figure 4.15 below. The daily fuel consumptions are calculated using equation 3.24 by taking values of nominal peak power of the generator set and daily output power of the Genset.

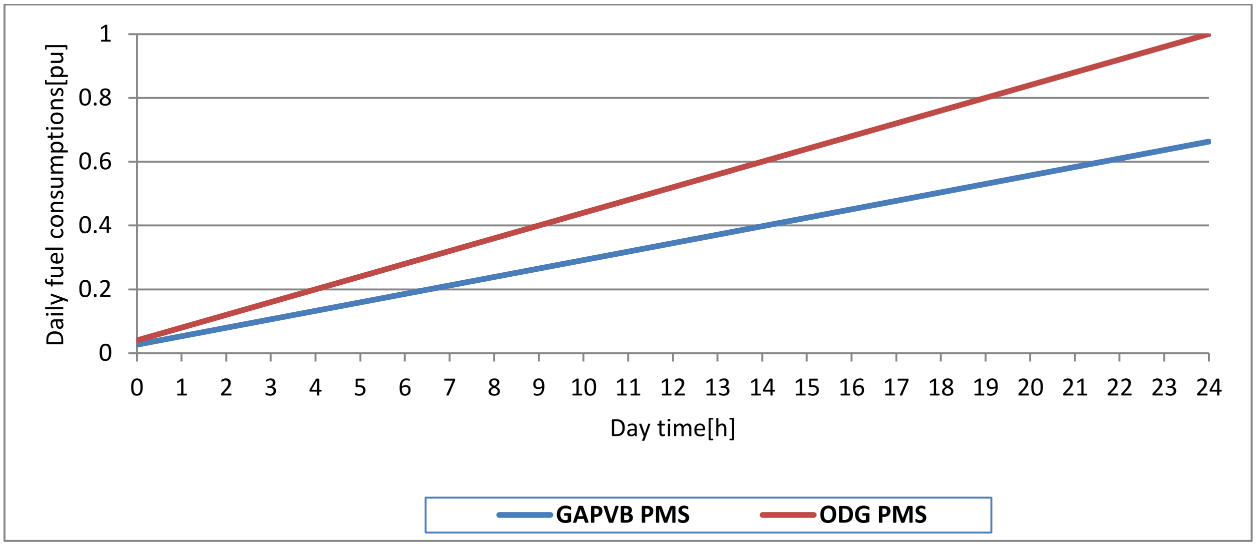

Figure 4.15: Daily fuel consumptions comparison of Genset for the proposed power management strategies.

As it can be seen from the figure above the comparison is between Only the Diesel Generator supply the load demand (ODG) and Genset supplies the average power whenever there is power demand (GAPVB) since the only Energy Source is PV-panels Supported by battery bank (OESPV) is not supported by Genset. From Figure 4.15, the ODG consumes high amount of fuel throughout the cycle than GAPVB. This high amount of fuel within a day results in large amount of fuel consumption in the life span of the system.

The high fuel consumption of the generator in lifetime of the system brings higher environmental effect. Thus, when the ‘Only the Diesel Generator supply the load demand (ODG)’ is used, high amount of gases such as Co_2, methane are released so that their negative impact on the environment becomes high. This brings problems like health problem and so forth.

Therefore, from the Figure 4.15 OESPV has not environmental effect whereas ODG brings high negative environmental impact followed by GAPVB. But to select the best system this criteria is not enough, the cost analysis should be taken into account so that it is discussed in next section in order to conclude and choose the most suitable system.

4.5.2 Results and discussion of comparisons of capital costs

Under chapter three, formula for capital costs for each power management strategy is discussed. Based on the data presented at Appendix-C (C4), comparison of capital costs for every power management strategy is shown by the figure below.

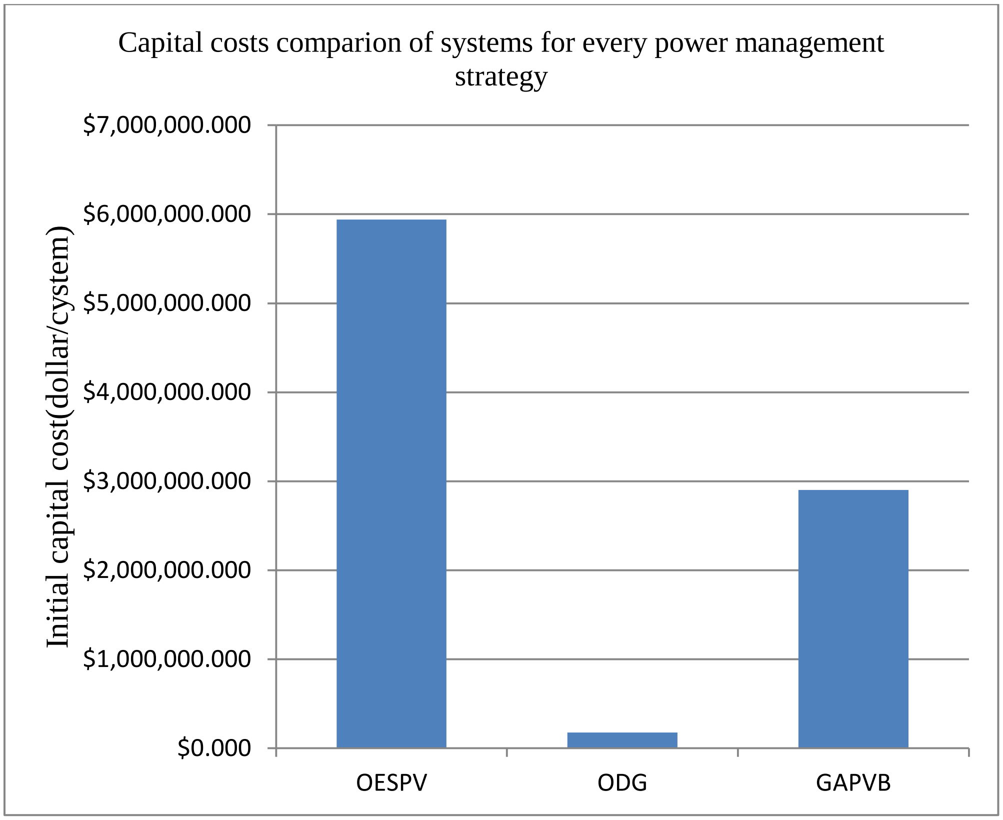

Figure 4.16: Capital costs comparison for each power management strategy

As it can be observed from the figure above, the systems have different capital costs. The system that consists only PV-array with battery bank OESPV power management strategy has high amount of cost when it is compared with that of the systems that involve diesel generator. The system with only Genset ODG has low initial investment among others. Therefore, the initial cost of with only PV-array (the only Energy Source is PV-panels Supported by battery bank (OESPV)) has more initial costs and followed by the hybrid system that comprises the renewable energy resource with diesel generator (Genset supplies the average power whenever there is power demand (GAPVB)) whereas the system with only diesel generator (Only the Diesel Generator supply the load demand (ODG)) has the lowest initial costs.

In general, the initial cost of diesel generator is very low when compared to PV-array. Systems that comprise renewable energy resources require high amount of money. From the initial investment point of view, the system with only diesel generator is preferable in order to be affordable. This is one reason why the consumers in developing countries cannot prefer to be involved in renewable energy sources. To give a conclusion which system is preferable another additional cost analysis is considered in next section.

4.5.3 Results and discussion of comparisons of variable costs

In chapter three, formula for variable costs for each power management strategy is discussed. Based on the data presented in Appendix-C (C5), comparison of variable costs for every power management strategy is shown by the figure below.

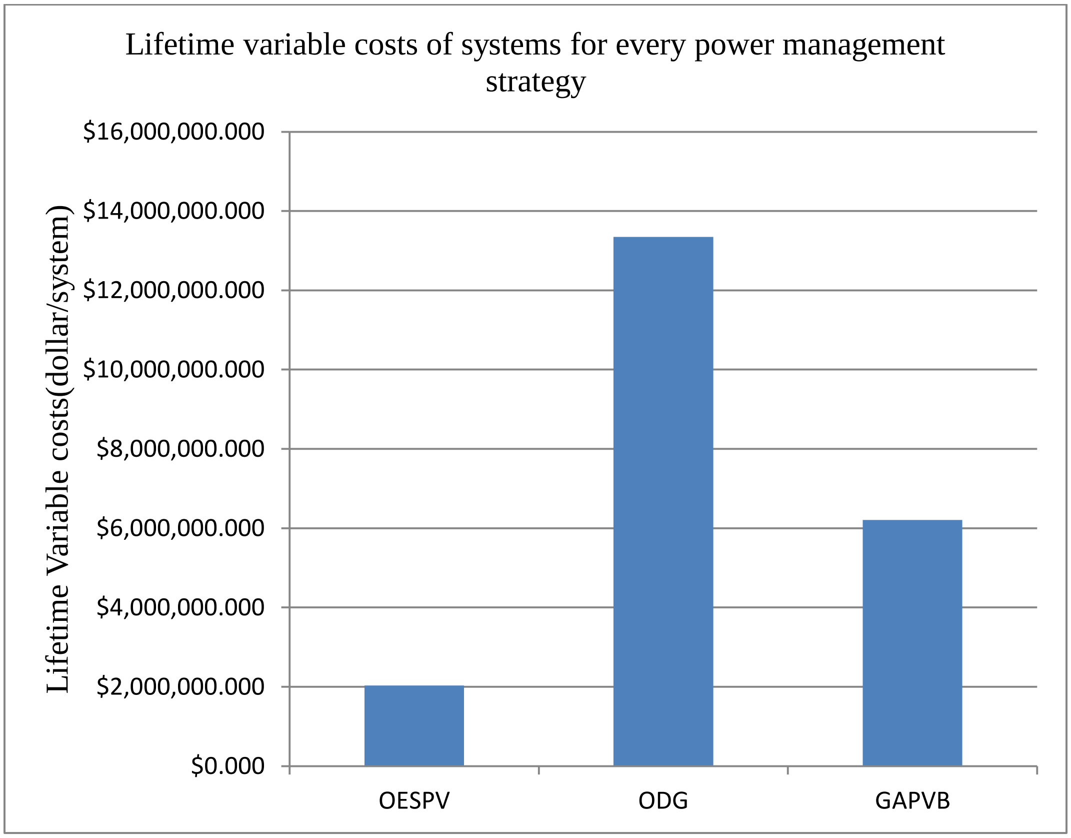

Figure 4.17: Comparison of variable costs for each system

As it can be seen from the figure 4.17, the systems have different variable costs. The system with diesel generator only (Only the Diesel Generator supply the load demand (ODG)) has high variable costs whereas the system which does not involve diesel generator array OESPV has least variable costs.

Generally, the system that has diesel genset energy resource (Only the Diesel Generator supply the load demand (ODG)) has big amount of money followed by the hybrid system (Genset supplies the average power whenever there is power demand (GAPVB)) but the renewable energy resource (the only Energy Source is PV-panels Supported by battery bank (OESPV)) has least variable costs. The big amount of money of the system with only diesel generator ODG is brought due to the continuous fuel consumption as there is always load, replacement cost and operation and maintenance. Whereas, the system which does not involve diesel generator (the only Energy Source is PV-panels Supported by battery bank (OESPV)) does not require components replacement within its lifetime (20 years is considered here) so that its variable cost is so small when compared with the system with only diesel generator (Only the Diesel Generator supply the load demand (ODG)) and the cost of variable of the hybrid system (Genset supplies the average power whenever there is power demand (GAPVB)) is higher than that of the system which does not involve diesel generator (the only Energy Source is PV-panels Supported by battery bank (OESPV)) due to the diesel generator fuel consumption, replacements and operation and maintenance.

Generally, the high variable cost of the system with only diesel generator (Only the Diesel Generator supply the load demand (ODG)) mainly comes from fuel consumption in addition to the replacement and operation and maintenance. Although the cost of fuel varies from time to time in Ethiopia, the value considered here is 0.71dollar/liter.

To conclude the discussion above related to the cost, sum of both costs (capital and variable costs) should be considered which gives total life-cycle costs (LCC). The following section is about total life-cycle costs (LCC).

4.5.4 Results and discussion of comparisons of lifetime costs

Under chapter three, formula and important points for total life-cycle costs for each power management strategy is discussed. Based on the data presented in Appendix-C (C6), comparison of total life-cycle costs for every power management strategy is shown by the figure below.

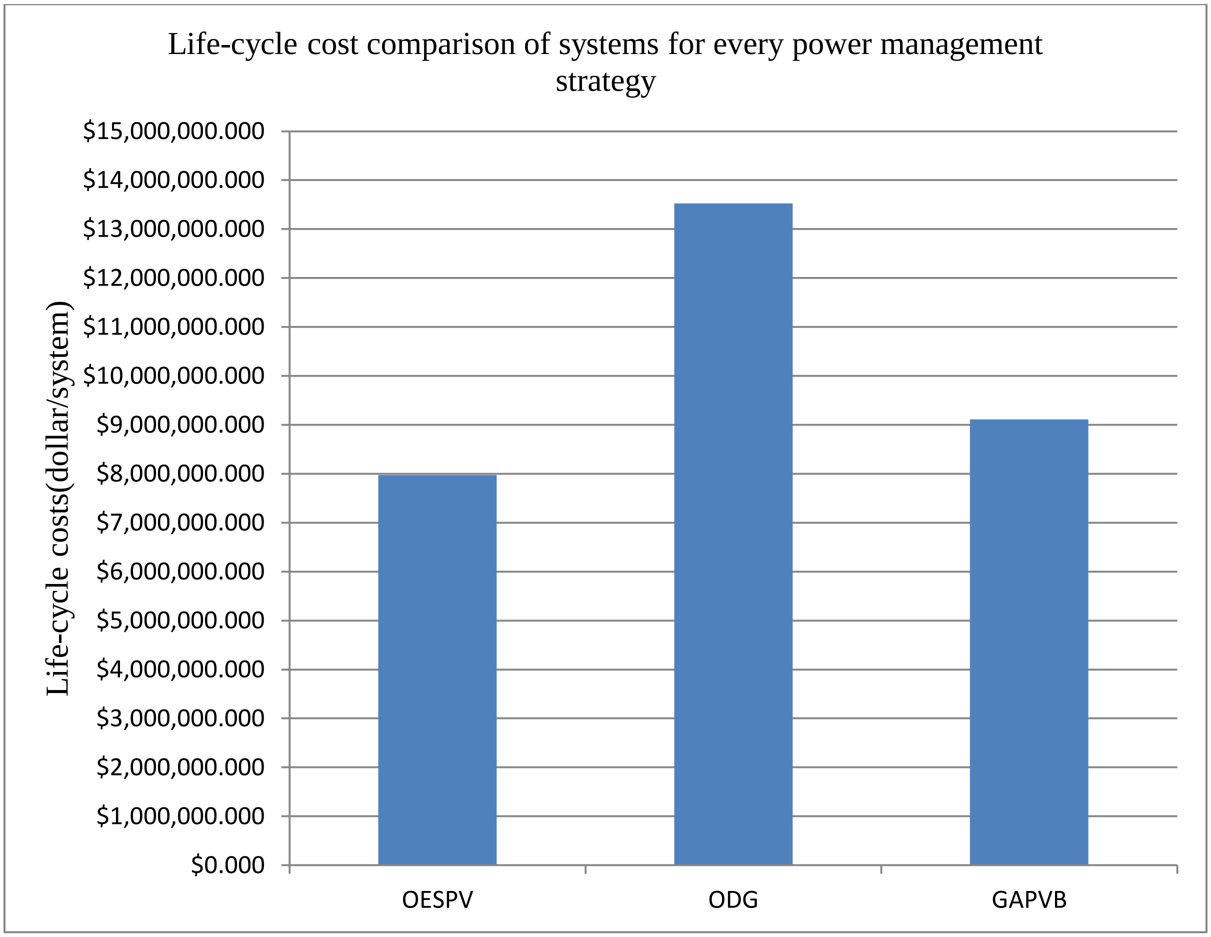

Figure 4.18: Life-cycle comparison (LCC) for each system

From Figure 4.18, the total life-cycle costs (sum of capital costs and variable costs) are different for different power management strategies. As it is observed, the total life-cycle cost of the system only with diesel generator ODG is higher than that of other systems and it is followed by the hybrid power system GAPVB whereas the renewable energy system OESPV has lower total life-cycle cost.

The following points can be deduced:

The renewable energy system OESPV does not require fuel so that there is no environmental impact. And even if it has high initial investment, the total life-cycle cost is smaller than that of others as its variable cost is so small.

The Genset system (Only the Diesel Generator supply the load demand (ODG)) require high amount of fuel so that it has high negative environmental impact. And its total life-cycle cost is the highest as the variable cost is high due to continuous fuel consumption, replacement and operation and maintenance.

The hybrid system GAPVB has high total life-cycle cost next to the Genset system. This system has environmental impact but less than that of the Genset system ODG. Therefore, the renewable energy system OESPV is the most cost effective followed by the hybrid system GAPVB whereas the Genset system ODG is the least and it has high environment impact.

Based on the above results (costs analysis) and discussion, the second null hypothesis of the research hypothesis is rejected as all proposed power management strategy of hybrid power systems have different total costs.

CHAPTER 5. CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Under this thesis paper, hybrid power system that involves PV-array, diesel generator, battery bank (storage device) and convertors proposed and has been discussed in detail to get the most efficient topology, efficient power management strategy, and affordable (cost effective) with minimum negative environment impact power system for remote area application where electricity has not reached yet in order to improve the life of community who live in that area.

The first work of this thesis was selection of best topology among the proposed configurations. To choose the most efficient, three connected topologies (DC-bus, AC-bus and Mixed-bus topologies) have been proposed that are connected to different energy sources, DC source (PV-array), AC source (diesel generator) and storage device (battery bank). The selection has been carried out based on the power output efficiency which delivers to the load demand. This has been conducted by taking every energy source independently, the efficiencies of the system elements (efficiencies of DC/DC converter, DC/AC converter, AC/DC converter and battery bank) and it has been analyzed using Microsoft Excel to compare them. Then, it is obtained that from the two graphs, the Mixed-bus configuration is the most efficient topology among the proposed configurations and this selected layout is considered for the further study.

Based on the load demand and the solar irradiation taken from typical village remote area which is located in Tsegede Wereda, Tigray, Ethiopia, the different components (diesel generator,PV-array and battery bank) of the systems are sized properly for each power management strategy. Three different power management strategies where the diesel generator is assisted from the renewable energy and battery bank are considered in order to investigate the best power management strategy by taking into account different criteria like total cost, environmental effect, power losses. Depending on energy balance between the two sides (supply and demand), Genset control and charging/discharging, mathematical modeling is designed for every power management strategy. This different mathematical modeling is modeled using MATLAB/Simulink blocks then, the Simulink models are simulated. The results of simulation (power shares of the different energy sources and battery bank, energy stored and power losses) are discussed and it is seen that the results are as per the mathematical modeling that is based on the governing equations. The battery bank charges and discharges between the limits (lower limit and upper limit) and the demand is supplied at each instant of time. It is also found that the depth of discharge (DOD) is different for different power management strategy and the life span of the battery is depending on the depth of discharge (DOD). Therefore, number of replacements of batteries may be needed for the system with batteries that have high values of depth of discharge (DOD) with in the lifetime of the system. As it is obtained from the calculated values and referring to curve of VRLA batteries of depth of discharge, the numbers of replacement of batteries for OESPV could be two times within the life of the system (20 years). This replacement of the batteries affects the life-cycle cost of the system.

Next, issues related to environment and costs are investigated for all different power management strategies. The environment effect is associated with fuel consumption of the diesel generator. Then, it is found that the amount of fuel consumption of the system by the generator is different for different power management strategy so that the impact on the environment is also different. It is observed that the Genset system (Only the Diesel Generator supply the load demand (ODG)) consumes high amount of fuel and followed by the hybrid system (Genset supplies the average power whenever there is power demand (GAPVB)) whereas the renewable energy system (the only Energy Source is PV-panels Supported by battery bank (OESPV)) does not require fuel so that the (Only the Diesel Generator supply the load demand (ODG)) release much more environmental pollutant such as Co_2, methane.

After that, the cost analysis is analyzed by categorizing into three sections. Firstly, the capital investment is investigated for each power management strategy and it found that the renewable energy system (the only Energy Source is PV-panels Supported by battery bank (OESPV)) has high capital money whereas the Genset system (Only the Diesel Generator supply the load demand (ODG)) has the least initial investment. Secondly, the variable costs for the entire lifetime of the system are performed for every power management strategy and it is observed that the Genset system (Only the Diesel Generator supply the load demand (ODG)) has high variable cost as it requires fuel continuously in the whole lifetime of the system. But the renewable energy system (the only Energy Source is PV-panels Supported by battery bank (OESPV)) does no need replacement except the batteries and small operation and maintenance so that its variable cost becomes small in amount. The replacement of battery is based on the depth of discharge (DOD) which affect the battery bank lifetime. From the result of variable cost, the Genset system (Only the Diesel Generator supply the load demand (ODG)) is the highest followed by the hybrid system (Genset supplies the average power whenever there is power demand (GAPVB)) and the least is the renewable energy system (the only Energy Source is PV-panels Supported by battery bank (OESPV)).

Finally, the total life-cycle costs are analyzed by taking the sum of the capital and the variable costs for every power management strategy so as to know and give conclusion which system is the most cost effective. Even if the capital investment of the renewable energy system (the only Energy Source is PV-panels Supported by battery bank (OESPV)) is higher, it is seen that OESPV and GAPVB are the most cost effective entire the lifetime of the system. Whereas, the Genset system (Only the Diesel Generator supply the load demand (ODG)) is the most expensive overall the life time of the system due to the continuous fuel supply, replacement and operation and maintenance. In addition to that ODG has high negative impact on the environment.

Therefore, important points that can be noticed from this paper are:

Although customers in developing countries have not involved in solar-PV system because of its high initial cost, it is feasible option for expansion of power generation in the developing countries to solve electricity problems as its life-cycle cost is small.

The system which is dependent on diesel 100% may not be reliable on access to electricity due to fluctuations of prices and fuel supply. In addition to that it has negative environmental effect. Only renewable energy resource system (solar-PV system) also might not be reliable since there is intermittency of energy resources from time to time and from season to season. It is obtained only day time but during cloudy and night time there is no access to solar energy. But it has no environmental effect and with less life-cycle cost. Thus, to solve the high environmental effect and non-reliability of the diesel generator and PV-arrays systems when they are used separately, it is recommended to replace them by hybrid power system.

5.2 Recommendation

For this thesis three configurations(AC-bus, DC-bus and Mixed bus) and three scenarios (The only Energy Source is PV-panels Supported by battery bank (OESPV), Only the Diesel Generator supply the load demand (ODG) and Genset supplies the average power whenever there is power demand (GAPVB)) are considered. But many configurations and scenarios can be taken to investigate the most efficient, cost competitive, reliable and with less environmental effect. Even if it is possible to investigate an efficient, cost effective, with less environmental impact etc. by considering few scenarios and topologies, it is recommended to consider many topologies and scenarios in order to find the most cost competitive, reliable, efficient and with minimum environmental effect.

A Hybrid system that includes diesel generator can be designed by involving many renewable energy resources in such a way that it brings minimum negative environmental impact and it becomes more reliable, sustainable and affordable. Thus, it is recommended to design a hybrid power system with less contribution of diesel generator in such a way that the environmental effect to be reduced.

About 94% of the generated power/electricity in Ethiopia is from hydropower and followed by wind renewable energy resource whereas generation from solar is not significant although the country has high solar potential and also these power plants are grid connected. In addition to that the settlement of the population is very scattered so that a number of off-grid hybrid power systems are required in such a way that the life of the people who live at remote areas will be improved since to reach electricity from the grid is so costly and not affordable. Therefore, it is recommended to give an attention to solar system by combining different types of renewable energy resources (wind, small hydropower etc.).

The available renewable energy resources potential in Ethiopia has not been studied well across the country. The recorded values of the potential are different for particular place. This might be due to different constraints like shortage of modern/ advanced technologies and the lack of professionals. Therefore, the data have been used for this thesis might not be real data (it is estimated data). Thus, it is recommended that, the government in collaboration with scholars should give an attention to know the real available potential energy in Ethiopia and based on t he real data hybrid power systems should be designed and installed.

5.3 Limits

The available renewable energy resources potential in Ethiopia has not been studied well across the country due to many constraints. The values of solar irradiation that have been recorded so far for particular place are different. This may be due to shortage of modern/ advanced technologies and the lack of professionals. Therefore, the data (solar irradiation, load demand etc.) have been used for this thesis might not be real data (it is estimated data). To get detail data for cost analysis was also one of the challenges. For instance, cost of each PV-array, convertors, batteries, batteries replacement values and so forth.

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