Design and Modeling of a PV System for a House in Saudi Arabia

By

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ABSTRACT

Consumption of electricity in the Middle East is quite high due to the high cooling demands during summer time in each home. However, Saudi Arabia has high solar energy resources that could be used to meet all home energy needs. In this Thesis, a solar energy system is designed using BEopt and Homer software. BEopt was used to build a thermal model for an actual house in Qassim, Saudi Arabia to stimulate the hourly kilowatt electrical consumption for mainly cooling purposes. Mathematical equations have been used to calculate the necessary photovoltaic and Battery size.

The collection of data and BEopt results are used by Homer software to design various options for a PV system. Results indicate that an 18.85 kW PV system, 52 batteries 200 Ahr each and a 10kw inverter can meet all house energy needs. This study presents a dynamic modeling of a photovoltaic (PV) system for a residential application using Simulink. The PV system designed here consists of 56, 325W, 24 V PV modules, 52, 200Ahr, 12V batteries, a maximum power point tracking (MPPT) charge controller and a 10 kW inverter to power a house.

This Thesis proposes a boost converter; (MPPT) to be applied to the system to obtain a maximum output power of the PV system. Additionally, varying weather curves data were implemented in the design to simulate potential conditions, namely solar radiation and temperature. A step-up transformer is used to achieve the house required voltage. The simulation results prove that such a PV system would work smoothly without grid connection at a location such as Qassim, Saudi Arabia.

The research aims to design the installation process of a PV system of a typical Saudi house. HelioScope Software is a fundamental tool to evaluate the PV system installation. Moreover, many installation factors have been investigated such as; wiring material, cables specs, shadow effect and protection devices.

ACKNOWLEDGMENTS

I want to earnestly thank my supervisor, Professor M.T. Iqbal, for his educational guidance, without his support, I would not have accomplished this development.

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List of Nomenclature

PV	Photovoltaic
APV	PV module area (m^2)
ηe	PV electrical efficiency
kW	Kilo watt
KWHs	Kilo watt per hour
Si	Solar irradition kW/m^2.day
Ah	Ampere hour
ROI	Return of investment
GW	Giga watt
BEopt	Building energy optimization software
Homer	Hybird optimization modeling software
ΔT	Change in time
M_F	The total mass loading of PM
E_{abs}	The particulate matter mass absorption
E_{scat}	The particulate matter mass scattering
D	Duty cycle
Vi	Input voltage (V)
Vo	Output voltage (V)
P_{max}	Maximum power (W)
V_{max}	Maximum voltage (V)
I_{max}	Maximum current (I)
C_{in}	Input capacitor (F)
C_{out}	Output capacitor (F)
ΔI_l	The change the indictor current value (A)
V_{rms}	The squar root of the mean voltage value (V)

1. CHAPTER 1 INTRODUCTION

With the rapidly growing human population, the need for electricity, water, and energy is also high. Factories are increasingly producing the best technologies with the hope of harvesting natural resources such as sunlight. While most of the natural resources are non- renewable and can deplete, renewable energy is an alternative source that has been gradually increasing. New electricity production should change and renewable energy systems could play a major role to minimize non-renewable energy use. Homes in Saudi Arabia are currently using electricity mainly for cooling purposes. The types of air-conditioning systems used are window-type systems and mini-split systems, consuming 52% of the total KSA electricity consumption [1]. The electricity is only produced by fossil fuel in KSA and it has a negative environmental impact.

For example, In Qatar, almost every building has air conditioning which increase the consumption by 70–80 % [2]. Moreover, The Gulf countries are the highest energy consuming countries in the world and the residential sector has a major role to increase the consumption [3]. The energy usage difference between these areas and Saudi Arabia is more than 50 kWh/m^2/year [1], which is enormous. In ideal situations, houses could produce electricity using a solar PV system and run air conditioning units.

This would greatly reduce electricity required from the grid for cooling purposes. Solar energy is one of the clean and renewable alternative sources that have been undoubtedly environment-friendly. As such, a considerable number of people use the solar panels for energy purposes, particularly because of the readily available sunlight in most regions such as Saudi Arabia.

1.1 Electricity Production and Use in Saudi Arabia

The use of electricity and resulting CO_2 emission in Saudi Arabia is increasing rapidly, as shown in figure 1-1, which is one of the largest challenge for the new government of the country [4]. However, the residential sector is getting financial support from the government to reduce the citizens' electricity bills, but within the next few years, this support won't exist because of the increasing population and dramatic fluctuating oil prices.

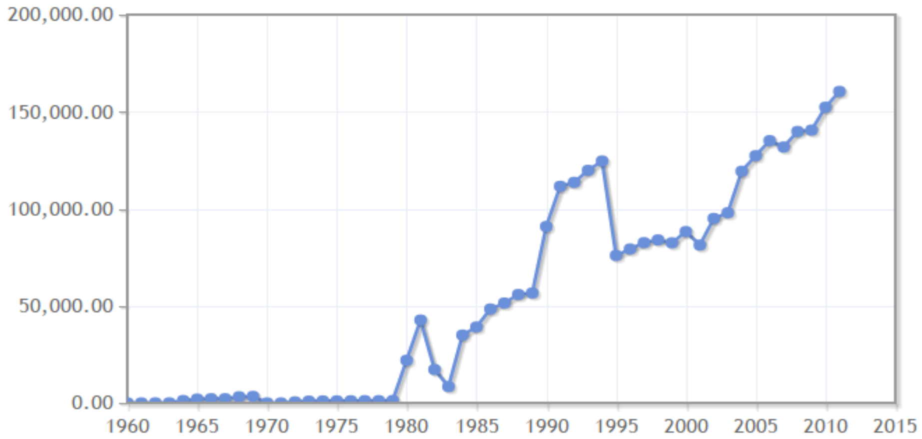


Figure 1-1 CO2 emissions from electricity consumption (kt) [5]

King Abdullah University (KAU), had a 2 MW PV plant installed at Jeddah city, and lunched in May 2010. It has 9300 modules of 215 watts each with 11,600 m^2 and it is going to produce 3300 MWh/yearly of renewable energy [6]. The total cost of this photovoltaic grid-connected power plant was 21 million $ [6]. One of the world's largest solar parking project is the North Park Project located in Dhahran, Saudi Arabia. It is located at the head office of the oil company Saudi Aramco, which has a 10 MW capacity to cover all the 4,500 parking spaces [7]. The Farasan solar power plant is going to produce a 5 MW, the project is a ground mounted PV installation using thin-film technology, with a stand-alone PV plant system to feed Farasan island energy demand, in south of Saudi Arabia [6].

1.2 Related Work

Saudi Arabia is the world leader in water desalination with 30% of the overall global desalination production and the government of Saudi Arabia mentioned plans and targets for reducing the energy use [8]. Half of the water demand is generated by groundwater resources, whereas the desalination plants generate the other half of the demand. However, a major risk of water demand–supply is due to the electricity consumption cost [9]. KSA energy usage is increasing yearly about 4.8% in the last decade and oil and gas production is increasing by only 1.36% in the same duration [10]. The relation between the two percentages are almost the double, which means the energy production is leading cause of financial inability. The target goal for green energy source is solar energy, and the economy of Saudi has experienced enormous PV development in recent years.

There are also short-term projects, in which the implantation of two PV industrial projects is expected to cost $200–500 million [11]. The ingots/wafers, silicon, and perhaps thin-film solar cells required for solar systems are the three major options anticipated to be using more than 50 MW [11]. These projects should attract the research companies within these fields to anticipate and enhance the solar energy business. The Phoenix Solar Company planned and built the 3.5 MW PV project in January 2013 named as “PV park in Riyadh’’ [12].

1.3 Methodology

In the past twenty years, the demand of residential cooling has increased enormously, while the electricity generation in Saudi Arabia is expected to be doubled by 2025 [13]. Solar energy could be expanded to meet growth as demand increases. Solar energy could be used for the generation of the required electricity to power typical air conditioners. PV modules’ efficiency depend on four parameters: location and sunlight availability, installation design, orientation with altitude, and materials used.

However, even if all these parameters have been achieved, there are other depending factors, such as dust, shade, clouds and maintenance that will affect its efficiency [14]. Solar energy is a major target, as peak solar radiation levels typically occur with peak refrigeration and air conditioning demands [15].

People are not surprised when they read that Saudi Arabia is one of known countries to have high directional normal sun radiation [16]. Renewable energy resources remain over wide geological areas, where the energy produced by the sun is considered as a clean energy source. Due to high level of solar radiation routinely experienced throughout the whole year at Qassim, Saudi Arabia, houses need to use air conditioners at maximum levels and for long hours. Moreover, the high sunny hours about 9-12 hours per day which provide a potential energy for residential applications in Saudi Arabia [17].

1.4 Literature Review

This literature search is to identify the best technologies to convert solar energy into air cooling for residential application. Air conditioning is a tempting area for solar energy use, also it is estimated that 45% of house energy consumption is used for cooling. Furthermore, 40-50% of all electricity produced in KSA is consumed by residential sector as shown in figure 1-2 [18].

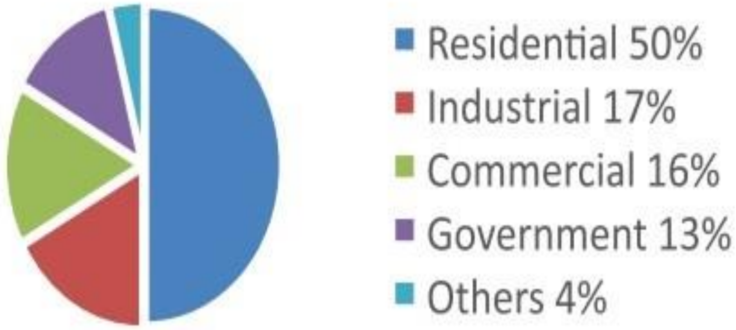


Figure 1-2 Distribution of Saudi electricity consumption by sector in 2012 [18]

Solar energy is a major target for any energy source, as peak radiation levels typically accured with peak refrigeration and air conditioning demands. There are two known methods to convert solar energy to cooling energy: an absorption chiller, and an evaporative cooler. Solar cooling can be classified further into two main categories, namely electrical and solar thermal [19]. The first category, electrical solar cooling system, consists of electron-generating solar technologies that drive cool air, well known as the vapor compression cycle. The second category, solar thermal, are solar cooling systems which are divided into two types: open cycle systems, and closed cycle systems. This section will examine two systems of air conditioning using solar panel technology by describing their systems as well as their schemes. This part will examine two air conditioning application namely Coolerado C60 solar powered air conditioning and Csiro Heating Ventilation and air condition (HVAC) technology.

1.4.1 Coolerado C60 Solar Powered Air Conditioning

Colorado lunched recently it is six tons air conditioning systems that are capable of cooling an area up to 3,000 ft^2 [20]. The Coolerado air conditioning only utilizes a 600 Watts of power energy which is a low amount of energy for a typical air conditioning system. There is no refrigerant used within the system of the Coolerado air condition system [20, 23]. It is application is suitable for homeowners because of it is energy efficiency capability. It is connected to only a four-photovoltaic solar panel.

How the system works and its scheme?

It has an air drawing system that consists of Electronically Commutated (EC) motorized impeller, which draws a most of the air into the Coolerado.

From the Figure 1-3, “the air is drawn in and channeled into 2 –inch thick filter to eliminate any fine particle and dust from the air [22]. The air is then channeled through the heat and mass exchange system, where it is saturated with water, and half of it expelled back into the atmosphere at the top of the unit. The other half cooled air is channeled into the building” [22].

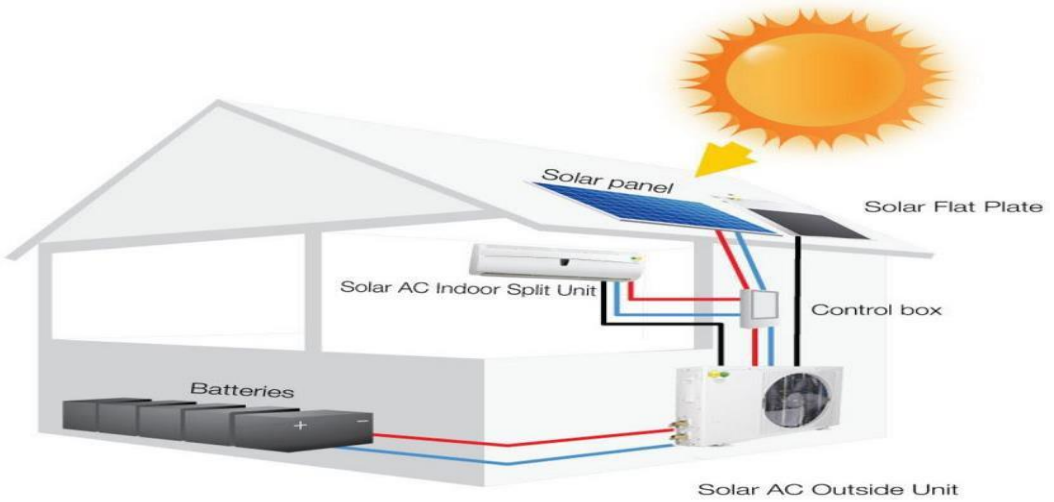


Figure 1-3 Coolerado system connected to the PV solar panel [24]

The AC fan and the solenoid valve are the only two mechanical parts of the Coolerado system. which is used for drawing and eliminating air and saturating the air with water respectively. After that it is channeled into a heat exchanger. When operating, the system utilizes 4 gallons of water per hour. The solar split unit is used for regulating cool air into depending, while the solar control box shows in figure 1-3 above control the amount of power supplied to the panel for the operation of the heat exchanger [20, 23]. When the PV solar panels are at 73 degrees Fahrenheit, each of the connected solar panels produces 200 Watts.

When the panels are hot with the summer heat, the PV panels can attain a 150-degree Fahrenheit, which cuts the energy supply with up to 30 percent [22]. This problem is however resolved by channeling the air system unused in the heat and mass exchange system to the PV panel cooling them in addition to maintaining 40 percent degrees’ cooler causing it to gain 15 percent of power from the PV panels.

Table 1-1 shows the solar cooling in different system.

Table 1-1 Solar thermal based on solar cooling systems

Open cycle	Closed Cycle
Adsorption cooling	Absorption cooling
Solar assisted heat pumps	Desiccant cooling

1.4.2 Absorption Cooling

A single-effect absorption chiller process of the thermodynamic system includes; evaporation, absorption and regeneration [26]. The system can be made more efficient by adding a stage to increase heat transfer efficiency; this is known as double-effect [26]. A disadvantage of this systems is that they are complicated, and contain moving parts. A flow loop is required in this system to obtain the heat exchanger effect. Moreover, adding a high-pressure loop will make the heat transfer within the loop more beneficial during heating purposes.

1.4.3 Csiro's Solar Heating Ventilation Air Conditioning (HVA) technology

The technology solution aims at cutting the energy cost in Austrian homes as well as reducing greenhouse gases emission. The Csiro air conditioning technology can, however, be used for three applications which can be integrated into its system [21]. The technology uses photovoltaic solar panels to supply the power demand necessary for the cooling. It supplements the power supply from the photovoltaic solar panel with the grid electricity which provides a fraction of energy demand for the system.

How the system work and scheme?

According to ECO Citizen Australia 2013 “the process begins working by heating the water using the solar panel systems after that is stored in the hot water tank system” [25].

The hot water stored in the reservoir is used for various applications including the air conditioning system throughout the building or home. From the figure 1-4, the water connected to the systems is essential for reducing the need for gas or electricity [23]. A portion of the water from the tank is diverted into air conditioning unit that is split into two compartments.

The hot water is channeled into a heat exchanger in the first compartment of the air conditioning unit. The same compartment where hot water is a channel, air is also drawn into this compartment. The hot water is used for heating the air entering the compartment from the outside via the vents of the unit.

Figure 1-4 Csiro solar air condition system connected into home [25]

The two grey bots in the middle of the house shown in Figure 1-4 represents the split compartment where the desiccant wheel is contained which dries the air which after that is ducted inside the building show with blue color. [22, 23] It also absorbs materials and moisture in the second compartment of the unit which is dried in the first chamber containing heat exchanger.

The heat exchange also assists in the drying of the material and the air which is channeled into the evaporative cooler that causing a stream of cool, dry air [21]. The heat exchanger is essential drying the ducted air channeled to the evaporative cooler creating an effect of a stream of cold air. [20] The cool, dry air is ducted into various partitions of the building using, cooling them. There are some disadvantages related to Csiro; high set-up cost and limited power supply to fixed area.

1.4.4 Adsorption Cooling

Solar adsorption can also be classified into two categories: Phys sorption and chemisorption [27]. These categories utilize a surface phenomenon where gas molecules are attracted to the adsorbent surface. Open cycles use liquid sorbents and rotating desiccant wheels, due to the heat exchange between the liquid and solid adsorption. A disadvantage for this system is the huge size and mass, due to many required components, the cost of adsorption chillers is high.

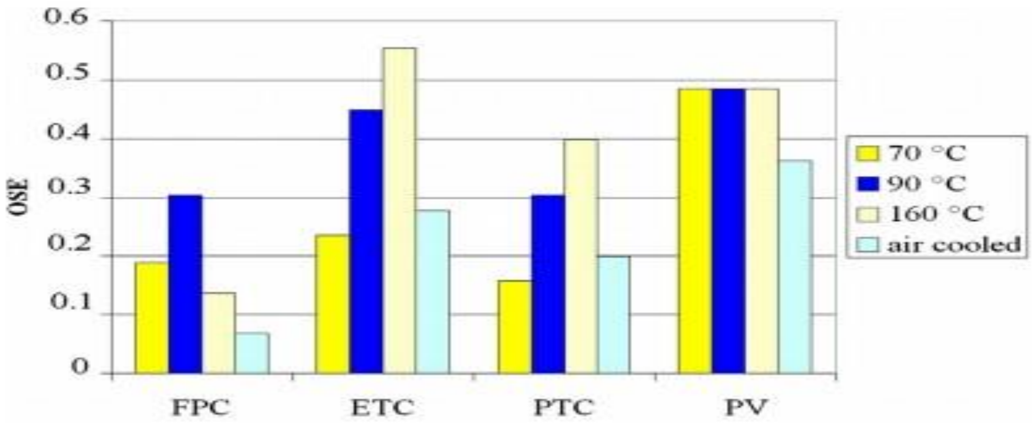


Figure 1-5 Efficiency results for four different solar cooling [28]

Figure 1-5 shows overall daily efficiency of the cooling systems; Flat plate collector (FPC), Evacuated Tube Collector (ETC), Parabolic Trough Collector (PTC) and PV [28]. At the three temperatures stages of 70 C^o, 90 C^o and 160 C^o. For the above three solar collectors compared with original chiller driven by PV, the graph result illustrates PV cooling efficiency as the second option after (ETC).

However, some of these technologies are still under development and not commercially available.

1.5 Recent developments of Solar Thermal Cooling Technology

Currently, there are studies on solar air condition applications have been applied to provide small scale solar cooling systems. The novelty in the cooling cycle using a small scale solar driven ejector cooling system. Furthermore, the system is designed such that it can be used for cooling and heating for a 16 m^2 room size and 1.5 kW load [28]. Desiccant cooling is a method for solar cooling in which heat is absorbed and converted through an evaporation process. A diagram is shown in Figure 1-6 illustrating the system mechanism.

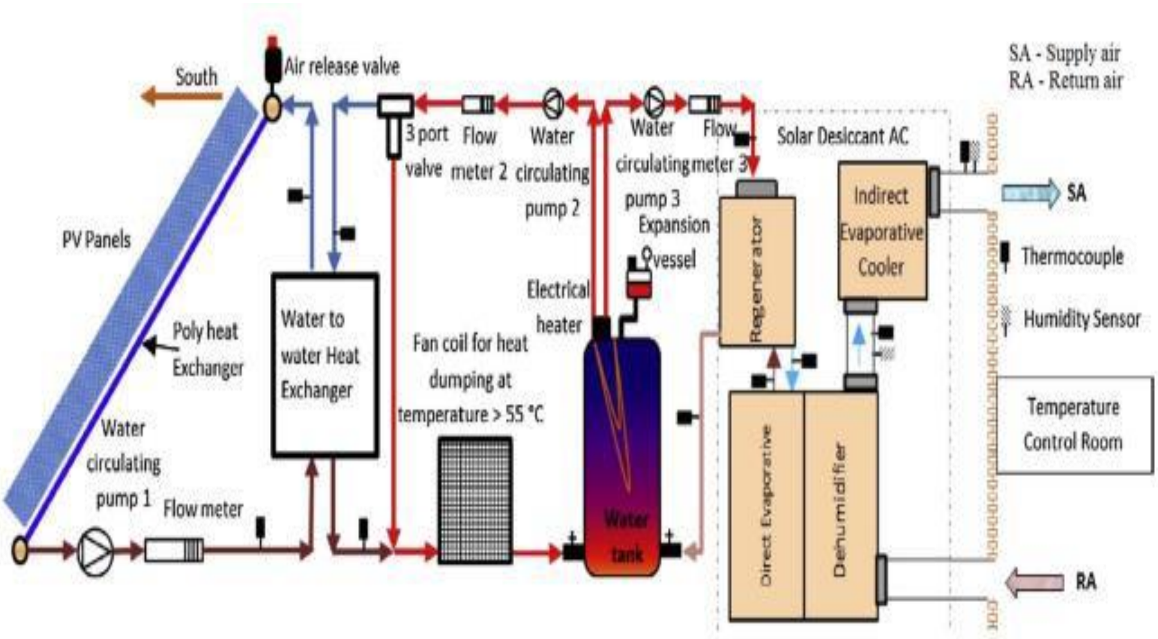


Figure 1-6 Desiccant cooling system [29]

PV collectors are combined to the Desiccant system shown in figure 1-6, due to providing thermal heat and electrical power to run the system. The air flow rate will reduce electrical consumption by the exhaust system and reach effective heat exchanger and evaporative cooling performance.

Moreover, it exposes the usage of solar energy with the waste heat from the PV collectors in cooling application [29]. The uses of evaporative cooler are to lower the temperature and increase the humidity of air by using the heat of evaporation, changing the water in liquid form to vapor.

The desiccant wheel is basically a heating coil to increase the liquid temperature when it circulates within the process. The tube heat exchanger allows the air to travel inside the desiccant coated tube. The cooling water flows surrounding the tubes, and cools the desiccant material on the dehumidification [26].

1.6 Some Case Studies

A case study with a similar objective of this research, has considered a typical house off grid located in Bihar and using PV system to generate electricity [30]. The average daily solar radiation is 4.9-7.0 kWh/m2, and the temperature in summers vary from 35-42 C^o and cool winters vary from 0-10 C^o [30]. This case study has considered a house consumption of 20 kW per day, and the total number of panels are 26. The PV system design of 26 panels and 185 watts each to generate the house required electricity [30].

Second case study of PV system residential applications, it mentioned the economic impact of using PV systems with battery storage. However, it resulted that installing PV (system1) in a grid connected house is not economically feasible in Sweden [31]. However, it is noticed that by adding a battery storage (System2) to a residential PV system in a two floors house in Sweden, it gave a lower amount to the net present value (NPV), as shown in figure 1-7 [31].

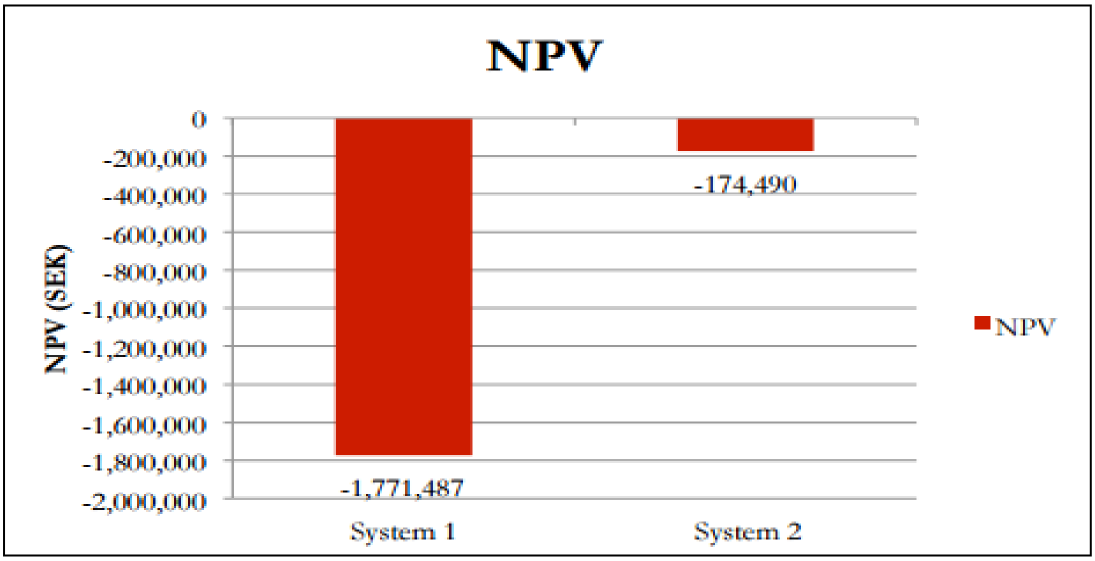


Figure 1-7 NPV of PV system without batteries (system1) and with batteries (system2) [31]

Third case study of PV system residential applications in Italy. The thought is to examine the working conditions of a system consumptions, that allows the greatest self-utilization of the energy produced by a 3.7 kW PV system and 3.8 kW ground source heat pump [32]. The system results are shown in figure 1-8, the design of the above specifications has been done to have a worldwide decision about balancing between electricity generated and electricity utilized [32]. Moreover, the solution depends on three factors; climate zone, loads appliances and system optimization.

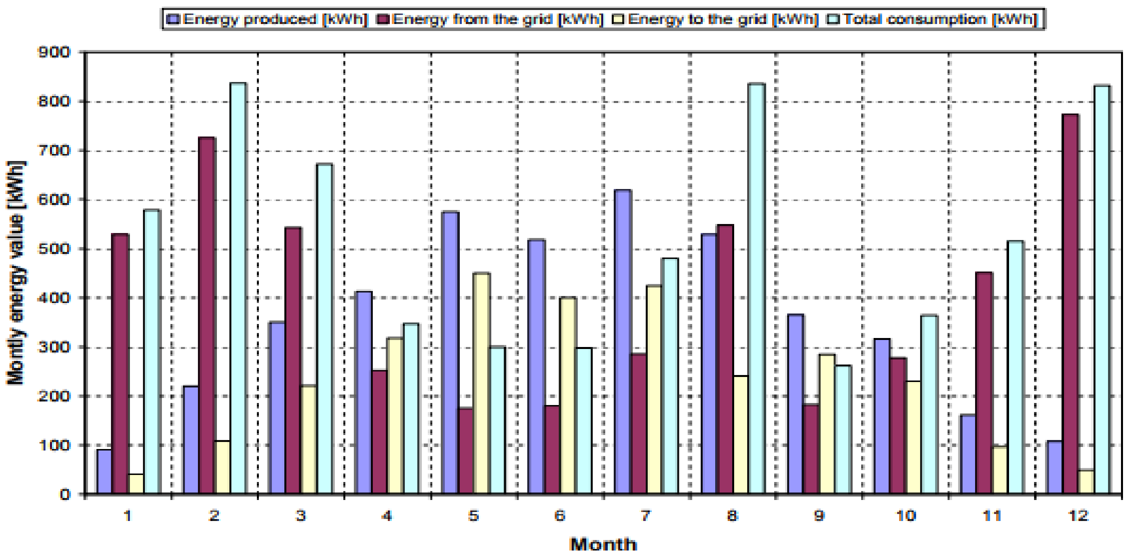


Figure 1-8 Monthly cumulative values of the various energy components [32]

Fourth case study conducted by Bergin et al., (2017) was informative and detailed research, regarding atmospheric particulate matter influencing the solar panels energy production [33]. An interesting point in this study was the dust and PM modeling, and their effect in the performance of the solar energy against the global changing environment, which was calculated according to equation (1-1) below:

$$\frac{\Delta T}{\mathrm{PM_F}} = -\frac{1}{\mathrm{PM_F}} \sum_{i=1}^{n} (E_{\mathrm{abs},i} + \beta_i E_{\mathrm{scat},i})\mathrm{PM}_{\mathrm{F},i} \tag{1-1}$$

“The current installed solar energy capacities for both India and China are estimated to be ~6 and ~65 GW, respectively, based on these values, the reductions in power generation due to dust and air pollution are calculated to be ~1 and ~11 GW, respectively” [33]. The previously quoted sentence has some weakness such as; PM mass varies from region to another. Moreover, Authors mentioned the PM mass variation, which is logically making the output of equation (1) not too accurate [33]. However, the contribution of their research is significantly presented, which is going to improve the performance of the solar energy against the global changing environment [33].

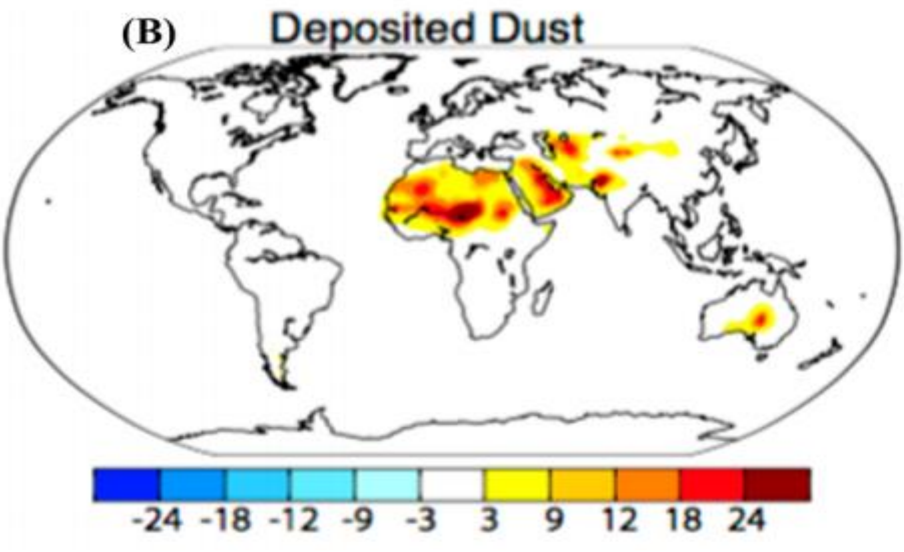


Figure 1-9 Dust PM deposition [33]

1.7 Objective of The Thesis

This thesis desires to address the following research questions: Given a typical Saudi residential cooperative,

1. Is a solar PV system, practically and economically interesting for home owners?
2. Dose a storage battery system makes solar PV more economically feasible?
3. System sizing using software; Homer, Beopt, and Simulink. Determine, if the PV system based solar house make sense for Saudi Arabia?
4. Do the shadowing and dust effect the PV system harmfully in Saudi Arabia?
5. Is the PV system economical and reliable within the selected area?
6. Develop a dynamic model of a PV air-conditioning system using MATLAB/ Simulink.

1.8 Thesis Outline

Chapter one is a brief introduction of the thesis and the objectives are presented. Also, a literature review about the history of using solar panels energy as a cooling source. Chapter two is about sizing a PV system for a house by using Beopt and homer software. Which includes the house measurement and energy consumptions to be implemented to both software, due to PV system simulations and analysis. In chapter three, a dynamic PV system modeling is presented. With the proposed boost converter and the load demand for the house which is without grid. The power flow is managed through MPPT system, the proposed PV system is modeled using Simulink. Chapter four, the architecture of the house and solar panels installation was done by HelioScope software. A discussion has been done about the effect of shadow on the PV system through several scientists' view. Chapter five, summarizes this work and recommends further investigation that can be done based on the thesis output results.

1.9 Conclusion

This chapter discussed the available studies of both non-grid and grid connected residential PV systems with or without battery storage. Moreover, this section illustrated different cooling technologies that were achievable for solar cooling. Three common cooling systems were discussed; desiccant evaporative cooling, absorption chillers, and adsorption chillers. Illustrated two deferent type of air conditioning systems which are powered by solar energy in the market; Coolerado C60 and Csiro’s.

2. Chapter 2

Sizing of a Photovoltaic System for a House in Qassim, Saudi Arabia

2.1 Introduction

In the past twenty years, the demand of residential cooling has increased enormously from 40 GW to 120 GW in Saudi Arabia [34], making a significant demand on the electrical grid consumption during the summer months [35]. Solar energy could be expanded to meet demand increases. Solar energy could be used for generation of the required electricity to power typical air conditioners. PV modules' efficiency depend on four parameters: location and sunlight availability, installation design, orientation with altitude, and materials used. However, even if all these parameters have been achieved, there are other depending factors, such as dust, shade, clouds and maintenance that will affect its efficiency. This paper focuses in evaluating the PV system performance for a chosen house in Qassim. Additionally, it will indicate multiple options for electricity production for residential applications. This research is to identify which methodology is valuable to convert solar energy into air cooling for residential application. Air conditioning is a tempting area for solar energy use, as it is estimated that 45% of house energy consumption is used for cooling. Furthermore, 10-20% of all electricity produced is consumed for refrigeration and air conditioning [36]. Solar energy is a major target for any energy source, as peak radiation levels typically occur with peak refrigeration and air conditioning demands [37].

2.2 Installation of PV System in a House

The primary issue to consider while designing a successful PV system, is ensuring the panels are tilted in such a manner to obtain maximum sunlight exposure. Below, a photo of a house on which such system is applied. In spite of the fact that the PV panels are installed fixed and without tracking system, these panels were tilted to the exact location altitude point which is 26° towards south. This system is yet adequate to meet the energy demand for this house.

Figure 2- 1 The selected house photo - North view and the sun direction - East.

Typical houses in Saudi Arabia are similar to the house shown in Figure 2-1. The roof is flat, and could be used for PV system installation. Batteries and inverters could also be stored on the roof in a purpose-built small shed. The roof is accessible from inside the home, and a person could go up and dust the PV installation when necessary.

2.3 Thermal Modeling for The House Using BEopt

Thermal modeling of the house is needed to determine how to load data. Free BEopt software is used for thermal modeling of the house [41].

The actual measurements of the housr are used in the BEopt design of the home to start calculating the energy consumption. Figure 2- 2 shows the house actual area to design the model based on it.

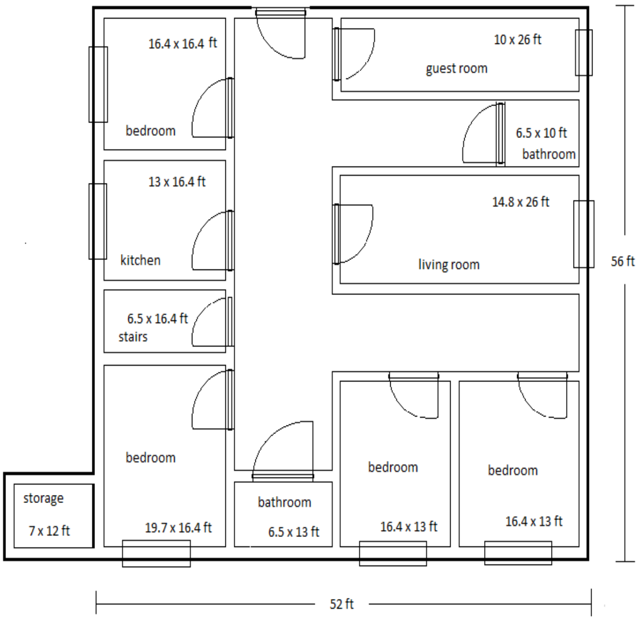


Figure 2- 2 The house actual measurements

Using BEopt software and house measurements, house is designed into a model with all actual characteristics. Moreover, data include house measurements, walls material, heat insulation material, windows, roof and doors, all appliances, ventilation, and air conditioners are typical of people living in the house, as shown in figure 2-3.

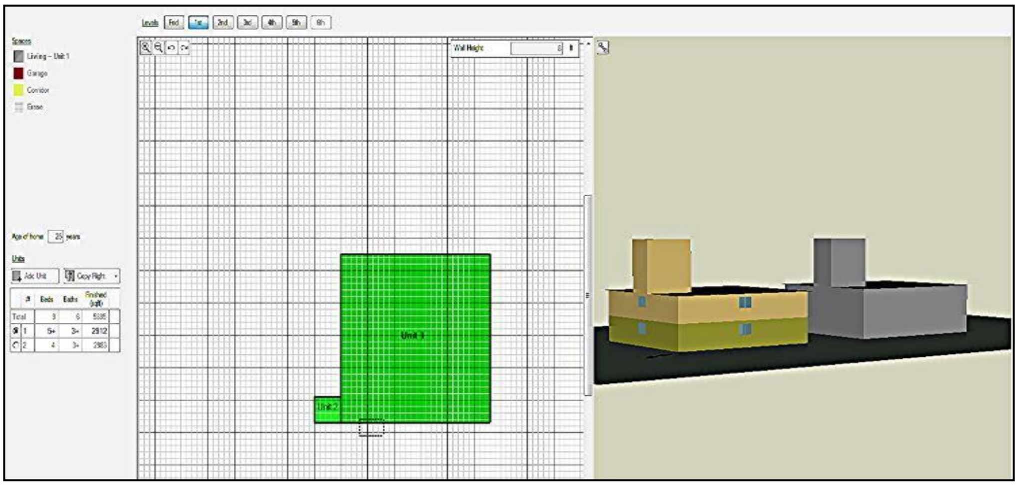


Figure 2- 3 The floors area Units and house characteristic

Using supplied input data and house design, BEopt calculates energy consumption in the house for each hour in a year. It uses NREL energy plus engine for calculations and site data, and solar resources from the NASA website. The house orientation is also an input to the software.

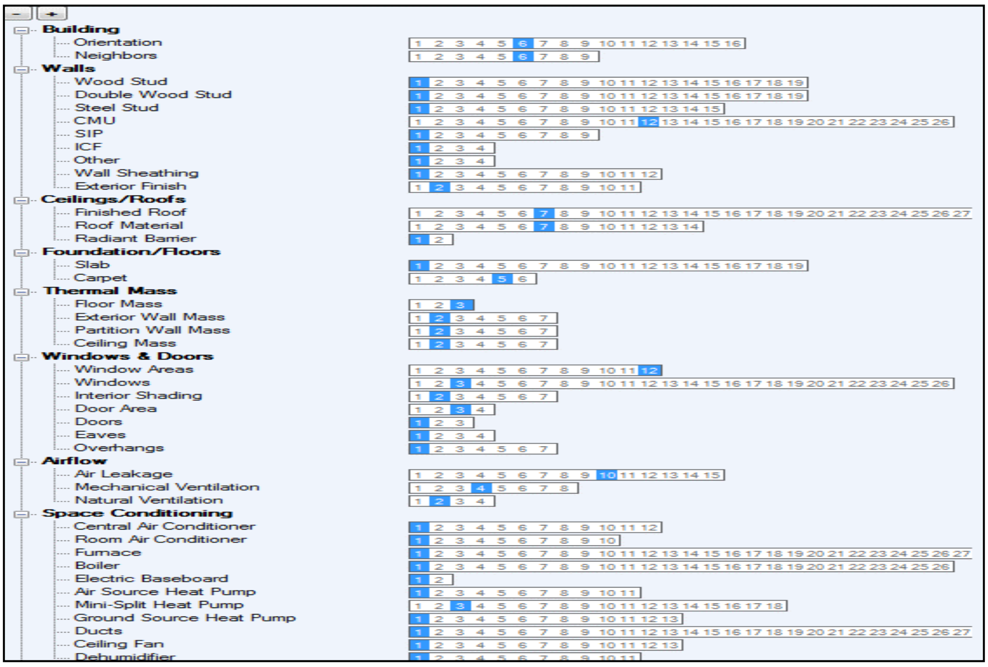


Figure 2- 4 Screenshot of the site design in BEopt

The house actual electricity monthly bills are shown in table 2-1, which depicts the total kWhr used was 23114 kWhr per year. The company charges here are including; meter reading, meter maintenance and bill preparation.

Table 2-1 The collected electricity bill of 12 months

Reading Date	Days in Billing Period	Read/Estimated	Total kWhs Used	Average kWhs Used Per Day	Total kWhs Billed	Actual Charge	HST	Residential Energy Rebate	Total Charge $
9/14/2015	21	Estimated	29	52	1096	125.34	16.29	0	141.63
8/24/2015	32	Estimated	740	23	740	92.53	12.03	0	104.56
7/23/2015	28	Estimated	652	23	652	84.06	10.93	0	94.99
6/25/2015	31	Read	1113	36	1113	137.99	17.94	11.04	144.89
5/25/2015	32	Read	1774	55	1774	210.77	27.4	16.86	221.31
4/23/2015	31	Read	2901	94	2901	334.85	43.53	26.79	351.59
3/23/2015	28	Estimated	2737	98	2737	316.8	41.18	25.34	332.64
2/23/2015	32	Read	3111	97	3111	357.98	46.54	28.64	375.88
1/22/2015	31	Estimated	3032	98	3032	349.28	45.41	27.94	366.75
12/22/2014	27	Read	1960	73	1960	231.25	30.06	18.5	242.81
11/25/2014	32	Read	1894	59	1894	223.98	29.12	17.92	235.18
10/24/2014	31	Read	1413	46	1413	171.03	22.23	13.68	179.58
9/23/2014	32	Estimated	691	22	691	91.53	11.9	7.32	96.11
		total	23114					total	2887.92

2.4 Simulations and Results

BEopt gives a yearly kW energy estimate for the 365 days needed, for the design withoutor with a PV solution. It can be obtained by BEopt software as shown below.

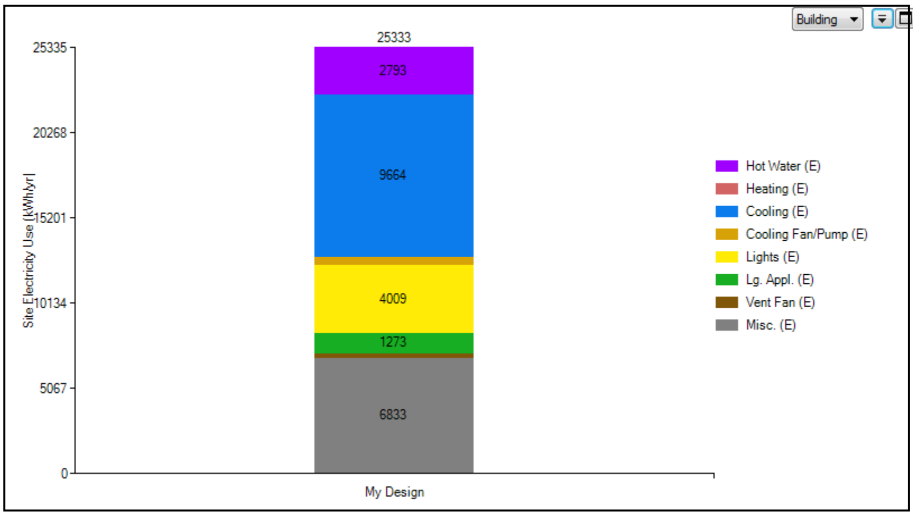


Figure 2- 5 Yearly energy consumption for the site without PV

It is clearly that most of the consumption goes to cooling as shown in figure 5 which is estimated around 9664 kWh/year, due to daily needs usage as a result of long and hot summer season in KSA. Table 2-2, shows the quantity and power rating of the air conditioning units and it is specifications. This in line with the available literature about the huge consumption of the electricity due to air conditioning [41]. The second large consumption was in miscellaneous load; electrical devices, kitchen electronics and any plug-in devices. It is estimated around 6833 kWh/year. The reason that heating is almost zero-consumption is that most of residents in Saudi Arabia prefer wood or propane over power resources as well as the winter season in KSA is very short and moderate. Reasons that made the hot water consumption around 2793 kWh/year are the use of hot tube and washing machines. The minor consumption was the ventilation section around 500 kWh/year, due to natural ventilation availability.

Table 2-2 Air conditioning parameters used in the house [43]

Amount	Type	Power rating (KW/h)	Cooling capacity (BTU/h)
5	Split Unit	1.2	18,000
3	Split unit	1.7	24,000

2.5 PV System Sizing by Homer Software

Upon entering all the above data into the Homer software [39], the program will provide an optimal electrical solution. Note, the changing load indicated is a result of using heaters and air conditioners at the house [37]. Site solar energy resource is shown in Figure 2-7. Load data provided by BEopt is used in Homer. The single line diagram of the system which contains load, converter, PV and batteries is shown in figure 2-6.

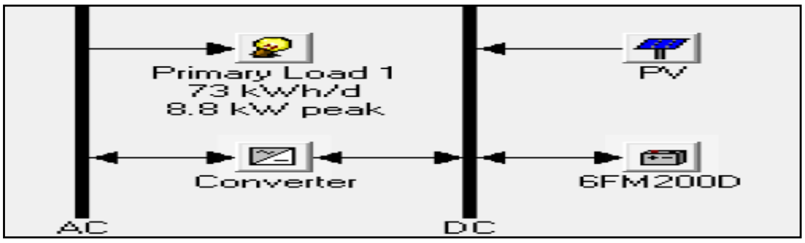


Figure 2- 6 System single line diagram

Below is the sun's radiantion curve for the selected location, the solar data were used to calculate the electricity production for the house.

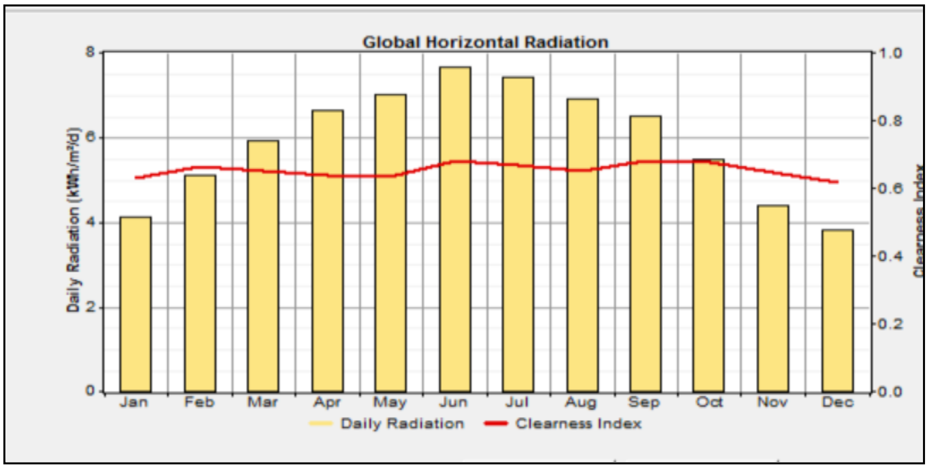


Figure 2- 7 Solar resource data using the correct site coordinates.

The actual load profile was included in the design, due to meeting the demand requirements by the PV system. Figure 2-8 shows the load profile in HOMER.

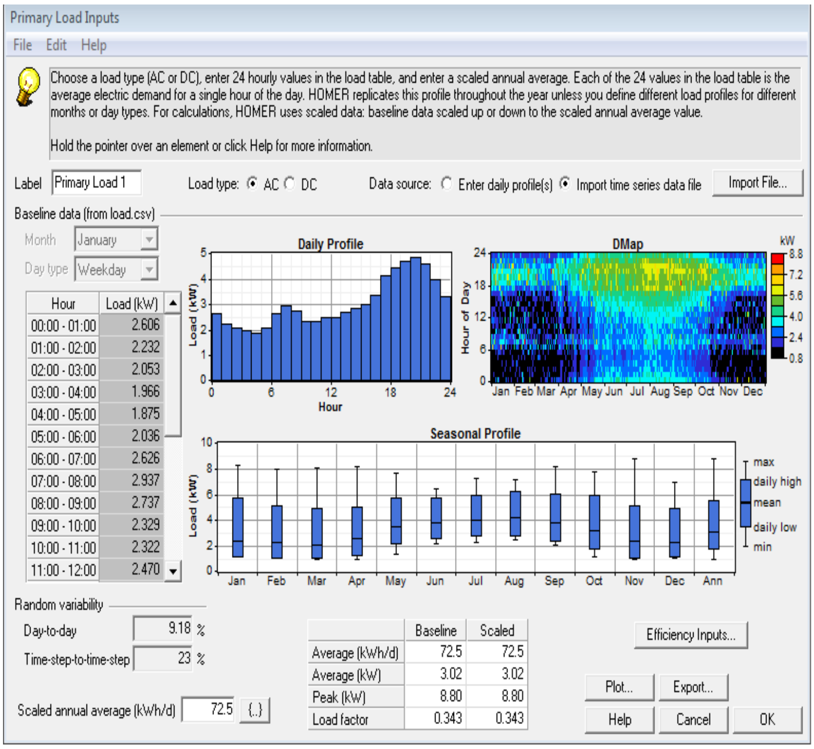


Figure 2- 8 Monthly average energy consumption for the site

The cost curve of the converter is shown in figure 2-9, which include the capital, replacement, operation and maintenance costs.

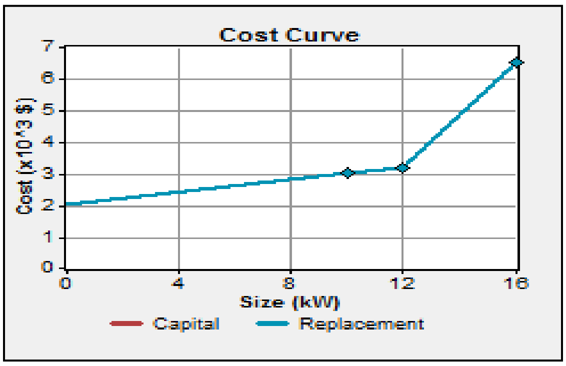


Figure 2- 9 Cost curve of the converter

The selected life time for the batteries was 4 years, Homer software can estimate the cost curve of the batteries as shown in figure 2-10.

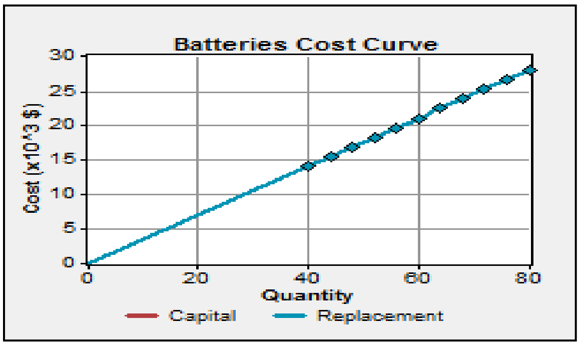


Figure 2- 10 Cost curve of the batteries

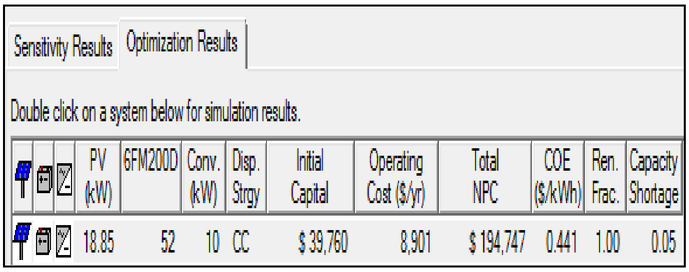
The possible scenarios and feasible systems for this model are shown in figure 2-11.

			PV (kW)	6FM200D	Conv. (kW)	Disp. Strgy	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage
			18.85	52	10	CC	$ 39,760	8,901	$ 194,747	0.441	1.00	0.05
			18.85	52	10	LF	$ 39,760	8,901	$ 194,747	0.441	1.00	0.05
			18.85	52	12	CC	$ 39,960	8,908	$ 195,078	0.442	1.00	0.05
			18.85	52	12	LF	$ 39,960	8,908	$ 195,078	0.442	1.00	0.05
			20.15	48	10	CC	$ 39,640	8,932	$ 195,173	0.440	1.00	0.05
			20.15	48	10	LF	$ 39,640	8,932	$ 195,173	0.440	1.00	0.05
			20.15	48	12	CC	$ 39,840	8,939	$ 195,504	0.441	1.00	0.05
			20.15	48	12	LF	$ 39,840	8,939	$ 195,504	0.441	1.00	0.05
			22.75	44	10	CC	$ 40,800	8,961	$ 196,837	0.443	1.00	0.05
			22.75	44	10	LF	$ 40,800	8,961	$ 196,837	0.443	1.00	0.05

Figure 2- 11 The system simulation and optimization results in Homer

The sensitivity variables for the system, shows the optimal combination to be as follows: 18.85 kW PV, 52 battery unit and 10 kW converter as shown in Figure 2-12. Levelized cost of PV energy by homer was 44 US cents/kWh, compared to the real (LCOE) of electricity generation from grid system highly subsidized between (1.3 – 6.93) US cents/kWh [44].

However, the long financial matters of renewables in Saudi Arabia stays positive, given that the sun powered PV system is almost free of charges for the next ten to fifteen years, unlike the grid cost which is more vulnerable to increase in the nearest future [44].



	PV (kW)	6FM200D	Conv. (kW)	Disp. Strgy	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage
	18.85	52	10	CC	$ 39,760	8,901	$ 194,747	0.441	1.00	0.05

Figure 2- 12 The system simulation and optimization results

By examining the cash flow results, we see that homeowners can expect a good monthly bill reduction by 100%, as shown in Figure 2-12. Note, the renewable fraction is one, indicating the size of the monthly energy bill discount equals 100%. Many homeowners are considering the value of installing a PV system, and the Return On Investment (ROI) should be in the green range. By evaluating Homer results and making a few simple calculations, the ROI was between 12 to 15 years.

Homeowners are sensitive to the upfront investment costs of installing a PV system. These results should be an encouragement for those considering such an investment. It is important to consider that one of the primary determinants of the energy production output is ensuring an optimal design an installation for maximum solar irradiance. Otherwise, the benefits may suffer [37]. Electricity power costs in Saudi Arabia have been settled in fixed terms. The power tariff for a house started at (1.33 US cents) per kWh for the initial 2 MWh every month and logically expanded to (6.93 US cents) per kWh for each unit utilized past 10 MWh every month [45]. By assuming that the PV system can generate an average 10-18 KWhs while the daily usage is around 55 KWh, so it might be feasible if the surplus will be sold to the main grid and taking in consideration the low daily consumption in winter seasons. Therefore, more KWhs can be sold to the grid in this situation, it might be economically feasible and worthy.

2.6 System sizing by BEopt Software with PV

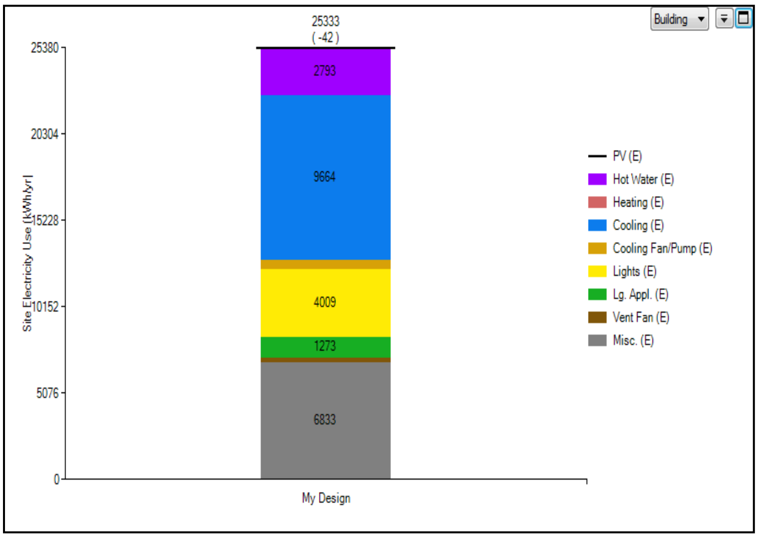


Figure 2- 13 The system energy consumptin and PV production

A PV system size determined by homer is also used in BEopt. The simulation results of BEopt shows that the PV system of 19 kW can supply the entire load. The reason behind that is due to most of the demand is cooling which is required in summer season, equally, sunlight or solar energy yield more in this season. Although the PV panels are fixed and tilted to the same altitude angle which is 26^{o} towards south, the system is still sufficient and meet the demand as shown in figure 2-13.

2.7 Conclusion and Discussion

PV systems are widely recognized and used throughout the world, but unfortunately, Saudi Arabia has not yet effectively embraced the use of such systems. As we know the energy consumption for each home is high, there is substantial benefit that could be realized [46]. Given the typical design and construction of Saudi houses, and with the aid of Homer and BEopt software, we can conclude that installing 19 kW PV system would be a beneficial as an alternate electricity source by excluding the grid consumption every month to zero.

The PV system was sized by Homer and BEopt, and the return of investment ROI results indicated about twelve to fifteen years for cost recuperation, which is fairly good, relative to a life expectancy of 25 years. The effectiveness and efficiency of PV system can be enhanced by reducing wiring system losses and using a micro inverter, improving reliability for homeowners [46].

3. CHAPTER 3

DYNAMIC MODELING AND SIMULATION OF A PHOTOVOLTAIC SYSTEM FOR A HOUSE IN QASSIM, SAUDI ARABIA

3.1 Introduction

Saudi Arabia is one of known countries to have high directional normal sun radiation over the whole year [47]. The energy produced by the sun is also known as a clean energy source. Because of the high level of solar radiation routinely experienced at Qassim, houses use air conditioners at maximum levels, relative to other locations with more cloudy conditions [48]. A block diagram of a typical house size PV system is shown in figure 3-1. A DC/DC boost converter is used in the PV system; its main purpose to achieve a higher dc voltage level. A DC to AC inverter is used to change the constant voltage signal to a sinusoidal wave voltage signal. The MPPT feature will extract the maximum power output of the system, by controlling the duty cycle of the boost converter and algorithm implementation [49]. The proposed PV power system is modeled using Simulink [50], as shown in Figure 3-1.

Figure 3- 1 The block diagram of a PV system for residential applications

The Homer results of the simulations that were obtained in chapter 2, show the optimal combination as being: 18.85 kW PV, 52 battery unit and 10 kW converter. By using this model, the house can expect a monthly bill reduction by 100%. Among all the generated results, Homer chose only one optimum solution with specific configuration, such as the inverter data as examples shown here in table 3-1.

Table 3-1 Inverter results

Quantity	Inverter	Units
Capacity	10	kW
Mean output	2.9	kW
Minimum output	0	kW
Maximum output	8.8	kW

3.2 Photovoltaic Energy Structure

The primary goal of using PV system is to extract electric energy from the sun radiation, the core device in that system is the PV. The cells combine together to make a module, and a group of modules create the PV array. In this design, there are two modules in series and twenty-eight in parallel to generate 48V DC bus and 16.8 kW to the system as shown in Figure 3-2. During the day hours, the load energy source is the PV arrays while in parallel charging the battery bank. Moreover, during the night hours, the battery bank will supply the load by electricity as discharging process.

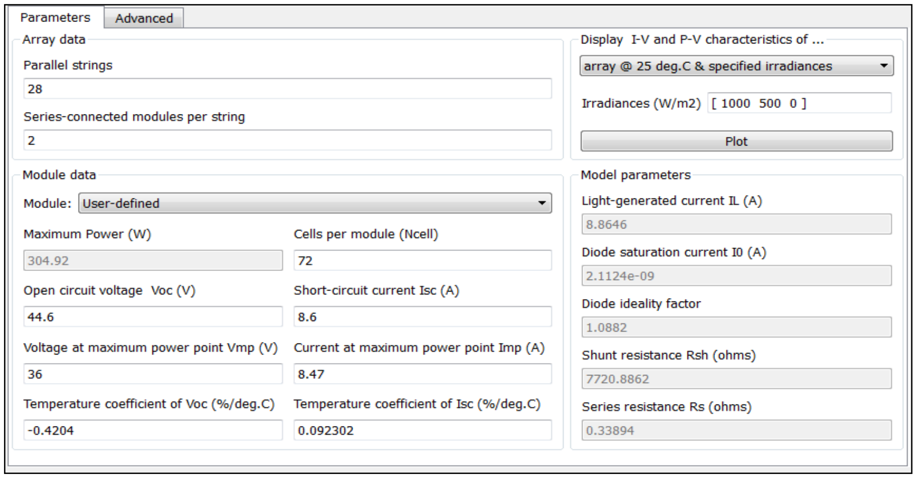


Figure 3- 2 Screenshot of PV parameters in Simulink

Two of the main factors that affect the PV module's output are the temperature and sunlight. In this design, the sun irradiation and temperature fluctuate. However, the value of irradiance fluctuates around 1000 W/m2, and the temperature curve also oscillates around 25 C^{o}, as shown in Figure 3-3.

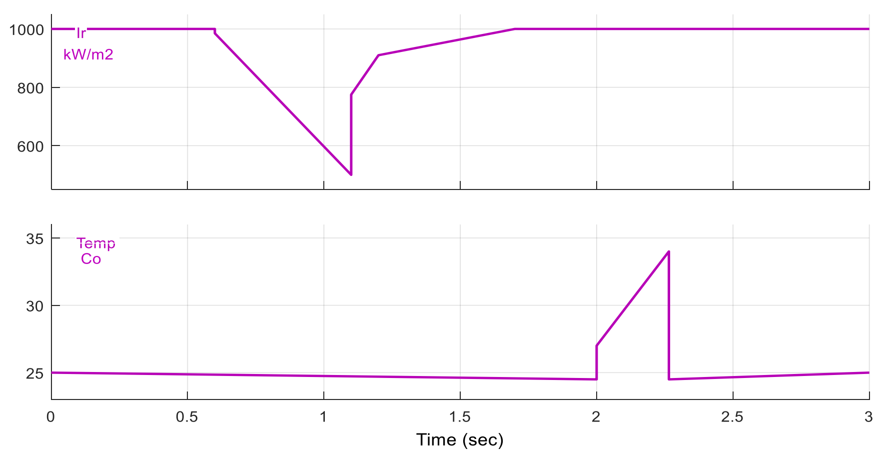


Figure 3- 3 The irradiance and temperature data

MPPT is implemented using the “Perturb and observe” method by controlling the duty cycle of the boost converter [53]. It is a widely used method, whereas voltage and current are applied to the function which controls the duty cycle value according to the relation given here:

$$D = 1 - Vi/Vo \qquad (3\text{-}1)$$

Since output voltage is nearly constant (as defined by battery voltage), the variations in the duty cycle balance the changes in the input voltage. As such, this maintains the current. The algorithm detects the point at which maximum power point can be tracked, hence:

$$P_{max} = V_{max} \times I_{max} \qquad (3\text{-}2)$$

For a given intensity of sunlight as shown in figure 3-4, the duty cycle is depending on PV voltage and current [54].

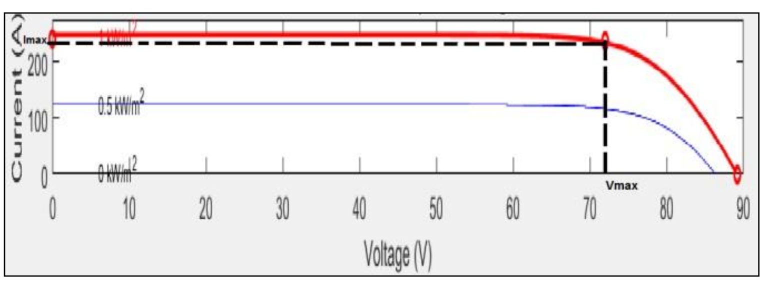


Figure 3- 4 PV current – voltage curve

The main key of this method is choosing a reference voltage, and keep changing the output PV voltage signal to decrees the power variation. (MPPT) is applied between the energy source and load, due to utilizing the available maximum power output of the PV. The algorithm is implemented according to the flow chart given here:

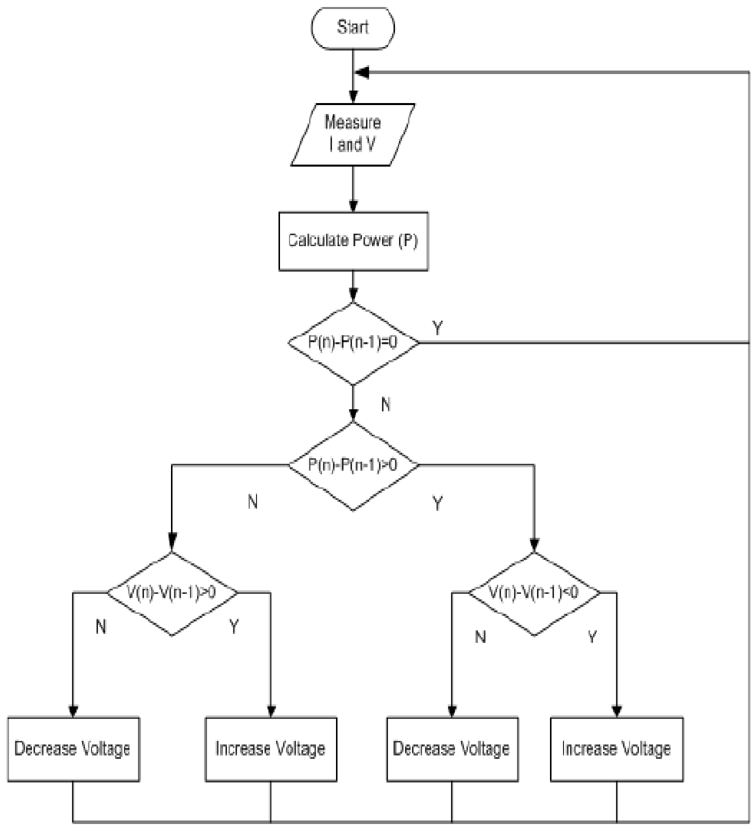


Figure 3- 5 Perturb and observe Algorithm [55]

3.3 Results and Discussion

Boost Converter Design

The boost converter will charge the 48V battery bank. The main parameters in the converter are: MPPT, PWM, Inductor and capacitor. The designed boost converter can deliver 17 kW DC power. There are equations for the boost converter, in order to find the input and output capacitors' values through equations (3-3) and (3-4) as follows [54]:

$$\text{Cin} \geq \frac{\text{Imax}*\text{Dmax}}{0.02*\,[(1-Dmax)*\,Vin\ x\ Fsw]} \qquad (3\text{-}3)$$

$$\text{Cout} \geq \frac{\text{Imax}*\text{Dmax}}{\Delta V*\,Fsw} \qquad (3\text{-}4)$$

Where, Dmax = maximum duty cycle, Fsw = switching frequency, ΔV = voltage ripple. Please refer to the Boost converter diagram as shown in Figure 3-6.

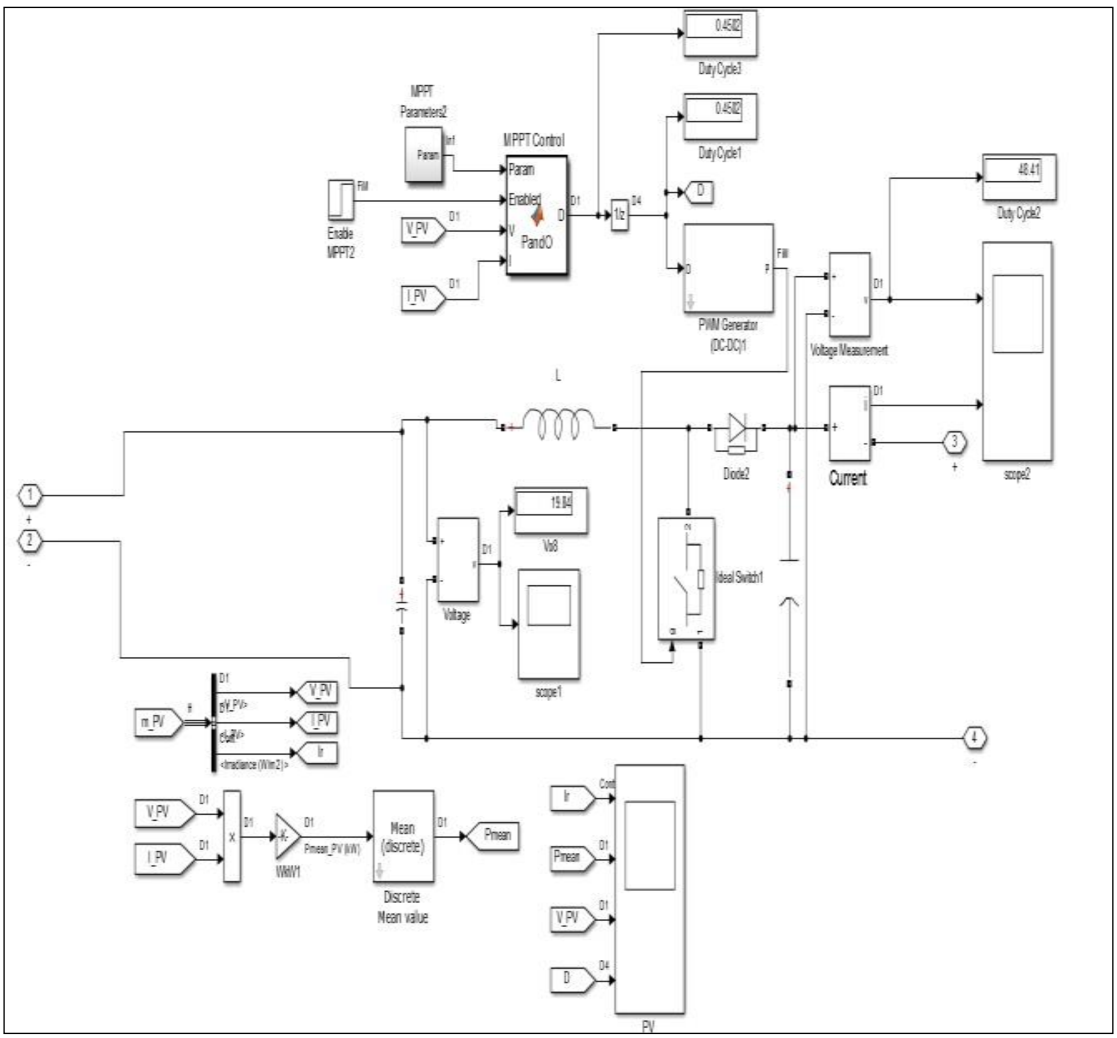


Figure 3- 6 The boost converter circuit

To make the inductor accumulate and raise the current, the frequency switch is implemented in the design. The capacitor stores and increases the DC voltage through an electric field effect. The Pulse Width Modulation (PWM) drive is implemented in the model to stabilize the converter output voltage. A capacitor unit is added to the system to store and smooth the voltage signal; refer to Figure 3-8. An online calculator is used to obtain the values of the inductor and capacitor parameters, as shown in Figure 3-7, the proposed value for *L* is achieved when these two conditions (5) and (6) apply [56]:

1- $\Delta I_L = 0{,}4 * I_{out}$ *for* $> V_{in\_max}$ *(3-5)*

2- The lowest value of *L* is achieved if $\Delta I_L = 2 * I_{in}$ for V_{in_min} *(3-6)*

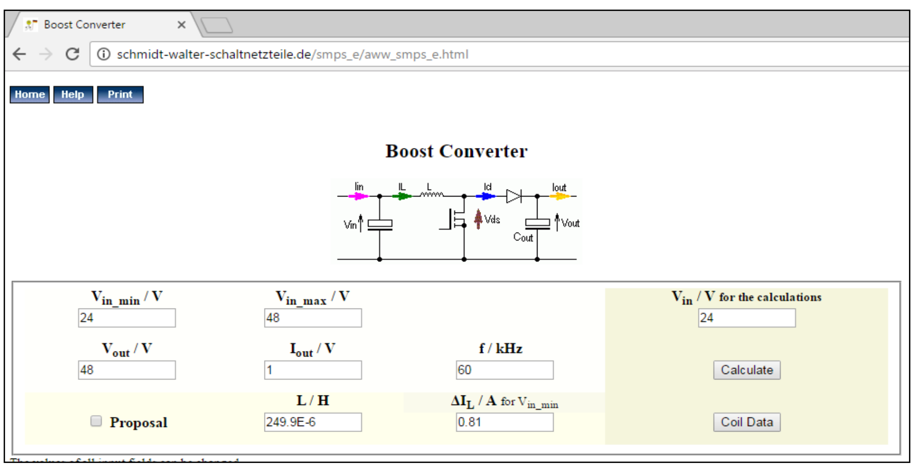


Figure 3- 7 Boost converter parameters values [56]

During the simulations, the ideal switch turns on and off systematically within milliseconds, to maintain the ideal voltage output with high efficiency. The switching inductor increases the output voltage by two times, as shown in the boost converter output voltage in Figure 3-13.

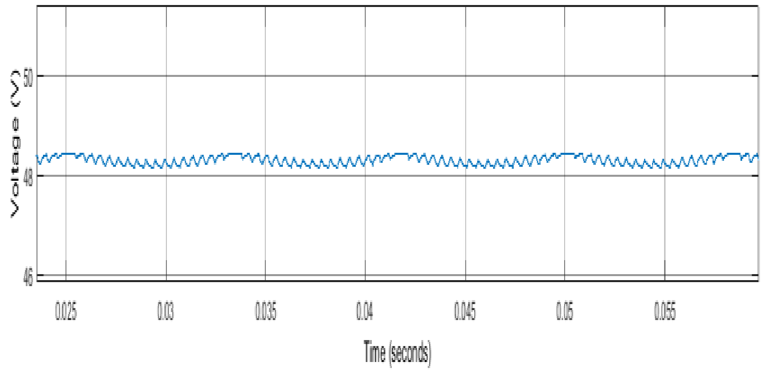


Figure 3- 8 The boost converter output voltage

In order to minimize the power losses by decreasing the number of instruments, no signal filters were used in the boost converter designed system. In spite of this, the signal was still high as shown in the Figure 3-11, at around 48. The output voltage is boosted from a minimum of 19.48 V DC to 48.41 V DC as shown in Figure 3-13, its semi-stable voltage signal is due to the inductor voltage ripples.

Battery Design

The battery bank size is significantly increased for an off-grid situation, to meet the demand requirements. The known battery type used for standalone PV system is lead acid, each battery from the total 52 has same specifications that are shown in Table 3-2 below:

Table 3-2 Battery parameters

Maximum capacity (Ah)	208.33
Cut-off Voltage (V)	9
Fully charged voltage (V)	13.06
Nominal discharge current (A)	40
Capacity (Ah) at nominal voltage	62.05
Internal resistance (Ohms)	0.0006

The battery model as shown in Figure 3-9, has 13 batteries in parallel, and 4 in series. Each battery is lead-acid, and has a nominal 12 V and 200 Ahr, the DC bus of these batteries carries 48 V DC. The maximum output values of the voltage and current are obtained by the nominal conditions of the load and discharging of the batteries [57].

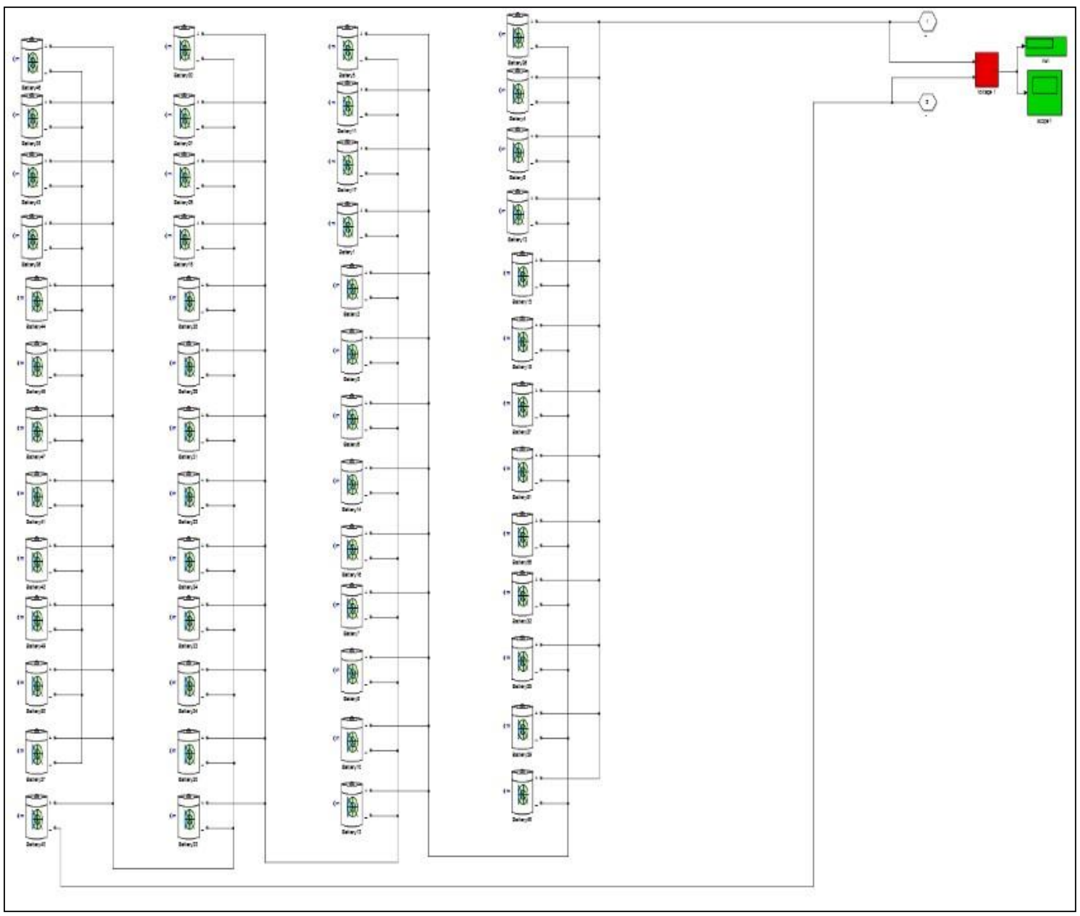


Figure 3- 9 Battery model

Inverter Design

The working principles of this inverter are as follows: there are four IGBT's switches (S1, S2, S3 and S4). When S1 and S4 operate under switching impulses, the transformer connection point voltage will have a positive voltage value. However, when S2 and S4 operate at the same time at the connection point of the transformer, it will have a negative polarity. This technique will generate an AC sinusoidal wave output voltage [54]. Two PV panels need to be in series to obtain the required input voltage 48V. The discharging voltage signal of the capacitor between the boost converter and the inverter, is the power signal source of the inverter. A block diagram of the inverter is shown below in Figure 3-10.

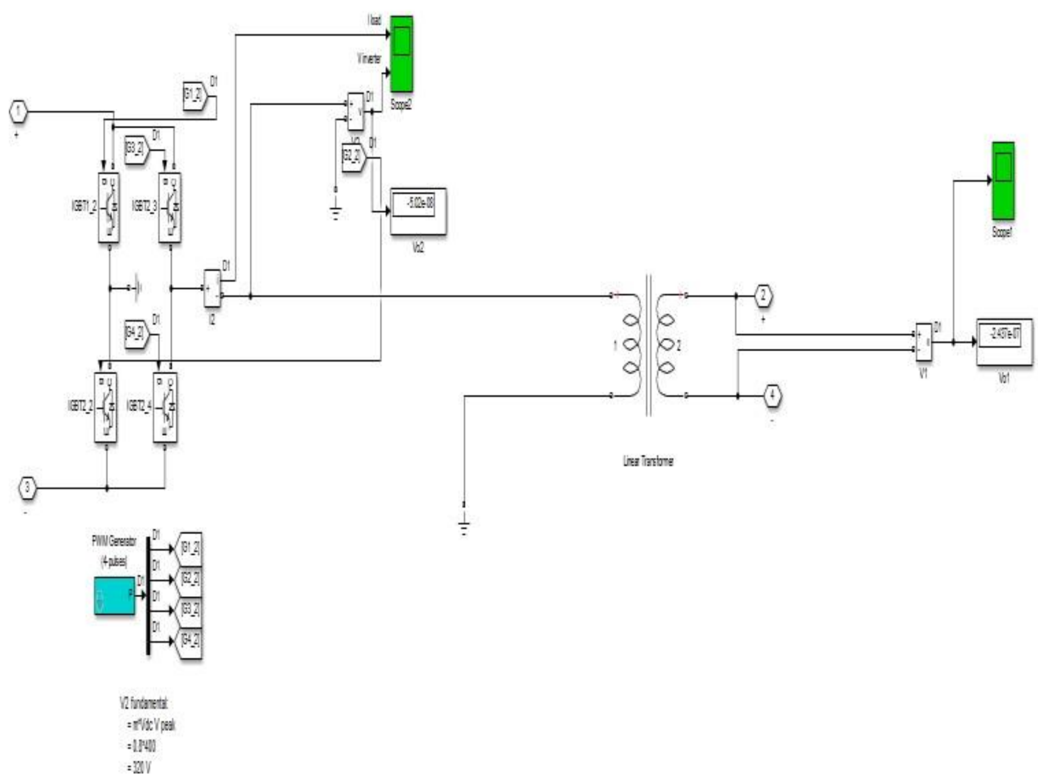


Figure 3- 10 Screenshot of the Inverter design

The output voltage and current of the inverter are shown in Figure 3-11. AC values of the voltage and current are (48.41 V, 360 A) peak respectively, but it still does not meet the load requirements. As such, the step transformer is added to the design. The high current value is a result of the current of the batteries and PV array. The inverter output power is presented as square waves of odd and even values, to obtain a pure sinusoidal wave form a high filtering circuits must be applied.

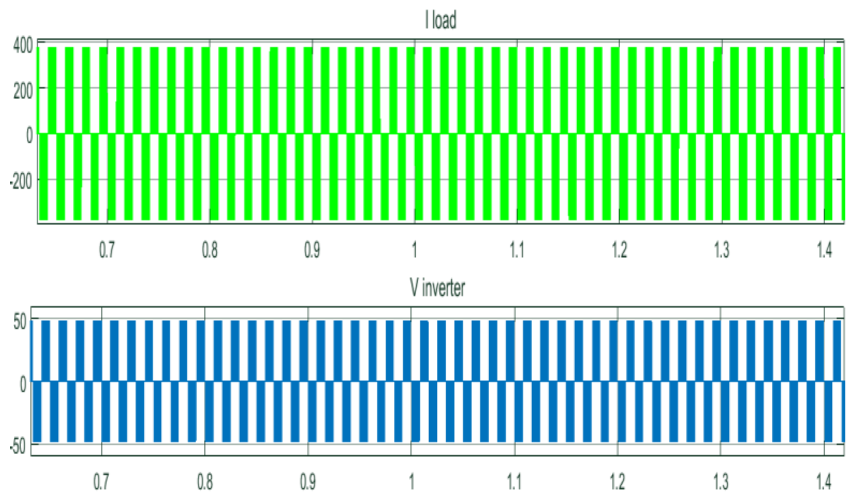


Figure 3- 11 The output voltage and current of the inverter

Transformer Design

The need for using a transformer in the model is to increase the AC voltage from 48 V to 230 V, which is the standard for houses' voltage in Qassim, Saudi Arabia. Figure 3-12 shows the transformer parameters.

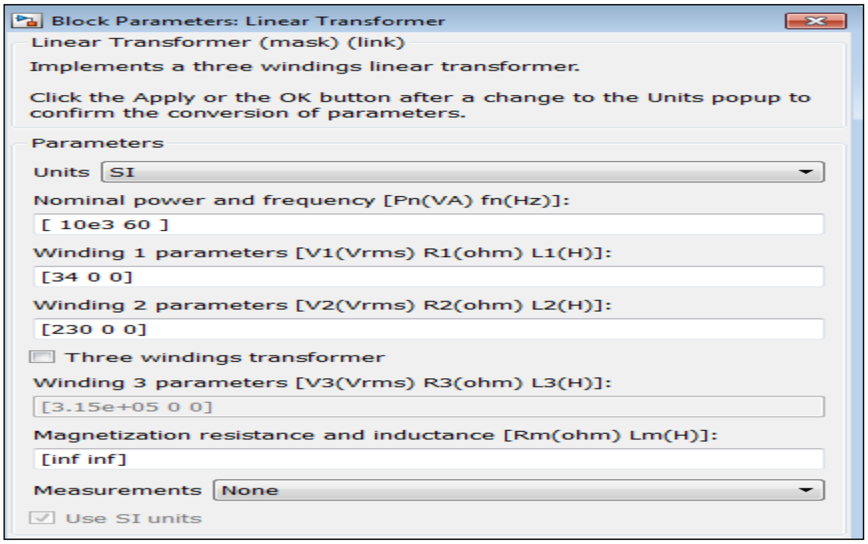


Figure 3- 12 Transformer configuration

Load Design

The load design here has resistance and inductor in series; this simulates the actual load structure. With 5.8 Ohm resistance and 0.5 mH, the model will resist aginst the flowing current, similar to the actual load. The equivalent circuit of resistor and inductor indicate an AC load, which is the chosen application from the system here. The resistor value was obtained by ohm's law P=V2/R, inductor value was taken from a load with same speacifcation [58]. The design is shown in Figure 3-13.

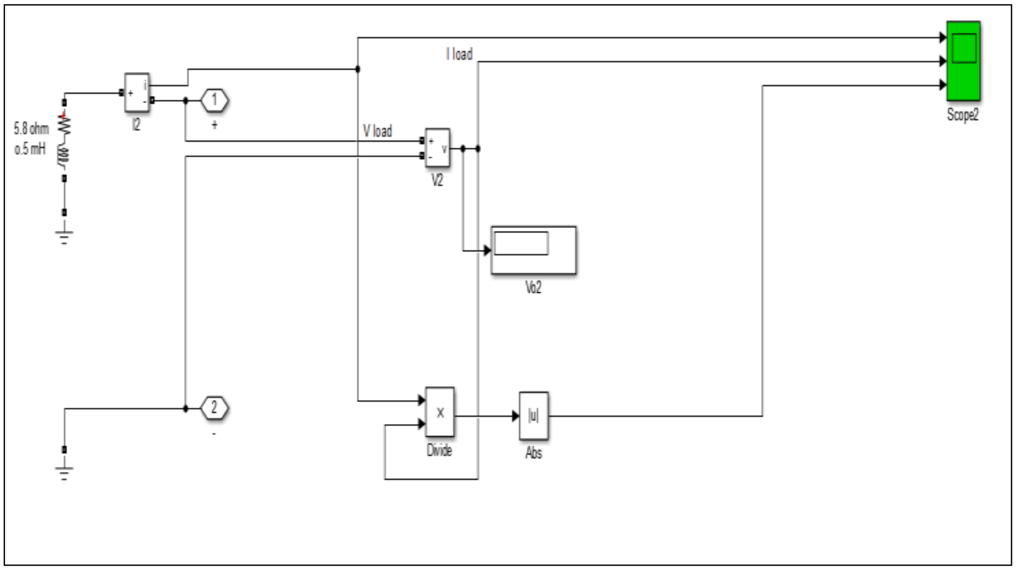


Figure 3- 13 Load design parameters

Figure 3-17 shows that the rms value of the voltage curve is 230 V AC, which is synchronizing with the standard voltage in Saudi Arabia. The rms value law (3-7) is given here:

$$V_{rms} = V_{out} / \sqrt{2} \qquad (3\text{-}7)$$

The load power curve is obtained by the product of the voltage and current curves in Figure 3-17. Moreover, the output power curve shows maximum value 19 kW which is the PV production, it will also cover the load average hourly consumption 9.9 kWh. The minimum output power is zero, which indicates it is night time, with no sun light and empty charge batteries. Figure 3-14 shows the control system output rejected the sunlight and temperature decreased pulses, as noted in Figure 3-4.

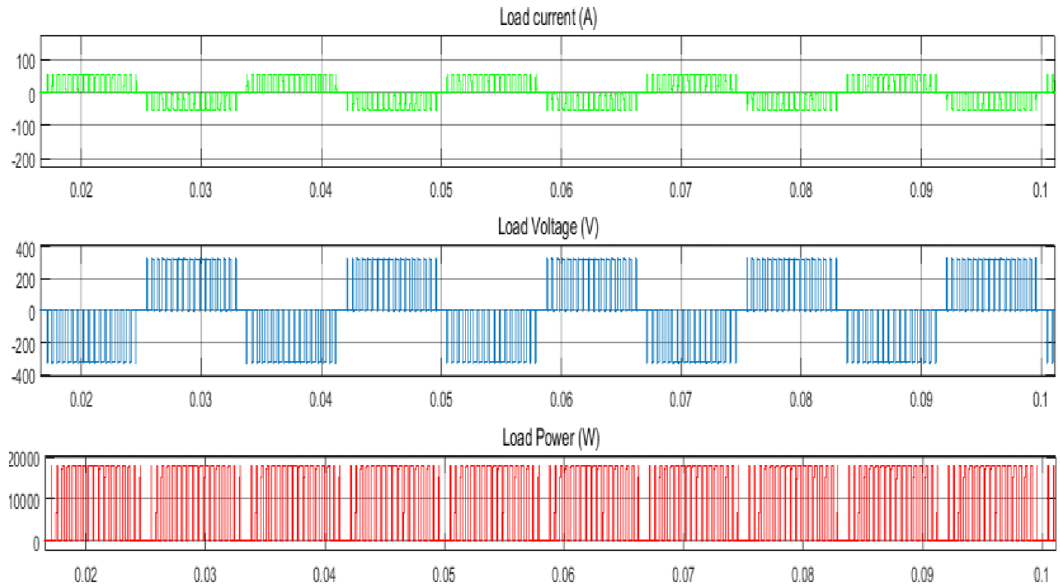


Figure 3- 14 Load output voltage, current and power

3.4 Conclusion

Many people in Saudi Arabia are considering using a PV system to provide electricity for their house, and this is their long-term goal [59]. The outline, which is covered in this paper, is the solar panel producing 48 V DC, and after designing and connecting the model to the system with the boost converter, MPPT, DC to AC inverter and step up transformer. The result was AC sinusoidal wave of 230 V. This design is ready to be converted to an actual system. The ripples in the voltage and current DC curves was due to the PWM inverter used in the model. Designed PV system can meet all energy needs of a typical house in Saudi Arabia. Simulink simulation provides details of power electronics and expected harmonics in the system. Due to air conditioning house load is inductive as assumed in the simulation. Design and implementation of such a system can greatly help house owners in Saudi Arabia to reduce their depending on oil.

4. CHAPTER 4

SHADOW, DUST EFFECT ON PV AND SYSTEM WIRING SIZING

4.1 Introduction

Some phenomenon such as solar irradiation, temperature, and shading are the factors affecting the photovoltaic arrays. Partial or whole shading is caused by adjacent buildings, clouds, trees, towers or telephone poles that affect the incident solar radiation and the cell temperature. The shadowing of the solar panels can reduce their efficiency.

Dust is a layer of small soil particles which are carried in the air by wind. They cover the solar panels' surface leading to limited sun light reaching the panels. This is called solar irradiance. Several sources can create dust, for example, soil erosion by wind, vehicle and animal movement, volcanic eruptions among others [60]. This is natural dust. There is also artificial dust that comes from cement, ash, limestone, carbon, calcium carbonate among others, which equally affects the efficiency of solar panels in different ways [60].

To avoid these losses a dust sensor should be used to alert the workers for cleaning. Dust has more impact to the radiation on the solar cell, also reduces the efficiency of the radiation angle. The dust accumulation can be cleaned in Saudi Arabia in many ways; human, tangential force, and cleaning by machines [61]. Cleaning frequency should be applied every time the accumulation becomes serious. It will improve PV performance based on the cleaning time schedule [62]. For instance, A small PV system of a house it might needs a cleaning process every week according to Saudi Arabia climate [62].

4.2 Shadowing of The Solar Panels

When a shadow falls on a group of PV cells, it reduces the total output by increasing the energy losses of the cells under a shade or the reduction of energy input into a cell [63]. The problem exacerbates when the shaded cells become reverse biased. Besides, when the array gets non-uniform shading, the problem worsens.

Shade affects the performance of many PV systems. Furthermore, it is challenging to measure the extent of shadowing on a solar panel because shadows move with the position of the sun, which changes throughout the day and the year. The source of the shade is another challenge because it determines the type of the shade. For instance, the shade of a tree is constantly changing as it sways with the wind or loses it leaves in some seasons, making the shade inconsistent. The impact of the shade depends on the area and the severity of the shade. It can cause mismatch resulting in loss of power.

An experiment conducted by Sathyanarayana [64]. sought to analyze the effect of non-uniform and uniform shading on the performance of the solar panel. In the experiment, the researchers used a rectangular PV panel and mounted it on an adjustable stand that was essential in investigating the influence of shading. The panel inclined 30 degrees towards the south. To analyze the effect of uniform shading on the solar panel, the researchers used butter papers in different quantities aimed at getting the shading at various percentages. This is shown in figure 4.1.

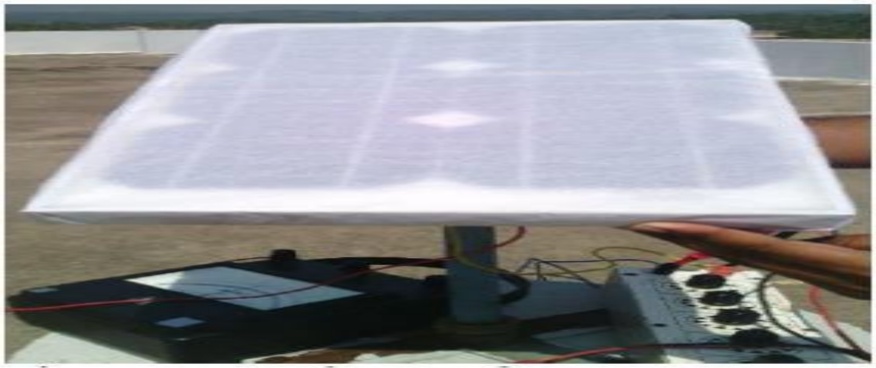


Figure 4- 1 A solar panel in uniform shading [64]

For the non-uniform shading, the researchers selectively shaded different regions with some physical objects that replicated buildings, birds, leaves, and cables, to analyze the impact. That is shown in figure 4-2 below.

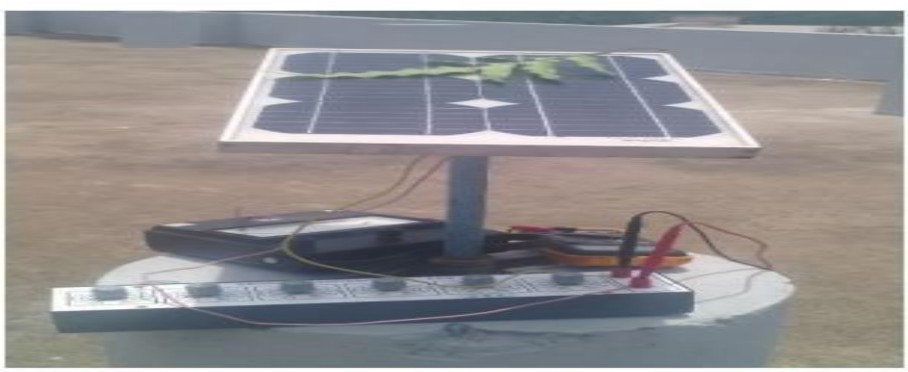


Figure 4- 2 Solar panel in non-uniform shading [64]

The researchers repeated each of the experiment three times to get reliable results; they reported consistent and average readings. Each of the experiments determined the conversion efficiency, fill factor, and power output. Results from the smooth shading showed the decrease in I_{SC} as the shading increased and formation of a linear relationship [64]. Resultantly, the growth in the uniform shading led to a reduction in the power output. Notably, the uniform shading allows the solar cells to receive an equal amount of insolation and therefore, the cells get equal sunlight. Consequently, the short circuit current that is directly proportional to the received insolation exhibited a direct relationship with the shading. Nonetheless, an increase in shading led to negligible variation in efficiency and fill factor. Besides, uniform shading has no impact on the cell performance or circuitry other than the significant reduction in the power output [63]. The table below summarizes the effects of uniform shading on the performance of the PV panel.

Table 4-1 Effects of uniform shading on the performance of the PV panel [64]

Sl. No	% Shading	Efficiency	Fill factor
1	0	8.35	78.20
2	25	8.50	80.66
3	50	8.63	80.88
4	75	8.78	80.80

On the experiment of the non-uniform shading of the solar panel, the effects realized were considerably different from the consequences of the uniform shading. For instance, a shade covering one complete cell area of the PV panel, the power output vanished completely. Conversely, if the shadow shaded the cells partially, the decrease in the power output was significantly proportional to the shaded area. Besides, the current production equaled to the least among the current outputs of the individual cells, which is attributable to the series connection of the individual cells making the entire panel [65]. The non-uniform shading conditions had different results on the solar panel. A crucial inference noted during the experiments of non-uniform shading on the PV panels includes the effect on efficiency and the fill factor. Shades of cables and leaves did not have a significant impact on efficiency because they covered a small part of the cell from receiving sunlight. The table below summarizes the effects of non-uniform shading on the performance of the PV panel.

Table 4-2 The effects of non-uniform shading on the performance of the PV panel [64]

Sl. No.	Object used for shading	Approx. area of coverage (%)	Efficiency	Fill factor
1	Leaf	9.061	6.01	68.10
2	Electric cable	0.72	7.85	79.02
3	Building model	19.82	2.46	62.63
4	Bird model	4.00	3.21	54.37

In photovoltaics, it is necessary to investigate shading caused by sun path or objects, but in this case the PV system is installed on the roof with no objects to cause shading effect except sun path effect and moving cloud. Moreover, Helioscope can generate a report of shading effect on the PV production. A screenshot of the software report as shown in figure 4-3, the highest solar access percentages were between May and August, due to the longer time of the sun light each day within these months. The results show that the average rate of reduction in the output power, due to irradiance transitions on the solar panels.

Shading by Field Segment

Description	Tilt	Azimuth	Modules	Nameplate	Shaded Irradiance	AC Energy	TOF[2]	Solar Access	TSRF [2]
Field Segment 1	26.0°	180.0°	56	18.2 kWp	1,993.2kWh/m^2	20.0 MWh[1]	96.5%	84.6%	81.6%
Totals, weighted by kWp			**56**	**18.2 kWp**	**1,993.2kWh/m^2**	**20.0 MWh**	**96.5%**	**84.6%**	**81.6%**

[1] approximate, varies based on inverter performance
[2] based on location Optimal POA Irradiance of 2,442.4kWh/m^2 at 26.4° tilt and 168.1° azimuth

Solar Access by Month

Description	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec
Field Segment 1	79%	81%	83%	86%	90%	93%	92%	87%	83%	82%	79%	77%
Solar Access, weighted by kWp	**78.7%**	**81.2%**	**82.8%**	**85.7%**	**90.2%**	**93.1%**	**91.9%**	**87.1%**	**82.8%**	**81.5%**	**79.4%**	**77.3%**
AC Power (kWh)	1,331.5	1,538.0	1,789.0	1,778.5	1,724.7	1,930.9	1,904.6	1,909.0	1,743.8	1,656.4	1,403.9	1,242.2

Figure 4- 3 A screenshot of Helioscope shading effect report

Sharp shading is mainly caused by surrounding objects or mismatch the solar panels spacing, it will affect the PV production enormously. However, in this case only partial shading occurred by the moving cloud and sun path, it will cause minor reductions of the PV output, as shown above in figure 4-3.

4.3 Google Earth and Satellite Imagery

Google Earth is an incredible apparatus for measurement of rooftop area [66]. A specific house in Qassim was selected in order to study its PV installation. Qassim is a typical Saudi Arabia city in the central area, and it is surrounded by desert as shown in figure 4-4. The chosen house can be regarded as typical house design for each city within the central region.

Figure 4- 4 Qassim location by Google earth

The exact location of the study area within the city is shown and pointed in figure 4-5, to start collecting house design data such as; walls, windows, roof and solar modules. This was mainly used to decide PV installation on the roof. PV installation layout also decide the PV wiring.

Figure 4- 5 The location and rooftop of the case study area

4.4 Wiring Layout and Design

This section aims to design the installation layout of a PV system within a typical Saudi house. HelioScope Software is primary fundamental tool in giving the most effective assessment of PV installation [67]. Previously the house PV size determined to be 18.2 kW array tilted 26 degrees towards south, to equal the house electric bill.

Major data should be considered before installing the PV system;

- The irradiation and temperature data of the site location.
- The short circuit and over current values of all the wiring materials should meet the system requirements.
- The system life time should be taken into account when buying the wiring parts.
- The roof available space should be considered as the installation area for the entire PV system.
- The current and voltage should meet the electric utility system standards.

Now it can be determined how large of an array the roof could accommodate through HelioScope. As shown in figure 4-7, 56 modules can be installed on the house top, in order to generate 18.2 kW facing south. Moreover, this software will evaluate the area surrounding the location regarding the weather and operation, the system output power profile will be presented per the design parameters. South faced fixed flat array model will be designed by Helioscope.

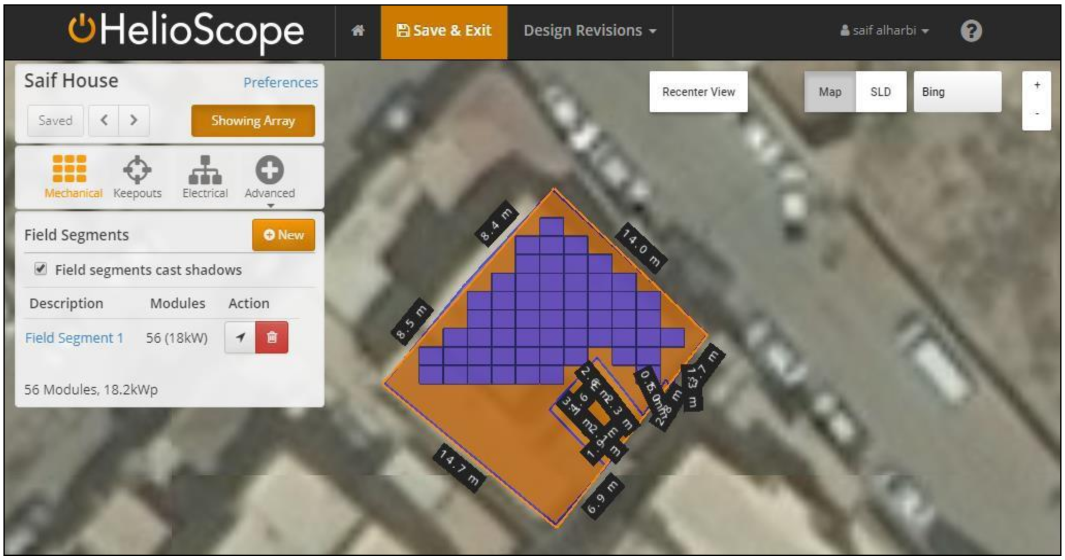


Figure 4- 6 HelioScope rooftop sketch and PV array model

The output power curve by the software in figure 4-7, shows maximum value 18 kW which is the PV production, it will also cover the load average hourly consumption 9.9 kWh. There are rapid fluctuations of the PV power output, due to multiple simulation factors; the moving clouds, wiring losses and sun path shading.

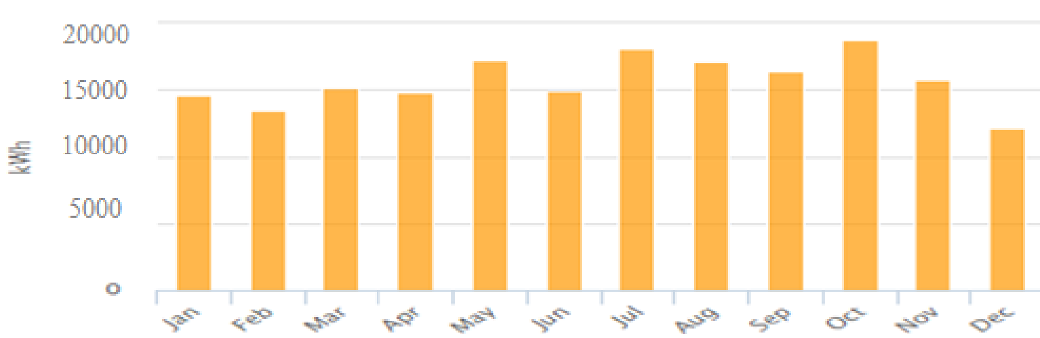


Figure 4- 7 HelioScope performance report of the PV

The software also can generate a chart illustrating the sources of System loss as shown in figure 4-8. The greatest loss is due to shading effect, and the minimum loss was due to AC system. Inverter saturation known as clipping, which is the extra DC power of the PV and the inverter reject it, the (MPPT) will adjusts DC voltage to reduce the DC power. When the DC power feeding the inverter is more than the inverter rating, the resulting power is clipped and lost, clipping losses comes as the second major loss by 23.07 %.

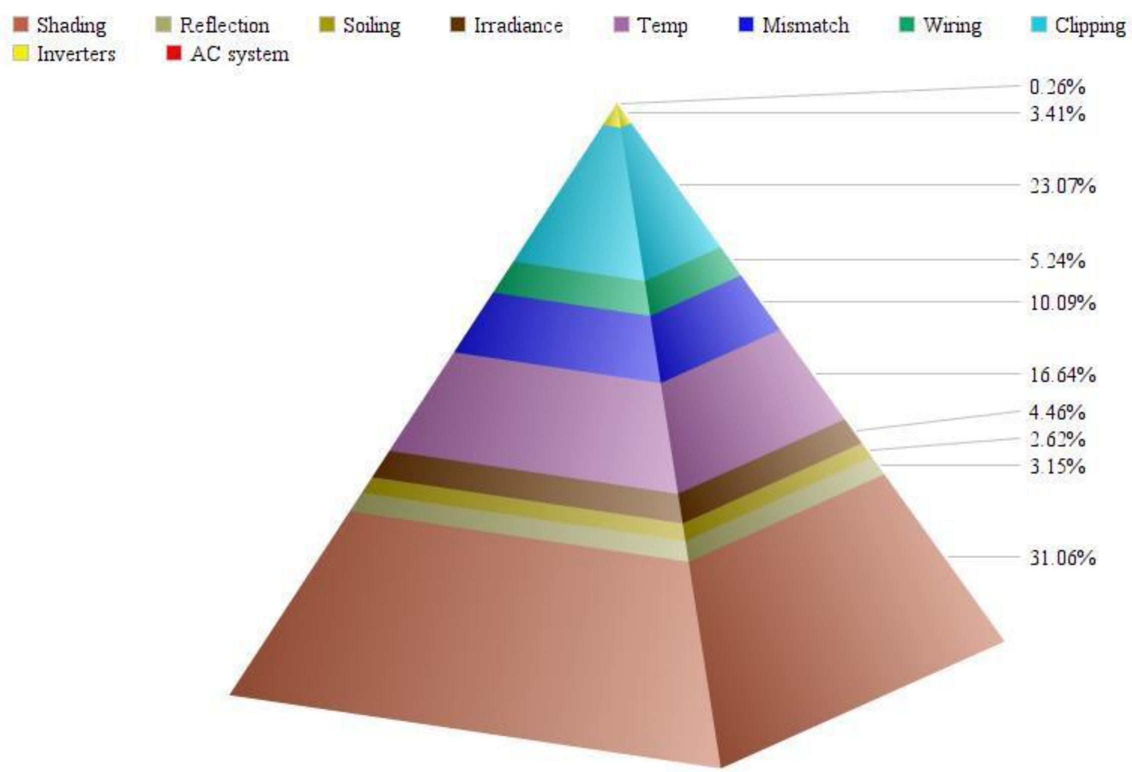


Figure 4- 8 System loss chart

HelioScope software can help automate array layouts, shade analysis, and electrical design. It contains 56 PV modules, battery storage, inverter, meter, disconnecting switches and circuit combiners. There were two proposed type of disconnecting switches; AC switches for the inverter block and DC switches for the (PV, battery and boost converter). Full single line diagram (SLD) of the proposed system is pictured below.

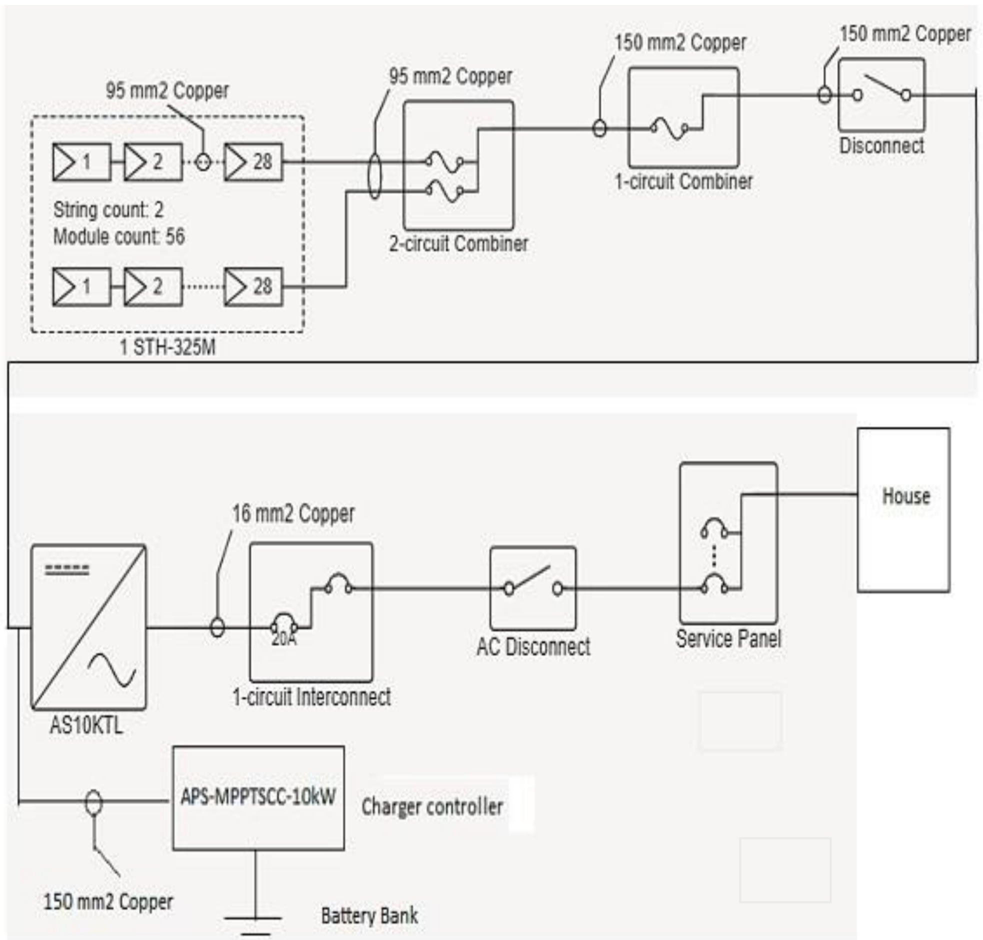


Figure 4- 9 Helioscope proposed SLD

Above HelioScope software proposed SLD, now the specification of each block is shown in table 4-3. The wiring configurations are important for effective installation, it can reduce the system losses and increase the safety of system operation. Moreover, all the system specification provided by Helioscope will be used during installation and simulation to achieve a higher level of PV production.

Table 4-3 The PV system specification of HelioScope SLD

Module Specifications	
56x 1 Soltech 1 STH-325M	
STC Rating	325 W
Vmp	40.4 V
Imp	8.05 A
Voc	49.5 V
Isc	8.72 A

Inverter Specifications	
1x Amerisolar AS10KTL	
Max AC Power Rating	10 kW
Max Input Voltage	1,000 V
Min AC Power Rating	0 W
Min Input Voltage	260 V

Wire Schedule		
Tier	Wire	Length
AC Branch	1x 16 mm2	48m
Trunk	1x 150 mm2	<1m
Bus	1x 150 mm2	<1m
String	2x 95 mm2	22m

Charge Controller Specs	
Frequency	60 Hz
Voltage	48-57 V
Battery Capacity	500-1000 Ah

Battery Bank Specs	
Voltage	12 V
Battery capacity	186 Ah
Battery amount	56
Parallel Batteries	13
Series batteries	4

4.5 Developing a Rooftop Measurement Data

AC cable needs to be sized to meet 125% of its load current. This result in wire sizes such as 14 AWG and 12AWG. For instance, the roof-mounted inverter tray cable is 10 AWG, and the circuit combiner of the PV strings is 2 AWG. Figure 4-10, shows the installation measurement in detail through Solar Design Tool for the same system requirement[65].

Installation Area	
Installation area length	20.33m
Installation area width	21.4m
Slope	flat (0.0°)
Installation area azimuth	180° (S)

Configured Layout	
Column spacing	25.4mm
Row spacing	25.4mm
Module orientation	landscape
Distance between tilted racks	0.14m
Tilt angle of modules	26°
Clearance at left	20mm
Clearance at right	20mm
Clearance at top	0.18m
Clearance at bottom	10mm
Total number of modules	54
Total number of rows	30
Layout length	1.97m
Layout width	26.41m
Area of array	104.57m²
North-south footprint of a single row	0.88m

Max. Values for Installation Area	
Max no. of modules	56
Maximum no. of rows	31
Max no. of modules in a row	2
Maximum row length	1.97m
Maximum column length	27.3m
Area if layout full	98.24m²

Figure 4- 10 Solar Design Tool system installation area [68]

4.6 Inverter, Transfer Switch and PV Installation

The inverter is used in this design to convert between DC to AC voltage, centralized inverter is one of the most common type of inverter used for PV application [69]. The main objective of the converter is to link between PV and load, since the output voltage of the PV is DC and the input voltage of the load is AC. Figure 4-11, shows the inverter circuit diagram for the PV system. If S1 and S2 are connected the transformer will receive a positive voltage pulse, also if S3 and S4 are connected the transformer will receive a negative voltage pulse, the switching will happen within milliseconds. The inverter uses an effective modulation technique which is the Pulse Width Modulation.

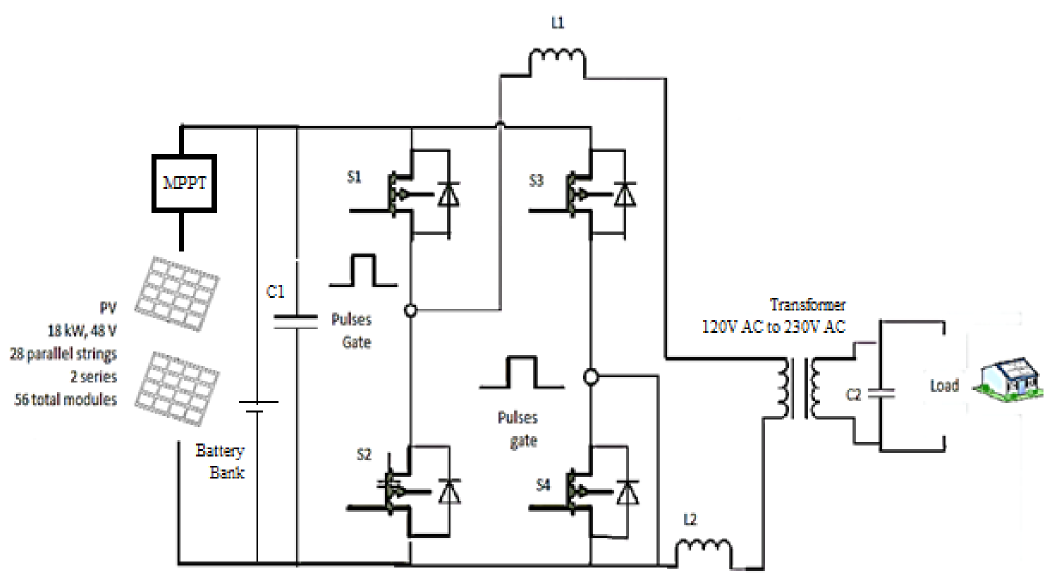


Figure 4- 11 The inverter circuit diagram

The Transfer switch, which is an automatic switch for a house load, that will change the voltage source instantly between an inverter and a grid connection. Off grid situation does not required a transfer switch to swap between the inverter and any alternating energy sources during night times, due to battery backup existence. Figure 4-12, shows the system equivalent diagram of a transfer switch.

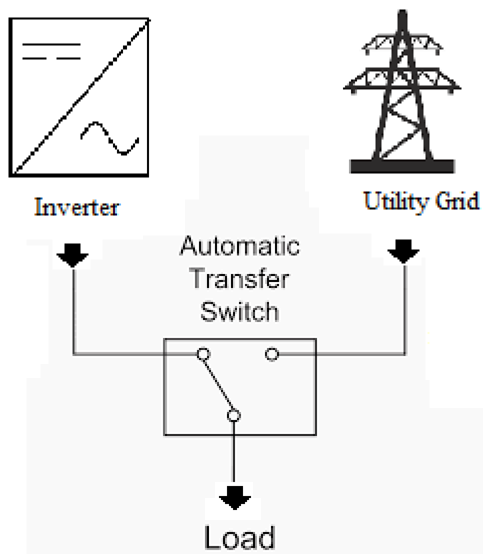


Figure 4- 12 The transfer switch diagram

Any automatic transfer switch has a fixed handle for manual control, the secondary service of this switch is to eliminates any short circuit risk between grid and battery. There are many type of transfer switch such as; automatic, manual and static switch. The purpose of using this device is to increases the power system reliability, due to shifting the power source in instants [70]. The battery circuit diagram as shown in Figure 4-13, has 13 batteries in parallel, and 4 in series. Each battery is lead-acid, and has a nominal 12 V and 200 Ahr, the DC bus of these batteries carries 48 V DC.

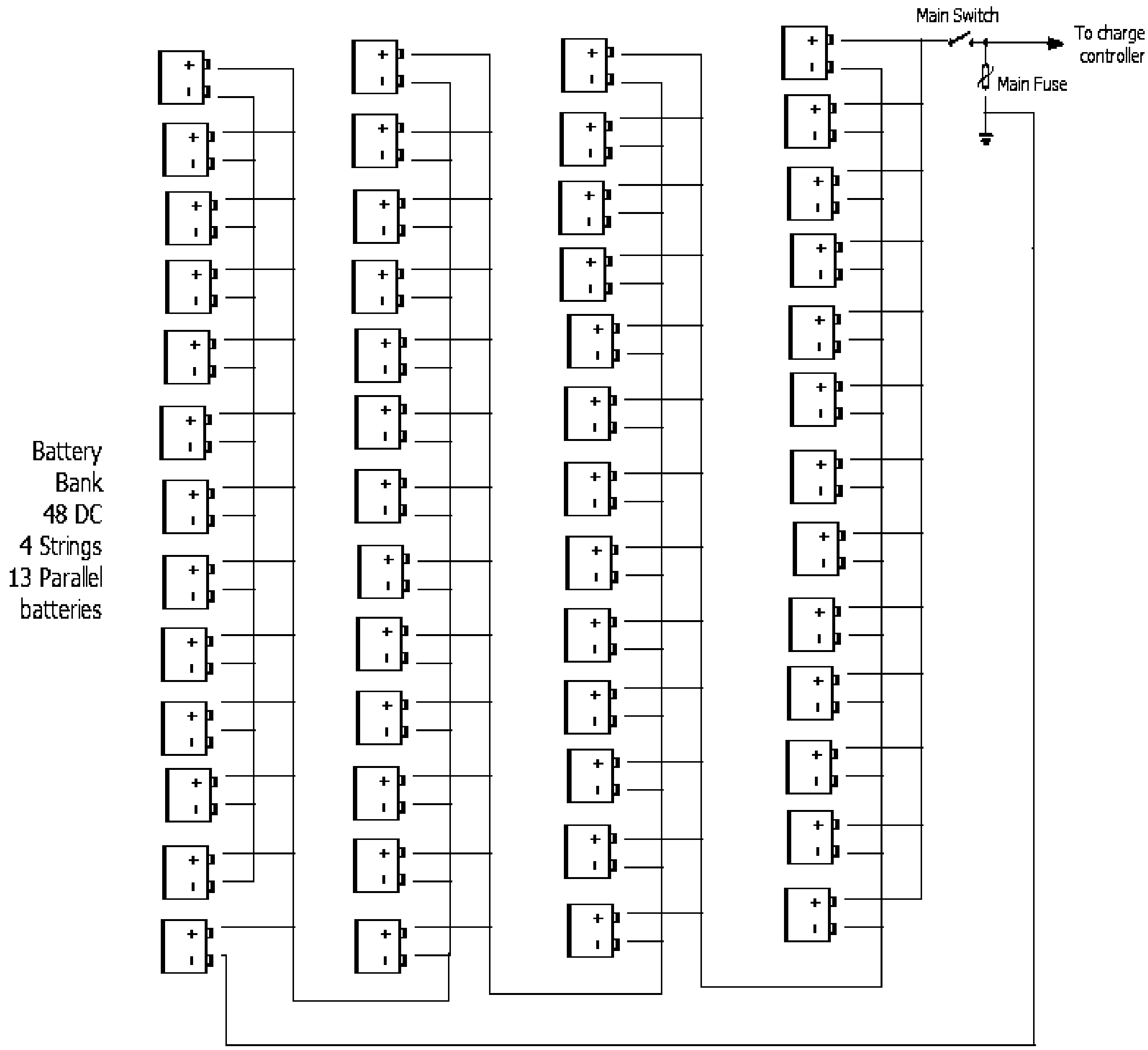


Figure 4- 13 Battery bank circuit diagram

PV installation need racks, because of the house roof faces east- west than north – south, the solar panels will be mounted on racks to orient it to face south. Although, it will be more cost than standard installation but the PV system will get much light in racks case. The solar panels tilt angle from horizontal would be chosen depending on the location latitude which is 26^{o} degrees. According to Helioscope software the PV frame installation will be same as shown in the next page.

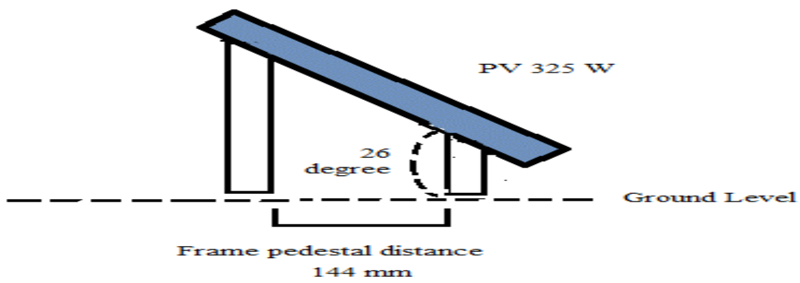


Figure 4- 14 PV frame tilt sketch

Solar Canadian 325W, which is the solar panel was selected in chapter two and designed in Simulink. The drawing and measurement is needed for the installation process, figure 4-15 shows the dimensions in mm of the solar panel frame.

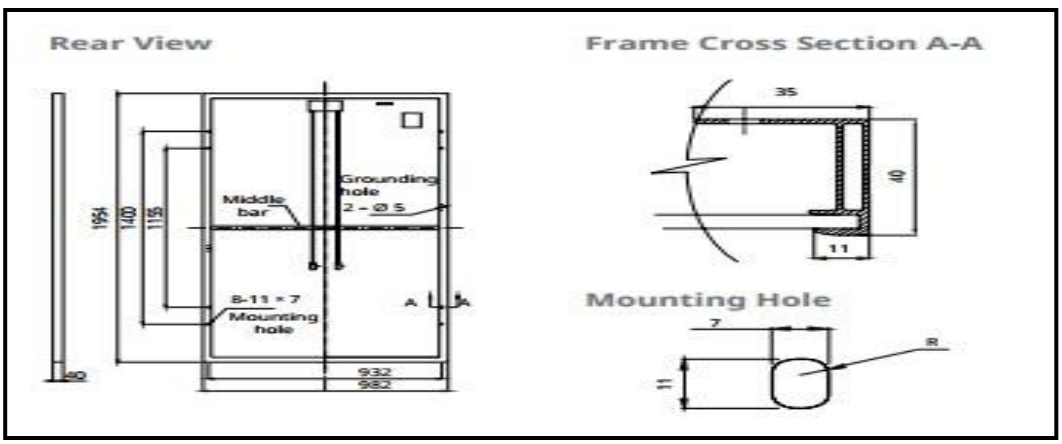


Figure 4- 15 PV frame dimensions [71]

In the design, there were 56 solar panels to produce 48 V off-grid, 28 panels in parallel and 2 in series. Therefore, all the array current must flow through the load, in figure 4-15 the series and parallel connections have been illustrated. There are two purposes of having fuses; to protect the cable and to protect the electrical equipment. The solar Canadian solar panel has built in fuse for protection [71]. Therefore, each panel is shown in figure 4-16 has built in over current fuse. The main switch shown in figure 4-16 is for charger controller connection, and the main fuse is for over current protection of the PV array.

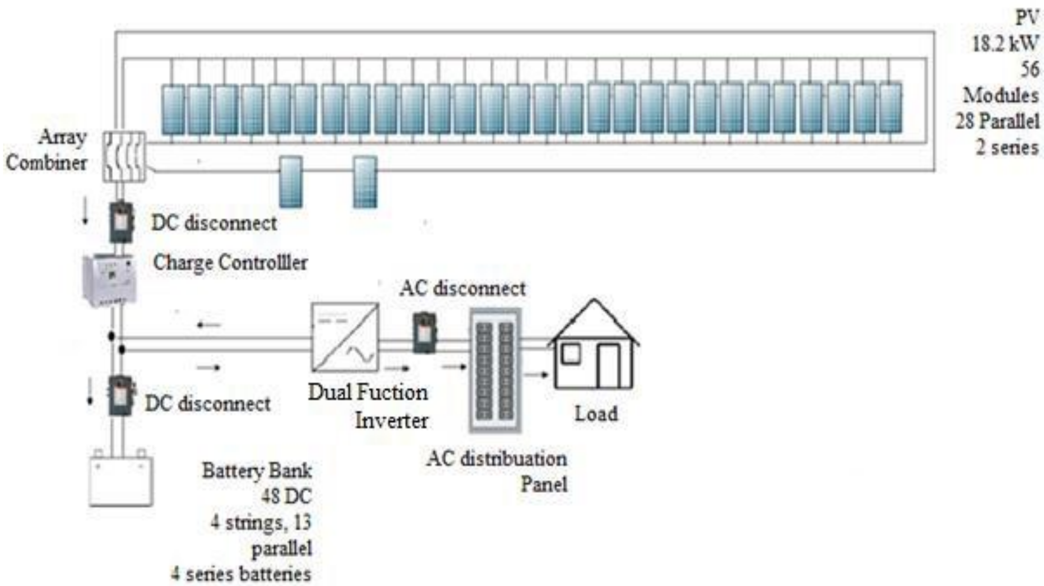


Figure 4- 16 PV series and parallel connections

4.7 Conclusion

This chapter provided some details of PV layout on the roof and wiring. The PV array with 56 panels could be successfully installed on the roof and simulated for sunlight by Helioscope. A detailed section about wiring materials and sizing, also single line diagram of the designed PV model was illustrated in this chapter. Moreover, installation process of the inverter, transfer switch and the PV were discussed in this chapter. Most PV systems have backup equipment should include a transfer switch mechanism as mentioned in section 4.5. This chapter also presented the shadow behavior through Helioscope simulations. All such issues are important for a PV installation. Although most of these issues are engineering design and less to do with research.

5. CHAPTER 5

CONCLUSION AND RECOMENDATIONS

Old electricity production should change and renewable energy systems such as PV energy, could replace or minimize non-renewable energy consumption. Homes in Saudi Arabia are presently using electricity of non-renewable energy sources, which are mostly for cooling uses. Corresponding to the PV system and load size, the correct system topology has been designed to achieve; high efficiency, lowest cost operation and installation of renewable system on roof. Depend on simulations and analyses of the cooling based on PV systems scenarios, the primary conclusions of the thesis are:

- An investigation in literature on renewable energy, especially PV systems with battery storages was done. It showed diverse cooling advances systems, that were achievable using sun light. Electricity production in SA was also revised.
- Three basic cooling technologies were talked about; desiccant evaporative cooling, ingestion chillers, and adsorption chillers. The determination of a reasonable cooling system powered by sunlight, through several evaluation aspects such as; software simulation, electrical theories and market prices, for the required modeling location which is Saudi Arabia.
- Based on literature search, it was decided to design system using PV modules, batteries and heat pump like air source mini split. It was decided because other cooling options are in research stage.
- Given the typical design and construction of Saudi homes, and with the aid of Homer and BEopt software, we concluded that installing 19 kW PV system would be a beneficial as an alternate electricity source to bring home load to net-zero.

- The PV system was sized by Homer and BEopt, and the return of investment ROI results indicated about twelve to fifteen years for cost recuperation, which is fairly good, relative to a system life expectancy of 25 years.
- Design include PV system producing 48 V DC, and connecting the system with the boost converter, MPPT, DC to AC inverter and step up transformer to produce an AC sinusoidal wave of 230 V. That will be used for house load.
- This design is ready to be converted to an actual system. System dynamic model was developed in Simulink. The ripples in the voltage and current obtained by simulation was due to the PWM inverter used in the model.
- Designed PV system can meet all energy needs of a typical house in Saudi Arabia.
- Simulink simulation provides details of power electronics and expected harmonics in the system. Due to air conditioning house load is inductive as assumed in the simulation.
- Geometrical data for the house were obtained, and used in the design process.
- Time zone for the house needed to simulate the sun rays and the PV production, was used for output energy analysis.
- The PV array with 56 panels could be installed on the roof and simulated for 24 hours' sunlight by Helioscope.
- A detailed section about wiring materials and sizing, was done along with a single line diagram of the designed PV model as illustrated in chapter 4.

5.1 Thesis Contributions

The main contributions of the thesis can be summarized;

- Literature review indicated PV systems are widely recognized and used throughout the world, but unfortunately, Saudi Arabia has not yet effectively embraced the use of such systems.
- A typical house was selected in SA for design.
- House thermal modeling was done in BEOPT to generate hourly load data.
- House actual load data was collected and compared with BEOPT results.
- System sizing was done using Homer.
- Dynamic model of the system was done in Simulink.
- Development of a control system by Simulink, which can be used for any similar PV kW size system.
- Development of a wiring system by Helioscope, which can be used as a data sheet for homeowners in Saudi Arabia for installation guides.
- A model of battery storage to support the output power of a PV system, which is to be installed for a house energy source.
- A PV system installed in a roof with 26º tilt is more economically feasible than on a flat roof.
- By adding a battery bank storage to such a PV system, it show that results are more economical for the homeowner through selling the surplus to the grid.

5.2 List of Publications

Alharbi S, Iqbal M.T. Sizing of a Photovoltaic System for a House in Qassim, Saudi Arabia. Journal of Engineering Science and Military Technologies. 2017; Accepted and not yet published:1-6. Available from: http://ejmtc.journals.ekb.eg/ [cited 28 July2017]..

Alharbi S, Iqbal M.T. Dynamic Modeling and Simulation of a Photovoltaic System for a House in Qassim, Saudi Arabia Journal of Clean Energy Technologies. 2017; Accepted and not yet published:1-6. Available from: http://www.jocet.org/ [cited 28 July2017]..

5.3 Future Work

The future work of the thesis can be summarized;

- The effectiveness and efficiency of PV system can be enhanced by reducing wiring system losses and using a micro inverter, improving system reliability for homeowners.
- Practical design, implementation and testing of the PV control design.
- A study should be conducted to support the homeowners about the long term financial benefits of PV systems.
- Actual site test of dust and humidity and their effect on the PV system in Saudi Arabia.
- Design of SCADA for use with the PV system as proposed in this thesis.
- A detailed study of house on how to reduce it energy consumption by improving it is insulation and adding overhang etc.
- Study passive cooling methods for SA applications.
- Study evaporation based cooling system for Saudi Arabia.

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