Design and Modelling of a Large-Scale Solar Water Pumping System for Irrigation in Saudi Arabia

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Abstract

This thesis illustrates a comprehensive study of using a large scale solar water pumping system in Riyadh, Saudi Arabia. This system is applied on an average farm located in Riyadh which has an average water consumption of 245 m^3/day. This study provides detailed system sizing and dynamic modeling. Sizing such a system has been carried out by using some useful tools such as Homer and PVsyst software. A 115 m deep well needs a 5.4 kW pump, 11.6 kW PV, 6.8 kW converter and 9, 200 Ahr- 12 V, batteries. The results of both softwares are compared to each other and showed almost the same system design. In addition, water cost has been estimated with the provided data, to be ₵4/m^3.

System dynamic modelling is done using MATLAB/Simulink which contains several models of sub systems such solar arrays, two stages DC-DC boost converter, energy storage, DC shunt motor, and centrifugal pump. The system dynamic modeling has been developed based on the sizing of the system. In order to improve the system efficiency, perturbation and observation (P&O) algorithm based maximum power point tracker (MPPT) was built in the system model for the first stage of the converter; as well as PID controller for the second stage. MATLAB/Simulink simulation shows that this system can deliver the required energy with quite satisfactory controller dynamic performance.

Acknowledgment

I would like to express my sincere gratitude to my supervisor, Dr. Tariq M Iqbal, for his guidance and support throughout the journey of the master degree. I'm grateful for what I have learned and achieved under his supervision.

I sincerely thank the Saudi government for providing me an opportunity to pursue my post-graduate studies. I am beholden to them for their financial and moral support over the course of these years.

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Chapter 1

INTRODUCTION

1. INTRODUCTION

The overall population of our planet is constantly growing and is expected to increase for several decades in the foreseeable future. The demands for energy of the humankind are projected to grow even at more rapid speed, and the amount of energy that will be provided by electricity will increase at the same time as well. More than thirty per cent of the electrical energy of the planet is utilized by electric motors in various pumping systems, for example, fixed-speed centrifugal pump, fan and compressor applications, according to a recent research [1]. The primary sources of energy these days are coal, petroleum and gas, which are widely utilized by the modern population of the planet, are supposed to be ending sooner than they will have an opportunity to replenish themselves. In addition, these energy sources are able to have a substantial negative impact on the natural surroundings. CO is a trace gas with a short life span, which is generated from partial burning of fossil fuels and biomass combustion. After that, this gas is transformed to CO_2, which is among the most notable greenhouse gas. Moreover, CO_2 is to some extent accountable for a worldwide temperature increase. This issue is closely connected to the environmental stability of the planet and can be partially alleviated by the constant search for substitute green energy resources in addition to the adaptation approaches that are aimed towards the lessening of those environmental negative outcomes. At the present day, one of the most promising green and renewable alternative sources of energy is solar radiation [2].

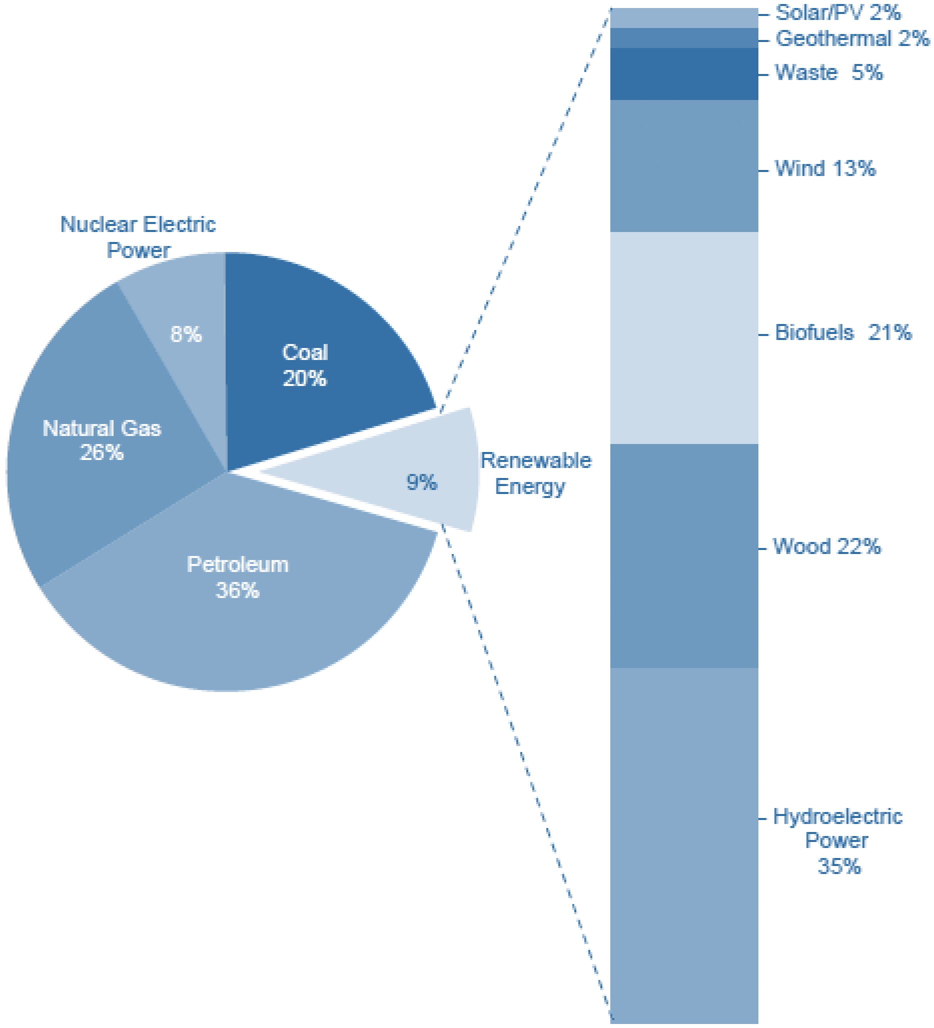

Figure 1-1 Sources of Renewable Energy as a Part of Overall Primary Energy Usage [3].

Various renewable energy systems, for instance, solar, geothermal, wind, wave, hydropower and biomass energy [3], are expected to play a substantial part in the creation of a sustainable energy system in advanced and developing countries, according to the research by Kishta [4]. These sources of energy are projected to assist in the mitigation of the climate changes, in the improvement of the security of the worldwide energy supply system and in granting the developing nations with an opportunity to use affordable energy. For these reasons, the utilization of solar energy is rapidly turning into one of the most debated issues of the modern day. The energy that is produced out of the solar radiation can be regarded as the most plentiful lasting source of energy that the humankind has in its disposal, as it was mentioned in the recent research [5]. At the same time as the solar energy is not widely applied as a key resource of fuel of the modern day, substantial research is needed on this subject and improvement efforts are in progress. They should be aimed towards the efficient development of the economic systems to accumulate solar energy and turn it into a primary resource of fuel energy, for the heating and cooling of the residential estates and providing access to clean water in dry areas [5,6].

Solar panels consist of the solar cells that are in essence a p-n junction. Any kind of machinery that is utilized in order to transform solar radiation into energy is regarded as being either solar cells or panels (see chapter 2) [7]. The equipment that is used as the foundation for the solar panels has progressed significantly in the course of the previous sixty years of research. At the same time as the solar cells were the original starting point of the up to date solar panels, contemporary researchers and engineers are moving away from them and starting to implement various innovative platforms and methods of accumulating the energy from solar radiation. These methods include the construction of the solar cells from silicon semiconductors that are intended to receive and transform solar energy. These silicon semiconductors are covered in an antireflective coating and kept under a glass protection plate in order to keep the cells away from various damaging elements [7].

The country of Saudi Arabia has desert areas, in which the residents utilize the conventional watering systems in order to take water from the boreholes, with the help of the internal combustion engines, for example, diesel pumps, according to the researches by Rehman et al [8] and Daud et al [9]. These pumping systems are simple to set up; on the other hand, they have proven to have substantial drawbacks, particularly those pumps require diesel fuel, for the reason that they have a need for recurrent site upkeep, refilling of the fuel and frequently the diesel fuel is not easily obtainable in those regions. In addition, excessive usage of fossil fuels has a substantial negative effect on the environmental impact, specifically the discharge of carbon dioxide (CO_2) into the air, as it was outlined in the report by the Department of Energy of the United States [5]. The commercialization of solar irrigation systems at the present moment has to deal with various limitations, including increased expenses for the manufacturing of photovoltaic cells and reduced productivities that can be overcome with the help of the solar thermal power cycles as claimed by Kishta in his research [4].

1.1. Renewable and Solar Energy

In spite of the fact that the fossil fuels (which are petroleum, coal, and natural gas) are still widely used at the modern day and are being produced by the planet, they are being spent by the humankind much faster than they are replaced by the natural resources. As a consequence, fossil fuels are regarded as being non-renewable at the current rate of consumption; for that reason, recent research indicated that the demand for renewable sources of energy is an issue of primary concern at the present moment. Today, the renewable sources of energy are tied with the solar energy and its primary and secondary impacts on the planet. These impacts include (solar radiation, the power of wind, the power of water, and certain types of florae, biomass, to be precise). In addition, the renewable energy sources are connected to gravitational forces (for example, tides), and geothermal forces (the heat of the core of the planet). Renewable sources of energy are known to refill themselves on the course of the human life span and might be utilized in addition to the appropriate technological machineries in order to generate foreseeable amounts of energy when needed. In addition, the renewable energy systems appear to be more consistently disseminated on the planet in comparison to other resources, for example, fossil fuels and nuclear power [2].

One of the most significant advantages of renewable sources of energy is their input in the reduction of environmental pollution and its possible elimination on a massive scale. Certain types of these energy systems have been utilized by the humankind for more than five thousand years. For the period of the preindustrial era, the renewable energy sources were, for the most part, utilized for cooking, heating the house and easy mechanical operations, which usually were unable to attain high energy productivity. For the period of the industrial era, on the other hand, the energy usage moved from the renewable energy systems with lower energy value to coal and petroleum, which had a lot bigger energy value in comparison to the previous energy sources at that time. In reality, it can be stated that renewable energy resources, for example, the power of falling water and wind power, possibly would have failed to offer the similar rapid growth in industrial efficiency compared to fossil fuels [10]. At the present day, biomass signifies no more than 3 per cent of the main consumption of energy in the advanced nations. On the other hand, the vast majority of the populace in the rural areas of the developing countries, who constitute around 50 per cent of the overall population of the planet, is dependent on biomass, for the most part using wood and stalk, as the primary source of energy [2].

In addition to the constant growth of the pollution of the environment because of the amplified utilization of fossil fuel, renewable energy systems are developing as being possible replacements. At this time, the renewable resources of energy are responsible for around 13.6 per cent of the worldwide energy usage. Furthermore, by the year 2040, the contribution of the renewable energy sources to the global energy consumption is projected to be around 47.7 per cent. The most considerable improvements in renewable energy production are projected by the researchers in the areas of photovoltaic (from 0.2 to 784 million tons in oil equivalent) and wind energy (from 4.7 to 688 Mtoe) in the course of the next twenty years, according to the research by Ahmad et al [11]. It is a well-known fact that energy resources are an indispensable constituent of the life span of the humankind. This can be explained by the fact that a vast majority of the day to day procedures are dependent on the accessibility to the energy resources. Currently, no less than 90 per cent of the energy demands of an average human being originate from fossil fuels. The fossil energy resources, in addition to its exhaustible essence, pose a threat from the environmental point of view that is related to its utilization. For example, carbon dioxide, which is a produce of burning of the hydrocarbon fossil fuels, appears to be among the biggest negative aspects with regard to the existing global warming issue.

Based on the problems that were described above, there seems to be growing and reintroduced search for renewable energy systems in order to be used by the humankind as promising alternatives to fossil fuel. The energy of the sun and solar radiation are known to be among the most used renewable sources of energy. One of the primary advantages of the solar energy is its environmental friendliness along with cost-effectiveness. The only expenses that are connected to the utilization of the energy of the sun originate from the possible methods of its harnessing and distribution. At the present moment, there are two primary methods, with the help of which solar energy can be accumulated and stored for later usage. The first method lies in the direct transformation of the energy to heat for solar heating usage, for example, water heating and warming of the house and storage areas or its usage for solar cooling usage, for example, water cooling. This method is frequently mentioned in the literature on solar thermal applications [12]. The second method is the transformation of the energy harvested from solar radiation into electrical energy with the help of an instrument that is referred to as the photovoltaic panel [11]. The resultant generated electrical energy is usually applied in order to provide power for diverse electrical or electromechanical machinery. A vast number of studies has been conducted on the subject of accumulation and application of solar energy in the course of the previous years.

Distribution of Solar Radiation on the Surface of the Planet.

It is a well-known fact that solar radiation is unequally dispersed on the surface of Earth, and that it differs in its concentration from one geographic place to another being dependent on the latitude, time of year, and time of day [13]. Up until a decade ago, usable documentations of the distribution of solar radiation have been rather small and insignificant in the scientific records of the developing nations. For the reason useful data seems to be absent, merely wide-ranging suggestions could be presented on the subject.

In an attempt of reaching maximum convenience and uncomplicatedness, the dissemination of the overall amount of solar radiation in different geographical areas on a global scale can be outlined from the point view of its concentration into the horizontal global solar irradiation as demonstrated in figure 1-2.

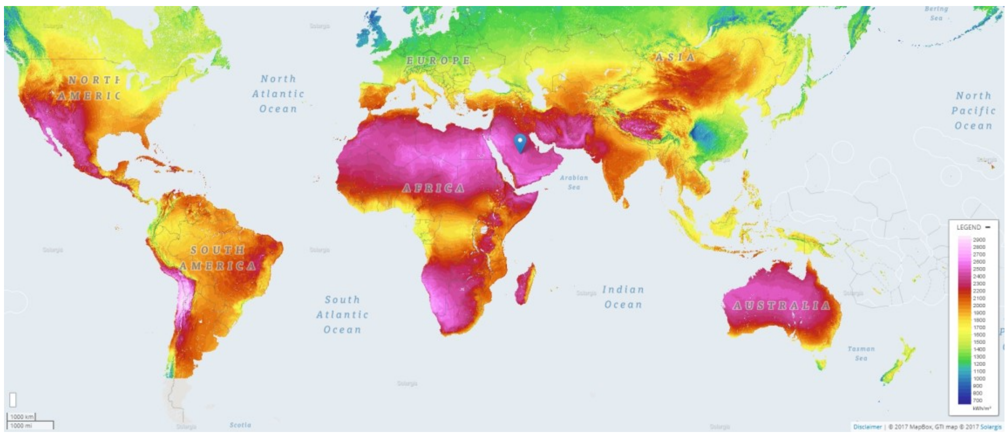

Figure 1-2 Global horizontal irradiation kWh/m2 [14]

1.2. Need of Solar Pumps in Saudi Arabia

The demand for solar powered water pumps in Saudi Arabia for irrigation is rather apparent for the reason that the population of the country is growing rapidly, which leads to the increasing need to inhabit the desert parts of the country, create new living areas there, and grow crops and livestock [8,9]. This extremely imperative matter is provision towards the expansion of the cities and subsequent urbanization of vast desert areas, which at the present moment have no groundwork, transportation systems, or utilities. In spite of the fact that energy is vital for the urban and rural progress, the development will not take place until the source of life itself, to be precise, water is easily obtainable for every member of the general population of the country. For that reason, there appears to be a demand for the establishment of the solar powered water pumping systems in certain parts of Saudi Arabia in order to distribute water from the boreholes to the levels of the ground to be applied in the establishment of the fresh agrarian communities in the desert areas of the country [8,6,9]. In an irrigation water pumping system, the pump is typically utilized in order to distribute water from one level to a higher ground level or enhance pressure with an intention of achieving the essential working pressure of the pump for the irrigation of the crops. For instance, the pumping system for irrigation in Saudi Arabia can be used to distribute water from a bore hole or a river to the rest of the irrigation systems or up to a reservoir for storage and later usage.

The territory of Saudi Arabia has great prospects of the extensive utilization of solar energy sources in solar water pumping systems in rural areas [10]. The region of Bahra valley, which is around 25 kilometers away from the Madinah city will be taken as an example, as it is located in the North West part of the country and has a serious need for alternative sources of watering systems. According to the research by Benghanem et al [3], the yearly monthly daily middling irradiance yield that can be achieved on horizontal plane is around 7.5 kilowatts per meter squared per day and mid static levels of water ground resources is changing between forty meters and one hundred and twenty meters. The primary objective of the installation of the solar powered water pumping systems is to distribute enough water for irrigation in dry areas of the country. In the course of the last decade, a vast amount of articles aimed the attention of the researchers and engineers towards the large deep photovoltaic solar powered water pumping system sizing, centered on the prospects of solar energy and water demands in comparable areas of the solar belt countries as it is stated in the article by Sahw et al [15].

Certain percent of the research on the subject of the solar powered water pumping system sizing were conducted on the basis of the performances of the pumping systems from numerous points of view. Various models were utilized in order to assess the performance solar powered water pumping system. On the other hand, a vast majority of the sizing research on this subject fails to take into consideration the significance of the photovoltaic array configuration that has an ability to deliver a highest rate of energy possible [11]. Recently, a performance study of photovoltaic powered direct current pumping system has been conducted on the setting of a superficial borehole with the full simulated head of 35 m and the equivalent maximal everyday middling volume of water was 3 m^3 [10]. The research demonstrated that these pumping systems were the most efficient in terms of water flow, cost-effectiveness and amount of work done during one day.

Extracting drinking water from the natural water supply resources, for example, bore holes and wells has a need of an enormous quantity of energy. In agrarian and off-grid regions of Saudi Arabia, the generators that run on diesel fuel are widely utilized as a primary resource of energy in order to extract water from the wells, bore holes or various other water resources [8,17]. At the same time as the financial expenses that are connected to this type of fuel is growing not only in Saudi Arabia but across the planet as well, utilizing renewable energy resources, such as energy harvested from solar radiation as a substitution to the traditional energy systems for the extraction of the drinking water for distant and isolated rural regions and distributing water in order to irrigate the crops and keep the livestock in various countries, including Saudi Arabia, has a broad variety of benefits [18]. First advantage includes the utilization of the natural resources that are easily accessible, and the second advantage includes the compensation of the foreign exchange expenses, which were disbursed in order to buy various types of fuels. The development of a grid system is usually rather costly for the reason that the communities of agrarian regions are situated far beyond the reach of the developed grid lines [6]. In addition, being depended on an traded fuel supply with regard to water resources is problematic and unsafe, as the foreign exchange rates constantly change and the economy of a vast majority of the developing nations could plunge as a result [4].

Large deep solar powered water pumping systems have the prospects of offering substantial improvements to the communities that are located in the desert areas of the country. It is not only by the means of the direct distribution of water to the areas where the water resources are in high demand but also with the help of the possible prospects of sociological and economic improvement in these regions solar powered water pumping systems need to be considered for implementation in the developing and advances countries [5,9]. The long-lasting outcomes that come after the prolonged utilization of the solar power pumping systems can go far more than the easy access to fresh water.

1.3. Structure of the Thesis

Chapter 1 of the thesis includes the introduction, the overall outline of the renewable and solar energy, and the justification for the installment of the solar powered water pumping systems in rural areas of Saudi Arabia.

Chapter 2 of the thesis is written in a format of a literature survey of the solar systems, pumps in general as well as solar pumps. It includes the steps of selecting a proper solar water pumping system as well as the main principles of the operation of solar pumps.

Chapter 3 of the thesis provides an outline of the solar system sizing in a form of a case study, which will define the sizing of the pumps and the photovoltaic, converter, and batteries sizing using Homer and PVsyst software. Also, the possible energy storage methods are provided.

Chapter 4 of the thesis presents solar system dynamic modeling of system designed in Chapter 3, with more attention aimed towards the photovoltaic modeling, maximum power point tracking modeling, two stages DC-DC converter modeling, energy storage, and DC motor and pump modeling.

In Chapter 5, the results of the research are demonstrated and further discussed, which includes sizing and modeling simulations outcomes as well as water and system cost.

In addition, Chapter 6 includes the conclusions regarding the completed work as well as the list of resulting publications. Recommendations and future work on this subject are provided as well. The appendices are added at the end of the thesis.

Chapter 2

PV SOLAR WATER PUMPING SYSTEMS: Literature Review

2. PV SOLAR WATER PUMPING SYSTEMS:

2.1 PV Systems:

Photovoltaic (PV)

Photovoltaic (PV) systems, have achieved commercial compatibility and acceptability with regular sources of energy generation due to its process simplicity that makes it convenient for people to install it in a simple way and utilize the produced power. So, let's start with the definition of the PV. A PV system is an electricity generator which absorbs sunlight and converts it into usable electricity [19]. It consists of many aspects such as PV modules, converter/ inverter, energy storage (batteries), starting with the PV cell which is the core of the PV system. It is made from semiconducting martials that gives it the ability to convert the light into flowing current. Figure 1 demonstrates the work of such conversion where a photon hits the surface of the conductive material; resulting in excited electrons. These electrons move from p- layer to n-layer; causing a difference in voltage in the circuit. This voltage differential pushes electrons to the rest of the circuit to keep the charges in stable condition.

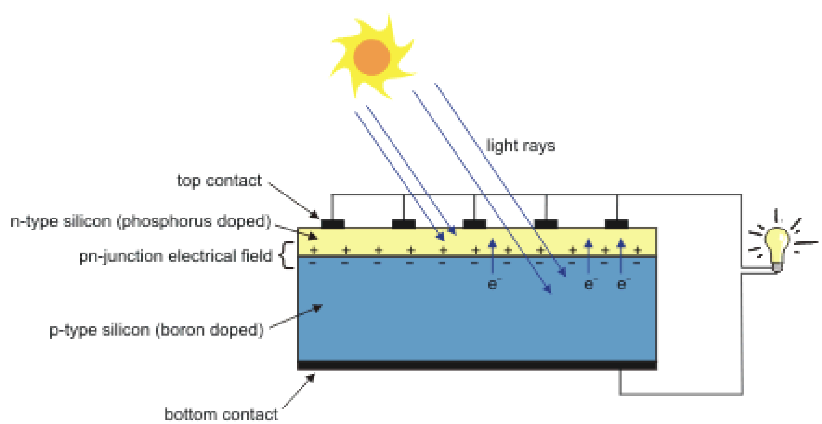

Figure 2-1 Solar cell structure [20]

Every solar cell consists of no less than 2 specifically arranged coatings of semiconducting material (the material is usually silicon), which generates direct current electricity due to the movement of electrons as mentioned before as the panel is open to solar radiation.

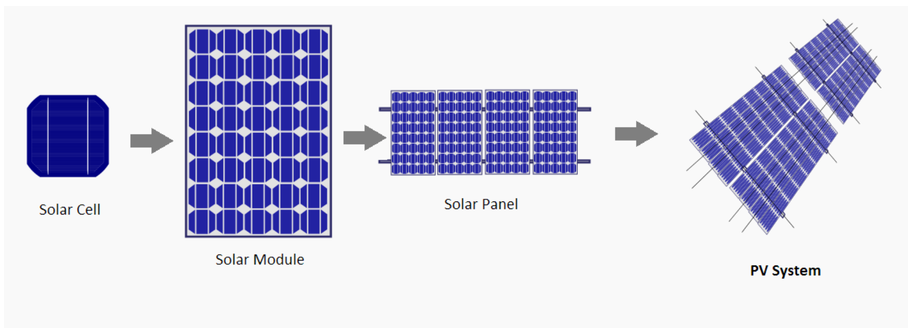

Figure 2-2 PV system construction

Quite a few number of cells can be connected in series and in parallel to form up the PV module as shown in Figure 2-2. The DC electricity is gathered by the wiring in the panels in series/ parallel [7].

Partially shadow effect:

There are many conditions that occur during operation causing an interruption in the system such as a partially shadow. However, to prevent that, a bypass diode can be connected anti-parallel as shown in figure 2-3. It is not necessary to be paralleled with each cell, but it can be sufficient with several cells.

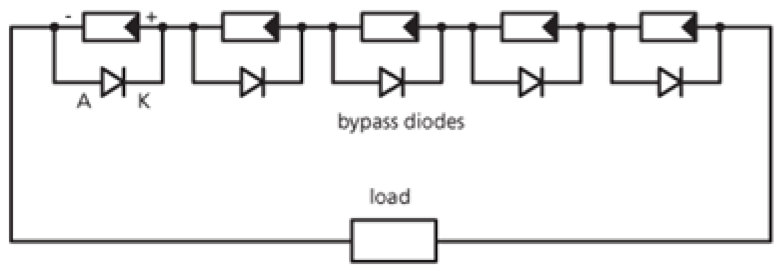

Figure 2-3 Parallel PV cell with bypass diodes [21]

On the other hand, these diodes are very efficient due to not causing any losses because they are not working under normal operation. If some cells got shaded, the output DC current of other cells would flow through diodes, protecting solar panel from overheating that would lead to cell damage.

Inverter/ Converter

DC voltage is either transformed into the AC voltage with the help of an inverter or stepped up/ down with the help of boost or buck DC-DC converter. After that, the harvested electricity is utilized in order to make the load operate which is in our case is a water pump using a DC shunt motor, so the load is DC. Then extracting water from the well or a borehole as soon as it becomes exposed to solar radiation again. As shown in figure 2-4, an example of DC coupled system structure is used as off grid connection. However, sometimes, two stages DC-DC converter can be used if the duty cycle is very large (for more details see chapter 4). In the diagram below, the structure of a solar water pumping system is sketched; depicting the example system of our study.

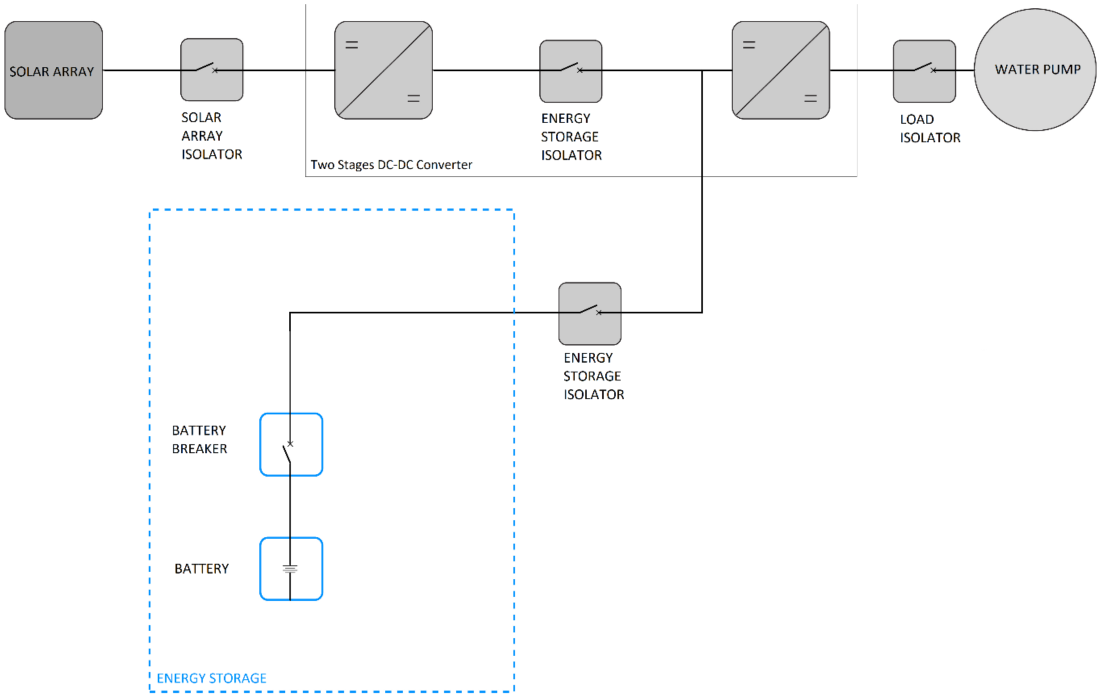

Figure 2-4 Isolated PV solar water pumping system

Energy storage:

A water storage tank is a typical energy storage alternative for solar water pumping system [22], especially in hot climate regions such as Saudi Arabia. However, using few batteries could be an option for emergency cases or at least for compensation the voltage drops due to any partial shadow during operation.

2.2 Solar Water Pumps

Pumps in General:

Pumps provide additional energy in order to boost or transport liquids, in this case, water, between two different locations [3]. These are usually applied in applications, for example, industrial, domestic and agrarian. The selection of a certain pumping system for a particular use is a rather central decision and it will be dependent on the necessary energy demand and discharge, head, performance, possible subsequent upkeep and financial expenses. There are several types of pumps with different subcategories (centrifugal pumps and positive displacement pumps are the most popular types), each of them used in a specific field. For instance, centrifugal pumps are applied for a broad variety of flow and head demands, as it was outlined in the report by the Department of Energy of the United States [5]. This category of pumping systems in general has a life span from 5 to 10 years with productivities in the 80 per cent range. They can be categorized as volute pumping systems, in which the impeller is walled by a spiral covering and turbine pumping systems, in which the impeller is walled by diffuser vanes that slightly bear a resemblance to the reaction turbines [3].

The second type, positive displacement pumping systems appear to be more effective at higher heads, and they are the most applicable for high-head low-flow use. Leaking fluids in the packing or in the valves of these pumps, on the other hand, will result in the rapid decrease of their output and productivity. Rotary pumping systems are utilized for low-lift use in spite of the fact that they are proven to achieve better productivity as they are pumping unclear water mixed with mud. These pumps are not advised for heads that exceed 20 meters. Manual or animal driven pumping systems (for example, hand pumps, water-wheel pumps etc.) are, for the most part, utilized in various developing countries in order to extract water from boreholes and wells for future irrigation. On the other hand, the power that these pumps require are rather inadequate in comparison to other power sources, for instance, renewable sources of energy. Moreover, hand pumps and other manual pumping systems are nearly at all times afflicted by system failures that come as a result of the insufficient efforts, unproductive design, absence of spare fragments of the pumping systems for further maintenance, or exhaustion and for that reason are not trustworthy [3].

Solar Pumps:

Those techniques of irrigation that include large deep solar powered pumping systems have to take into consideration the fact that the necessities for the irrigation water systems are expected to differ in the course of the year. For instance, it can be said that the topmost demand for the duration of the irrigation system seasons usually demands no less than twice the regular norm for the rest of the year. Based on this statistics, the research that was conducted for this literature review indicates that solar pumps for irrigation appear to be not used sufficiently for the most part of the year [18]. Therefore, increased consideration has to be devoted to the systems of irrigation in the framework of their water dispersal and its use for the crops. The conventional irrigation pump systems are expected to minimalize, if not eliminate at all, losses of the water throughout the year, without the application of the substantial extra head on the irrigation pumping systems and being cost-efficient at the same time. At the present moment, there appears to be a certain amount of technological substitutes for the delivery of power or lift to groundwater systems, which include solar arrays, wind turbines, windmills, electrical generators, and manual pumps that are powered by hand, as it was outlined in the report by the Department of Energy of the United States [5].

The primary motivating aspects for the selection of the applicable technological alternative are the feasibility of the area, water demand, the effectiveness of the selected system on this particular region, and preliminary and lasting expenses. Various other aspects that have an impact on the selection of the technological alternative for the delivery of power to the irrigation system usually comprise the necessity for power and water reserves in the usage of batteries and storage tanks [12]. Solar-powered systems are more and more considered for usage in developing and advanced countries, including Saudi Arabia, as a substitute for other practices of alternative energy for the reason that they are hard-wearing, long-lasting and show numerous economic profits in the long run, according to the review by Rehman et al [8].

Solar powered water pumping system has been regarded as an appropriate choice for the grid-isolated countryside regions in developing and advanced countries, including Saudi Arabia, in which high amounts of solar radiation are available [8]. Solar powered water pumping systems have the ability to distribute drinking water without any type of additional power or the complicated upkeep, which, for example, require diesel pumps. In addition, in spite of the fact that solar powered water pumping systems are not suitable for large-scale irrigation, they are able to efficiently operate in the areas with small-scale drip irrigation systems [23]. The solar powered water pumping systems could be regarded as being large-scale in a case when it serves more than two hundred and forty people. However, Photovoltaic solar panels are frequently utilized to perform various agricultural operations, in distant regions or in areas in which the utilization of an alternative energy sources is preferable [11]. To be precise, the solar powered water pumping systems have been established in the course of the last decade to consistently generate an adequate amount of electricity straight from the radiation of the sun in order to deliver water for cattles [18].

Solar water pumps might be particularly valuable in the framework of the small scale or community based irrigation, for the reason that maintenance of the large scale irrigation has a need of larger amount of water, which consecutively needs a larger solar photovoltaic array, according to Akihiro et al [23] The larger pumping systems are able to deliver around 150,000 liters of water per day from an overall head of ten meters, according to the research by Ahmad et al [11].

The longstanding financial expenses and the capability of solar powered water pumping system of being adjustable in accordance with the constantly altering demands has to be realized in the feasibility of this pumping system. This development is to some extent connected to the capability of the general population that utilizes the pumping system for irrigation of being able to adjust to constantly altering demands as well. According to Vishwa et al [24], solar powered water pumping system is the one of best alternative solution for irrigation.

Pump sizing and system design

There are many factors that affect the selection of solar water pumping system; however, these are the most aspects that should be considered [22] (They are briefly mentioned but they are explained in detail in chapter 3, next chapter, based on a real case study):

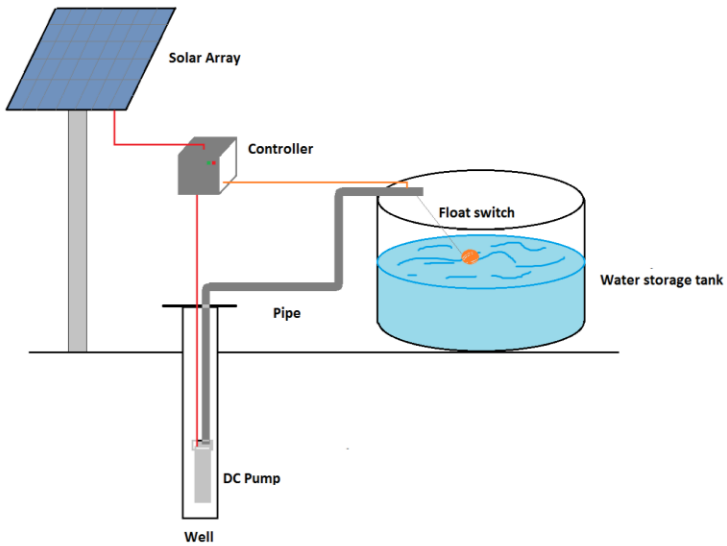

Figure 2-5 Constituents of solar powered water pumping systems.

Water source which can be either a surface or a ground water. Most of water sources in Saudi Arabia are pores.

Water need which can be expressed as the flow rate (m^3/s) or the volume of water for a specific time, for example 200 m^3/day.

Total dynamic head (TDH), it can be expressed in feet or meter. Some mechanical friction factors should be considered such as elbow friction.

Solar irradiation (W/m2) is one of the most crucial aspects in term of sizing such a system. It should be the first factor to be taken into consideration, so building such system should be based on that.

Figure 2-5 shows the components of the solar powered water pumping system and the typical control method which is float switch. It is one of the simplest control methods in solar water pumping systems.

2.3 Solar Water Pumping Principles

In any solar pumping system, the ability of water pumping is an operation, which takes into consideration the following primary aspects: pressure, flow, and power to the pump [25].

Pressure. For the objectives of planning a creation of the solar powered water pumping system, pressure can be regarded as an exertion, which the pumping system has to go thought in order to transfer a certain volume of water. The research that was conducted for this literature review indicates that pressure is most frequently demonstrated in either feet of head or psi (which is pounds per square inch). In addition, these variables from time to time are also mentioned as pressure loss. Any elevation alteration among the sources of water and the finishing endpoint will have an impact on the extent, to which the pumping system has to function, or what amount of pressure has to be generated to make the water reach its final point of destination. A pumping system has to generate 0.433 psi for every foot of elevation increase, to be precise. As the water flows downward, the same 0.433 pounds per square inch for each foot of where the difference in elevation levels is increased [25]. In a case when there appears to be various topographical features on the way of the water, and the flow is constantly going either up or down, the changes in elevation levels among the surface of the water at its starting point and the level of discharge at the final point is the among the primary variable that need to be taken into consideration while designing a solar powered water pumping system with regard to the amount of pressure that the system has to generate. Furthermore, the diameter and length of the pipes, along with curves and restraints, for example, piping valves, have an impact on the amount of pressure that will be lost and that consequently has to be generated by a pumping system in order to create a constant flow. The loss in pressure that is related to various issues with the pipes diverges more drastically as the flow escalates, as it is demonstrated in Fig. 2-6.

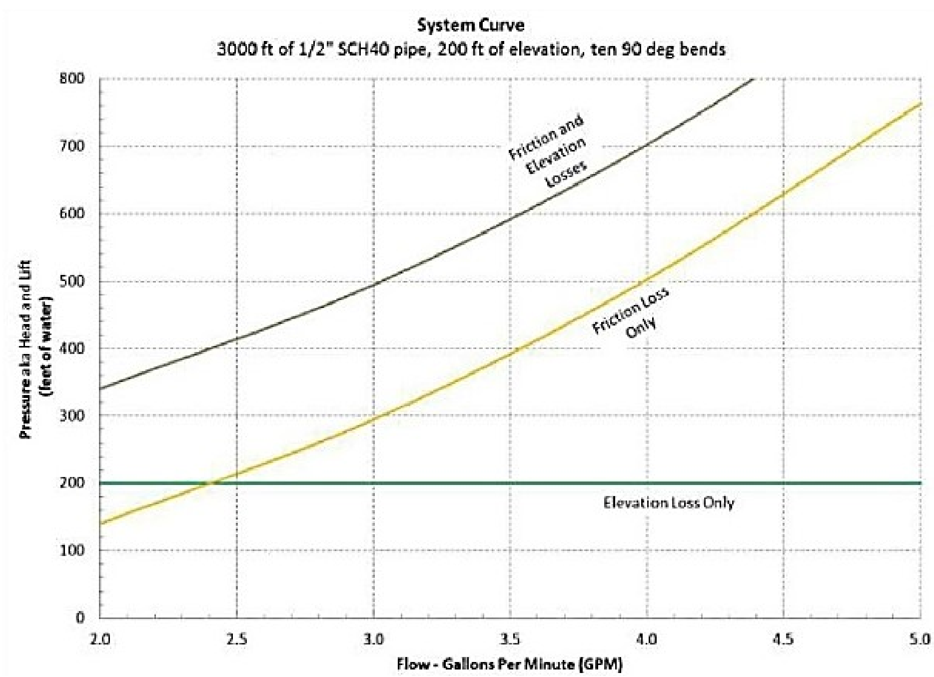

Figure 2-6 Pressure variable in the solar powered water pumping system [26].

Flow. The research that was conducted for this literature review indicates that flow is usually referred to the amount of water, which can be distributed by a solar powered water pumping system throughout a certain time period. Flow of water in a solar powered water pumping system is typically demonstrated by gallons per minute or gallons per hour. In a case when every variable in the system remains to be unchanging, flow of water will reduce as pressure grows and it will grow as the pressure weakens [25]. For instance, on the example of the identical pumping system and the identical power set-up, in a case when the amount of efforts the pumping system has to overcome by the means of elevating the discharge or with the help of the pipes of smaller diameter (generally speaking, increasing the pressure that has to be generated by the pumping system) is amplified, then the pumping system is expected to distribute smaller amount of water (in other words, less flow) in gallons per minute, as it is demonstrated in Fig. 2-7.

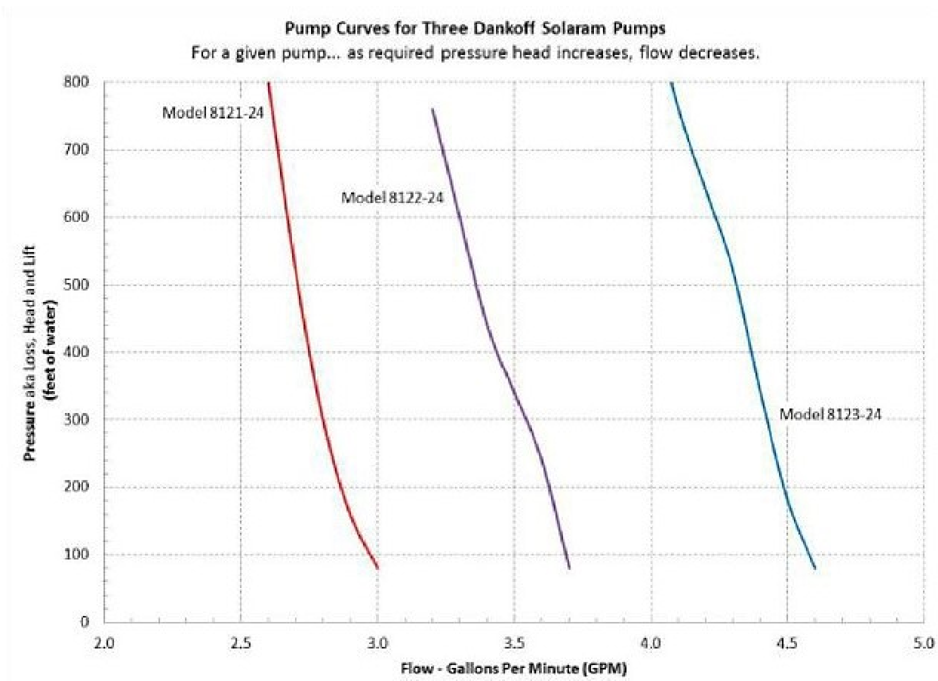

Figure 2-7 Flow variable in the solar powered water pumping system [26].

In order to decide the place in which a pumping system is going to be functioning, it is essential to take into consideration both the system curve (which consists of the pressure that is lost because of the issues with the pipes, for example, length and restraints, that are demonstrated in Fig. 5) and the pump curve (gallons per minute of the water flow that will be delivered by the pumping system at altered pressure, as it is demonstrated in Fig. 3). The operating point, or the genuine amount of exertions (which is pressure and flow together) the pumping system has to overcome could be determined by putting the curves that were shown above in Fig. 2-6 and Fig. 2-7 at the same time on one scale and axis, as it is demonstrated in Fig. 2-8. With the intention of profiting from the solar energy resources in this kind of installation resourcefully and effectively, the photovoltaic array design improvement and calibration assessments are essential [10], as it is correctly mentioned by the authors of the case study for Madinah, Saudi Arabia.

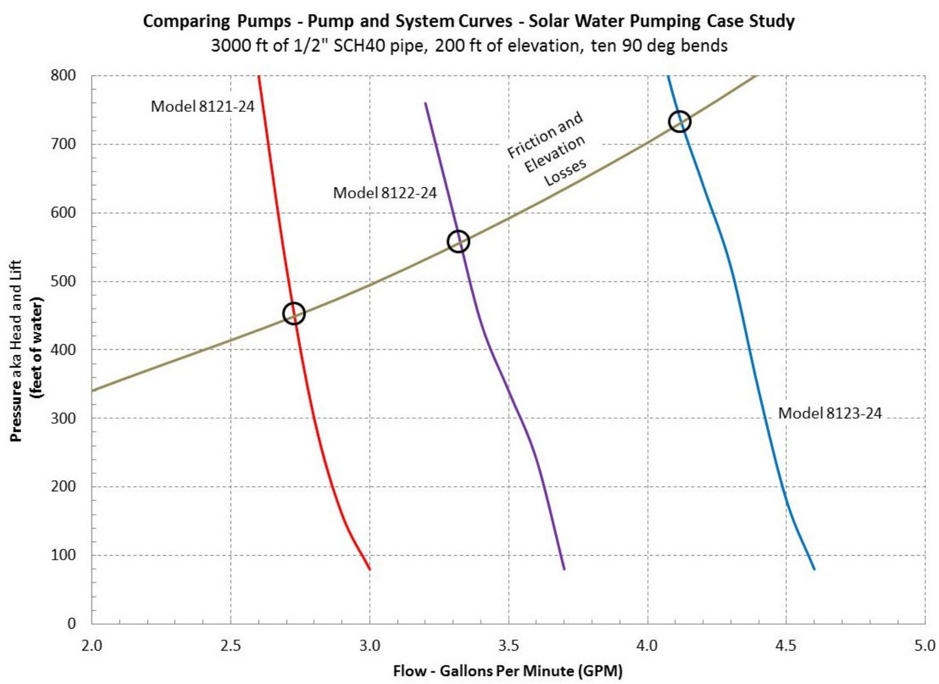

Figure 2-8 The actual amount of work for the solar powered water pumping system [26].

Power to the pump. Each solar powered water pumping system has the ability to generate a broad variety of different combinations of flows and pressures. Solar pumping systems take a certain per cent of power in accordance with the total of pressure, which is needed to be generated in order to distribute the given water. Power is demonstrated in Watts, and photovoltaic panels are evaluated in Watts as well. At the same time as measuring a photovoltaic panel array, it is essential to deliver the exact amount of power needed for the solar pump [27,11]. It can be explained by the fact that installing more photovoltaic panel arrays than required may allow the pumping system to turn on faster or slower as the day begins or in the setting with poor lights. On the other hand, installing more photovoltaic panel arrays to get more power may fail to amplify the flow rate in the middle of the day when the sun is the brightest, this is why installing maximum power point tracker (MPPT) along with the PV arrays is very essential as it was tested by Akihiro et al [27]. As shown below, they concluded their study with the fact that more than 85% of water production was increased due to the reflection of MPPT.

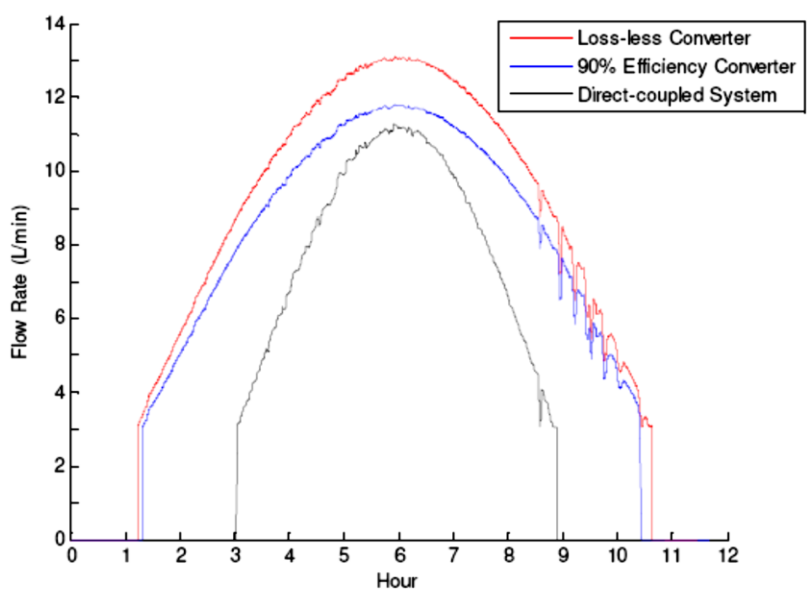

Figure 2-9 Flow rate out of solar water pumping system [27]

The proposed system in this thesis is similar to what was illustrated in figure 2-4. The system is a DC coupled system, has a two-stages DC-DC boost converter equipped with MPPT and PID controller as shown below in the block diagram. This system is capable to deliver the required amount of water with satisfied controller performance.

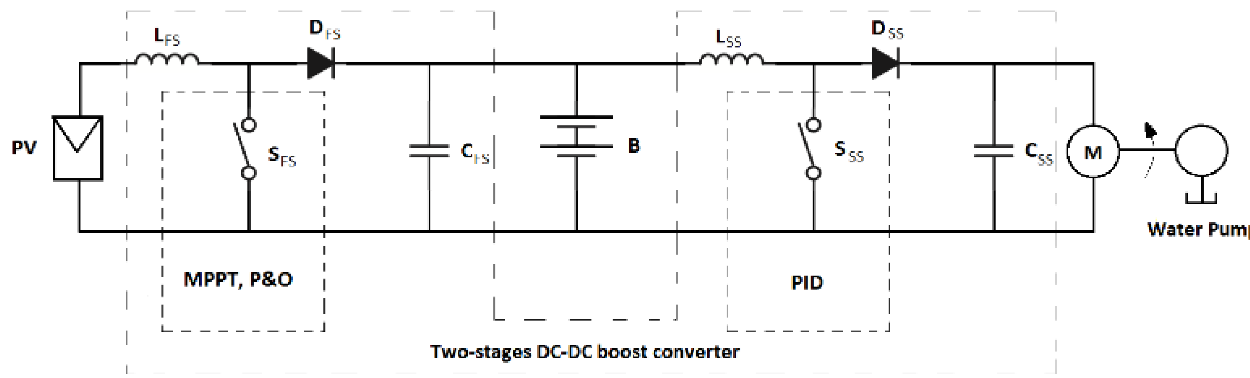

Figure 2-10 The block diagram of the proposed system.

Chapter 3

SOLAR WATER PUMPING SYSTEM SIZING: A Case Study

3. SOLAR WATER PUMPING SYSTEM SIZING: A Case Study

3.1 Site details

This study is applied on an average farm which is located in the northern area of Riyadh province. The farm mainly consists of 1260 palm trees. These crops are fed by a 115 m deep bore powered by diesel generator. It's surrounded by desert where there is no grid connection. Its location considered as a remote area due to the hardships in diesel transportation.

Figure 3-1 Date palm trees, Riyadh.

3.2 System Design and Size:

Choosing the proper solar system size is very essential especially with high demand loads' consumptions such as large pumps. At the same time, if sizing was done inefficiently, it would affect many aspects like cost and energy production. Sizing any solar water pumping system must go through some steps, mentioned briefly in chapter 2, to ensure that such system is secured and selected properly. In this research, the previous case description has been used to size such system in order to examine how effectively these steps work.

a) Water source:

Water source, either it is a well or pond, is one of the most crucial factors to be determined due to the pump type. Pumps type selection depends on the head and flow rate as the water source play big role in that. In this case study, a well with 115 m depth is the water source but the pump level was selected to be on a depth of 111 m. Four meters were left to accumulate water underground, avoiding pump damage from any sands or stones.

b) determination of water need

Two usage ways typically demand large proportion of water which are potable water and irrigation water. Each one has different set up of sizing; however, in our case, utilizing water for irrigation is the way that would be followed.

A daily water demand has been projected to irrigate an average farm which contains more than 1260 date palm trees (figure 3-1). These trees approximately consume 95% of the water supply. According to a study conducted in the gulf region show that the average daily water consumption for each mature date palm tree is 184.4 l/day [28].

Consequently, the average daily consumption of the whole farm can be obtained from the below expression.

$$\frac{\text{Number of palm trees} \times \text{Consumed water per a tree}}{0.95} \qquad (1)$$

$$= \frac{1260x184.4}{0.95} = 244900 \text{ l/day} = 244.9 \text{ m}^3 \text{ / day.}$$

The water demand is not fixed every day but there is fluctuation happens on a seasonal basis as shown in figure 3-2. For instance, in summer, vegetation needs more water than in other seasons due to summer fruits including dates.

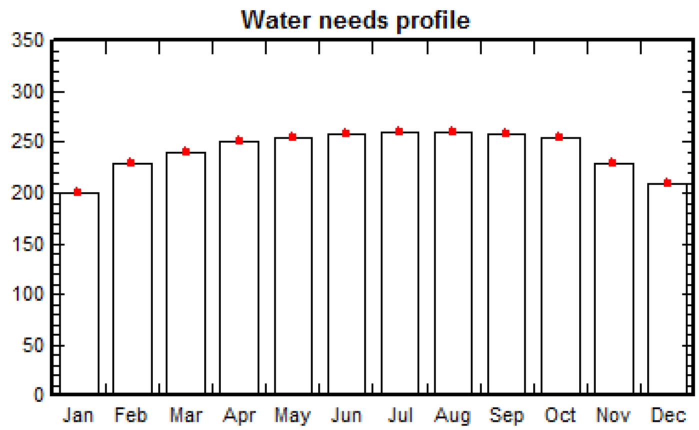

Figure 3-2 Water demand in m^3/day in a year.

The average typical desirable amount of water per day by 1260 fruit date palm trees is almost 245 m^3/day from a deep well typically using 4-inch pipe as shown in figure 3-3.

c) *Calculating the total dynamic head (TDH).*

As mentioned in the previous point, irrigation process has a different way for calculating the pump size which is based on estimating the total dynamic head (TDH) for pumping water. It is considered as pipes length as well as some mechanical frictions.

The following parameters are considered for TDH estimation and they are based on such case study. Those parameters are illustrated in figure 3 as well as pipes' length.

- The pipe internal dimeter is 4".
- The bore depth is 115 m; however, the pump will be installed at 111 m depth, while the average water level is 45 m.

- 3, 90° standard elbows are installed as shown in figure 3.

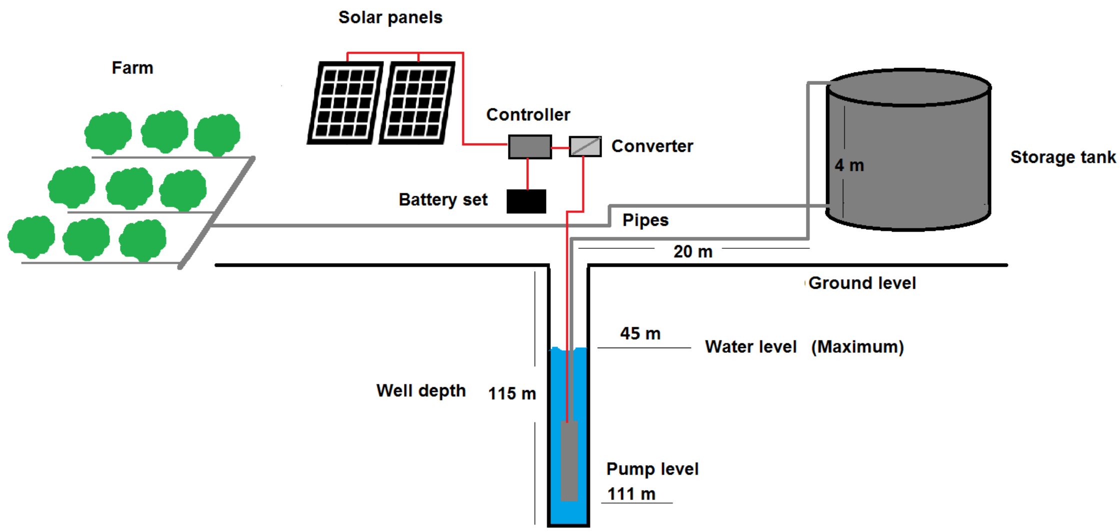

Figure 3-3 Schematic view of the solar PV Water-Pumping System.

Elbows as well as the horizontal pipes have some friction which is represented by factors shown in appendix A table 1.

TDH = 111 m (vertical) + [(1.8 x 3 elbows) + 20 m] x 20% + 4 m (vertical) = 120.08 ~ 120 m

Thus, the total dynamic head is approximately 120 m that will be used in pump size selection. This was based on the lowest water level in the well.

d) *Estimating the solar resource or solar radiation.*

It is unclouded that Saudi Arabia is blessed with high intensities of solar radiations as it is one of the largest regions receiving high solar energy as mentioned in the chapter 2. This would be defiantly the best place that this energy can be exploited. Homer software was used as well as the literature review to estimate how much energy of solar could be reached in such place. As figure 3-4 depicts, in month of June it would reach 7.8 kWh/m^2/day as the monthly average solar irradiation.

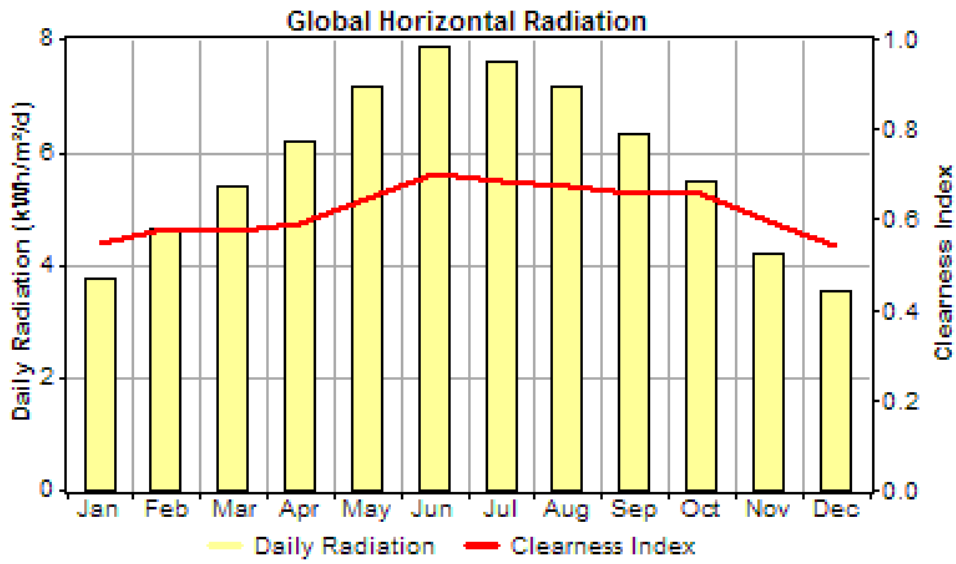

Figure 3- 4 Monthly average solar irradiation in Riyadh, Saudi Arabia (Homer).

According to M. Mohandes et al. [29], Saudi Arabia receives, on average, more than 5,500 W/m^2 global solar radiation each day on a horizontal surface. Depending on geographical location, the global solar radiation varies between a minimum of 4,493W/m^2/day in the northern part and a maximum of 7,014W/m^2/day in the southern part of KSA. As they noticed, the minimum and the maximum duration of sunshine varied between 7.4 and 9.4 hours that means and proves that Saudi Arabia has high solar radiations for long hours.

3.2.1 Pump Sizing

There are several strategies that have been followed to select the best or the optimized system. One of these methods is using Homer software along with some calculation. Homer was developed and tested by National Renewable Energy Laboratory (NREL) and now it is maintained by HOMER energy company [30]. Homer can be very useful tool when it is utilized with accurate values of PV, converter, batteries and other components' prices and sizes. In this study, all prices and sizes have been selected properly.

To start sizing such a system, the pump size is an important aspect that needs to be assessed. As the total head and water demand are known for a farm, the pump size calculation is forthright, and can be completed using the following expression [31].

$$P_{hyd} = \rho g H Q \qquad (2)$$

$$P = \frac{P_{hyd}}{\eta} = \frac{\rho g H Q}{\eta} \qquad (3)$$

where

P_{hyd} is hydraulic power (kW), ρ is water density (1000 kg/m3), g is the gravitational constant (9.81 m/s2), H is the total head (m), Q is the flow rate (m3/s), P is shaft power (kW), and η is pump efficiency (65%).

The total head includes the distance from pump level to the tank as well as the fraction of elbows. As shown earlier, the total head dynamic is 120 m and the maximum flow rate is 260 m^3/day

Results from equations 2,3 show that the calculated pump size is 5.4 kW which can deliver the required amount of water.

3.2.2 Solar PV System sizing

Based on the pump size, the PV panel and batteries can be selected using Homer software. As shown below in figure 3-5, the schematic of all electrical components built in Homer. Apparently, it is shown that system is AC coupled, however, it is not. Since we have two different DC voltage level, thus it needs two buses which is not provided in DC configuration.

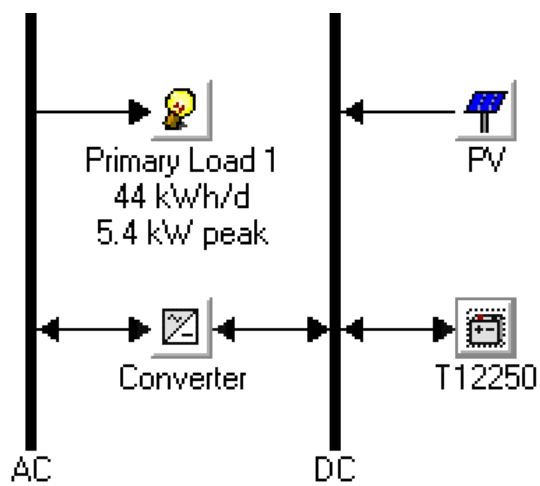

Figure 3-5 Schematic of electrical system components connection.

Starting with the energy source which is solar irradiation, so the selected location which is Riyadh has magnificent amount of solar energy as shown previously in figure 3-4. These data have been inserted along with the load data which is pump size in kW.

Results from equations 2,3 show that the calculated pump size is 5.4 kW with contemplation of other factors, which necessitate more power. After approximating the load, Homer can be used to select the optimized system.

Load has been inserted into Homer as shown in figure 3-6. The same concept applied to the load which appears as an AC but in reality, it is DC. The reason behind that is to keep the converter since we have different voltage level as mentioned before. This would not affect the system configuration. Consequently, the result would be the same for both AC and DC that has converter.

It can be noticed that the pump runs for 8 hours per day from 9 am to 5 pm. The aim is to utilize it as much as possible, in daylight, particularly during the peak time from 10 am to 6 pm.

11.6 kW solar panel, 6.8 kW converter, and 9 (200A, 12V) batteries, are selected as system components. As a standalone system, this power supply will be enough to pump the required amount of water with small percentage of excess electricity.

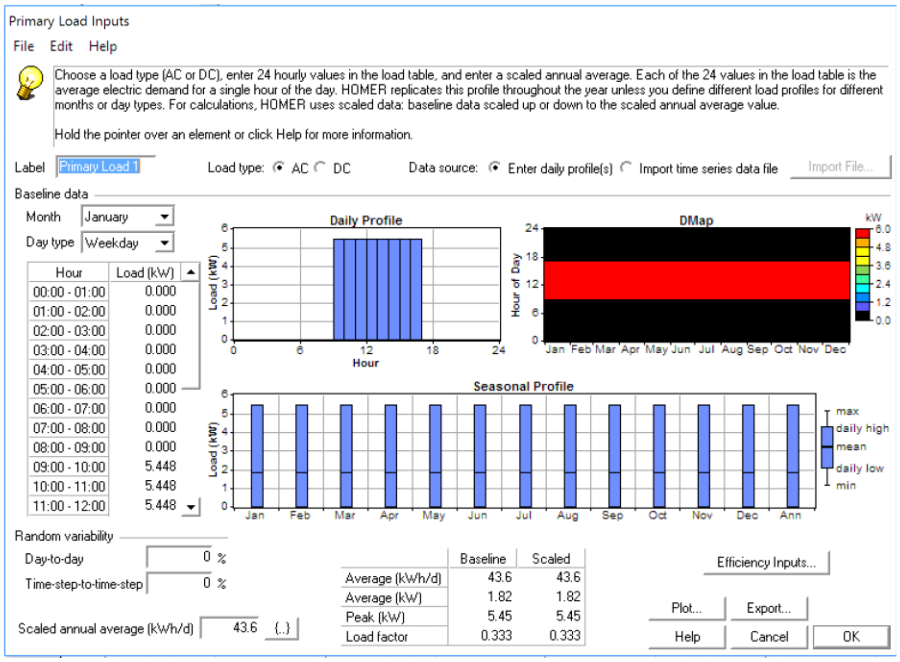

Figure 3-6 The load inputs (Homer).

Along with the load data, solar irradiation for the selected location has been used. Furthermore, different system sizes have been involved as well as their real costs including delivery and installation. Thus, simulation shows the optimized system as demonstrated in figure 3-7.

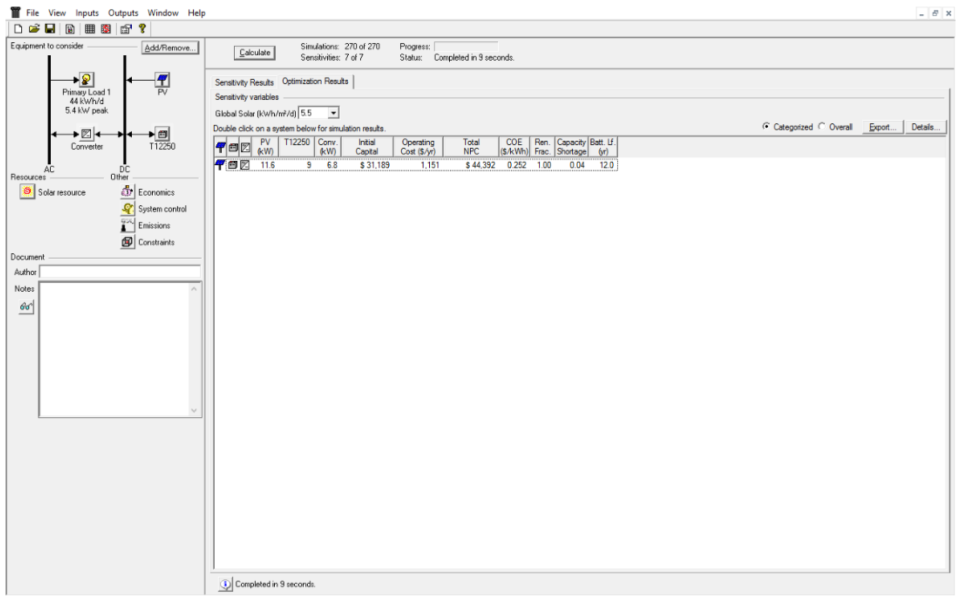

Figure 3-7 The selected optimized system after simulation (Homer)

Another method for sizing is PVsyst software [32] which has the ability to select the proper pump as well as the PV system; however, for storing energy, a tank has been chosen instead of batteries, unlike Homer. Same input data, as in Homer, have been inserted into it including water demand, total head, pump level, and site characteristics.

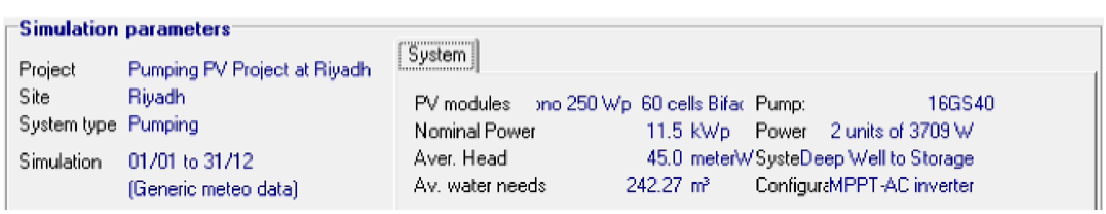

Figure 3-8 Screenshot of PVsyst the simulation parameters.

Figure 3-8 shows the parameters of the selected system in PVsyst which are very close to the ones in Homer. The PV size is 11.5 kW and pump size is 2 x 3.7 kW. As mentioned in Homer sizing section, the pump size was 5.4 kW, which was close to accurate due to the use of some formulas. However, in PVsyst, there is no such size; therefore, 2 pump stages x 3.7 kW each were recommended.

3.3 Possible energy storage methods:

Battery sizing

As shown in Homer sizing, there were 9 batteries have been selected to help the system stabilized. However, they are not enough to cover the total shutdown of such system for a day. It may operate the system for few hours as it can be estimated by:

$$Number\ of\ hours = \frac{9\,(\,200\ \mathrm{Ah} \times 12\ \mathrm{V})}{5448\ \mathrm{W}} = 3.96\ \approx 4\ hrs \tag{4}$$

Thus, it could help filling the voltage drop while operation or working for emergency cases.

Estimating the number of batteries for two cloudy days can be obtained as shown below.

$$\text{The energy consumption for 2 days } = 5.448\ \mathrm{kW} \times 8\ \mathrm{hrs} \times 2\ \mathrm{days} = 87.16\ kWh \tag{5}$$

As the voltage bus is 110 V and the depth of discharge for battery is 80%, the number of string can be calculated as below:

$$Number\ of\ strings = \frac{8726\ \text{Wh}}{110\ \text{V} \times 200\ \text{Ah}} \times 0.8 = 3.1\ \approx 3\ strings \tag{6}$$

Therefore, the number of batteries can be easily known as we have 9 batteries per string.

$$Number\ of\ batteries = 3\ \text{strings} \times 9\ \text{batteries}\ = 27\ batteries \tag{7}$$

As shown below in the diagram, the connection of 27 batteries.

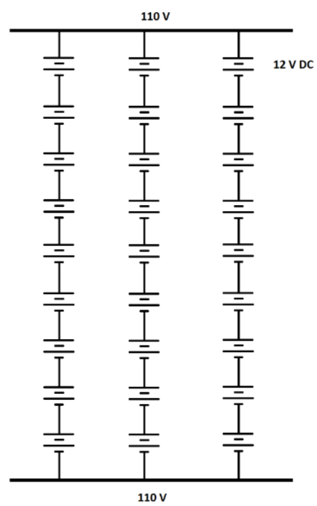

Figure 3-9 Batteries connections diagram.

Financially, it is not feasible since the cost of replacing batteries and maintaining them is very high. Water storage tank could be better choice as will be shown next.

Water storage tank sizing

Same period of time in the battery sizing is applied on the water storage tank. It was assumed that the absence of lighting or the cloudy days are only two. Thus, the size of tank is going to be estimated as:

$$Proper\ tank\ size = Number\ of\ the\ Cloudy\ Days \times$$

$$The\ AverageAmount\ of\ Water \qquad (8)$$

$$= 2\ days \times 245\ m^3 = 490\ m^3$$

Therefore, if the height of the tank was already known, which is 4 meter, the diameter of the tank is shown below in the layout.

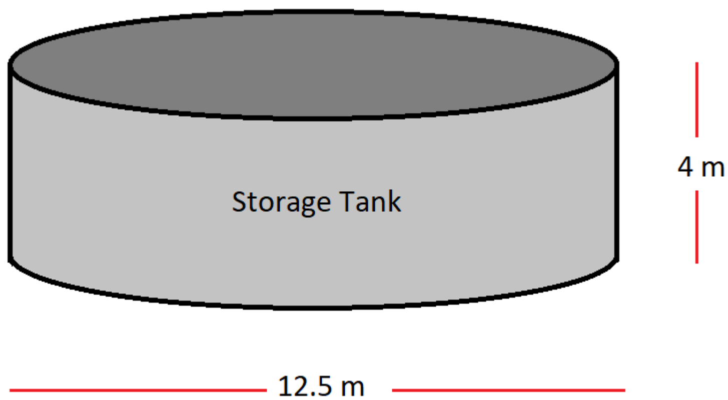

Figure 3-10 490 m^3 capacity water storage tank

The cost of the tank is much cheaper than batteries; the estimation is provided below with some details.

The tank is made from concrete which is the common type for irrigation in Saudi Arabia. The tank is a cylinder shape based as shown in figure 3-10. The cylinder volume should be as same as estimated in expression 5.

$$V = r^2 \times h \times \pi \qquad (9)$$

where

V: volume in m^3,

r: radius in m

h: height in m

$$V = 6.25^2 \times 4 \times \pi = 490.5\ m^3$$

In Saudi Arabia, such a tank costs around 6337 US$ (Appendix A - table 2) which is reasonable price for a very large tank. Yet it is highly recommended instead of batteries.

3.4 Installation challenges

Although Saudi Arabia is blessed with high solar energy, there are some challenges that any solar power user faces. The most critical challenges are high temperature and dust accumulation.

1- High temperature impact

Based on a study conducted by Skoplaki E et. al. [33], there is a correlation between the temperature changes and power of PV modules as well as efficiency. They found that, the relationship between those factors is any increase in the operating temperature results in decreasing power and efficiency. Another study [34] showed the effect in numbers where the PV power dropped by 0.5%/C and reduced the efficiency by 0.05%/C considering the variation of temperature from 25 to 50 C degree.

2- *Dust accumulation impact*

A recent publication has been conducted on a case study in Jordan [35]. Its authors concluded this experimental study with 0.607%/day as a reduction of the efficiency based on 192 day as an exposed duration. This drop in efficiency resulted in 8.14 kWh/m2 as a power losses with cost of 2.98 US$/m2. However, based on Saudi Arabia Solar Industry report for 2017 [36], there is a new type of solar glass with properties that resists dust has been developed by KACST (King Abdulaziz City for Science and Technology). As the plant manager of PV module production in KACST announced, the outcomes of their new invention are very promising.

This chapter provided sizing of a water pumping system. In the next chapter, the dynamic modelling of solar water pumping system will be presented.

Chapter 4

SOLAR WATER PUMPING SYSTEM DYNAMIC MODELING: A Case Study

4. SOLAR WATER PUMPING SYSTEM DYNAMIC MODELING: A Case Study

4.1 The Proposed System

A large-scale solar water pumping system has been developed and designed in chapter 3. Based on such system size, a dynamic modelling is carried out. A standalone 11.5 kW solar water pumping system is designed with 9 batteries (200A-12V) to prevent voltage drop during operation due to say moving clouds or temporary shadow. Such system is a DC coupled consists of 50 PV modules, maximum power point tracker (MPPT), two-stage DC-DC boost converter, and DC water pump as shown in figure 4-1. These components will be modelled separately as will be shown in the next sections and then combined together to study the dynamic behavior of the system.

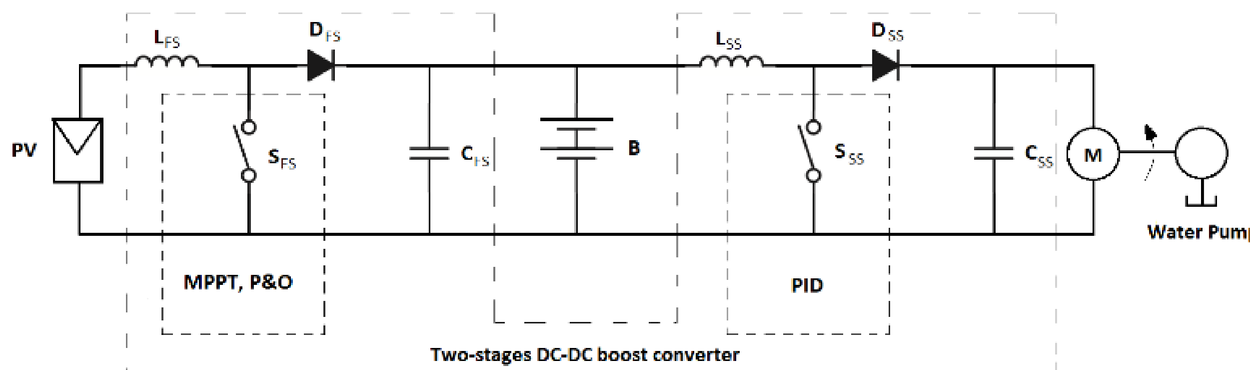

Figure 4-1 The block diagram of the proposed system.

4.2 PV Modules Modeling

The specifications in table 4-1 for a 230W PV module have been used as well as the equations 1-7 to build such module based on the equivalent circuit of solar cell shown below in figure 4-2.

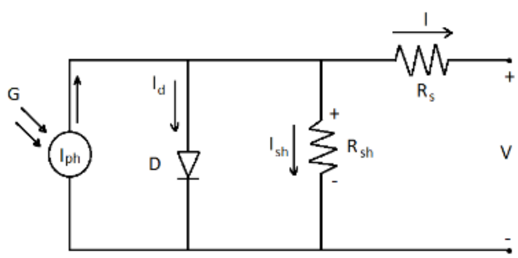

Figure 4-2 The equivalent circuit of solar cell.

TABLE 4-1 SOLAR PV MODULE SPECIFICATIONS

Peak Power W	230
Max power voltage Vmp	29.23
Max power current Imp	7.88
Open circuit voltage Voc	36.54
Short circuit current Isc	8.38
Module efficiency %	14
Ns	2
Np	25

As shown in figure 4-3, Matlab/ Simulink based model for PV module was built using the following equations. [37,38]. They show the relationship between the voltage and the current.

$$V_t = \frac{KT_{op}}{q} \qquad (1)$$

where

V_t: Thermal voltage,

K: Boltzmann's constant 1.38e-23,

T_{op}: Operating temperature in Celsius, and

q: Charge of an electron 1.6e-19C.

$$I_{rs} = \frac{I_{sc}}{[e^{\frac{V_{oc}\,q}{KCT_{op}\,n}}]} \tag{2}$$

$$I_{sh} = \frac{V+I_{rs}}{Rp} \tag{3}$$

$$I_d = [e^{\frac{(V+I_{rs})}{(NV_tCNs)}} - 1]I_sN_p \tag{4}$$

In practical, one solar cell usually is not sufficient to be applied for any load due to low capacity of energy provided. To give more capacity of PV system, solar cells must be connected in series and parallel [39].

$$I = I_{ph}N_p - I_d - I_{sh} \tag{5}$$

$$V_{oc} = V_t \ln\left(\frac{I_{ph}}{I_s}\right) \tag{6}$$

$$I_{ph} = G_k[I_{sc} + K1(T_{op} - T_{ref})] \tag{7}$$

where

G_k: Solar irradiance ratio,

T_{ref}: Reference temperature 25 °C,

I_s: Diode reverse saturation current, A,

I_{rs}: Diode reverse saturation current, A, I: Output current from the module, A,

I_{sh}: Shunt current, A,

V: Output voltage from the module, V,

N: Diode ideality factor,

C: Number of cells in a module,

N_s: Number of modules in series,

E_g: Energy gap of silicon, 1.12eV, and

N_p: Number of modules in parallel.

Module described above was simulated in Simulink. The figure below shows detailed Simulink model of solar array.

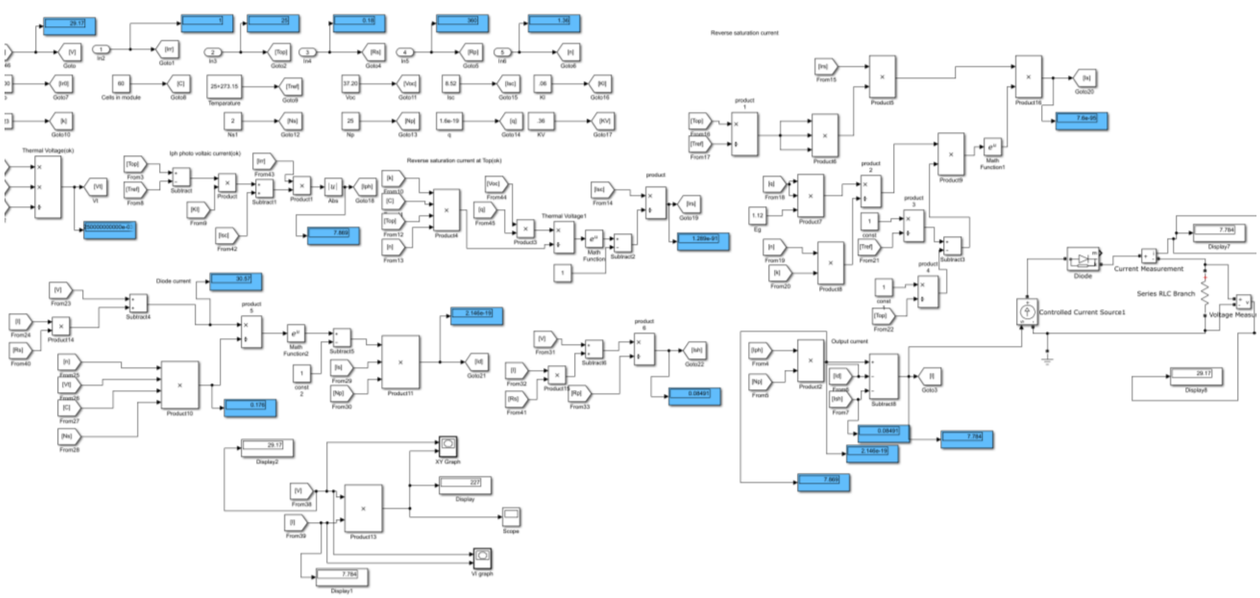

Figure 4-3 Overview of the solar array modeled in Simulink.

4.3 Two Stages DC-DC Boost Converter Modeling

This part illustrates the design of two stages DC-DC boost converter based on Matlab/Simulink. It helps regulating voltage of PV array to a fixed high-level voltage which is going to meet the demand of 380V water pump.

Generally, the principle for any boost converter is having two states [40]:

- On-state: The current (I_L) increases in the inductor (L), figure 4-4, by closing the switch (S).
- Off-state: The current (I_L) that was accumulated in the on-state has only one path which is through the diode (D), then to the capacitor (C), after that to the application (R).

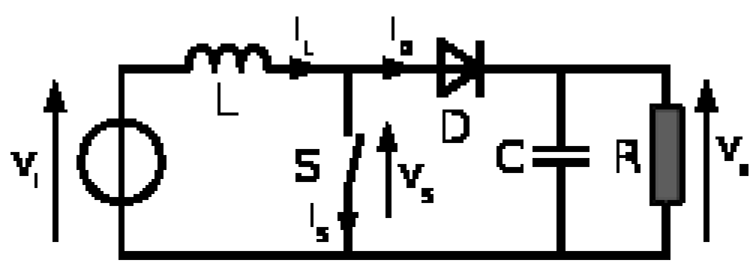

Figure 4-4 Schematic of boost converter [40].

However, in this the case study of this research, boost converter has two stages. In another word, it has two circuits, including: two inductors, two switches (Ideal switch), two flyback diodes, two capacitors. It is shown in figure 4-5.

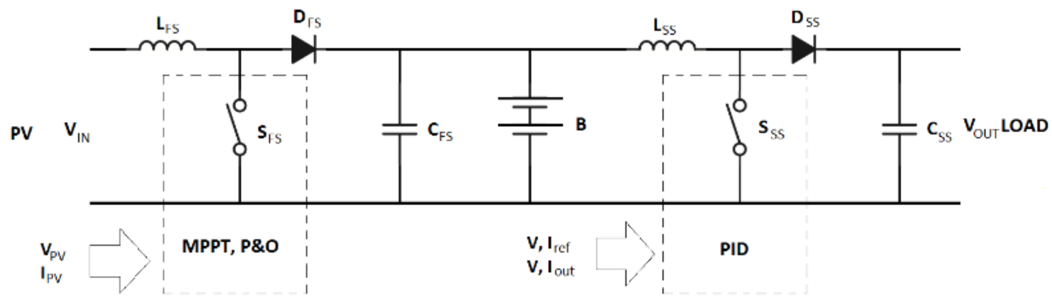

Figure 4-5 The block diagram of two stages DC-DC boost converter.

Since the duty cycle of a single stage boost converter is very large, 85%, the two stages boost converter was proposed as depicted in figure 4-5. First stage DC-DC get maximum power from PV modules, while the second stages converts that to a voltage suitable for DC pump. The main design parameters for the first stage and the second stage DC-DC are shown in table 4-2.

TABLE 4-2 THE PARAMETERS OF DC-DC BOOST CONVERTER.

First stage (FS)		**Second stage (SS)**	
$\mathbf{V_{in}}$	58V	$\mathbf{V_{in}}$	110V
$\mathbf{V_{out}}$	110V	$\mathbf{V_{out}}$	380V
fs	25kHz	**fs**	40kHz
η	90%	η	90%

A. Duty cycle:

The maximum duty cycle for both can be obtained from this expression:

$$D = 1 - \frac{V_{IN(MIN)} \times \eta}{V_{OUT}} \qquad (8)$$

where

$V_{IN(MIN)}$: minimum input voltage,

V_{OUT} : output voltage,

η : converter efficiency.

$$D_{FS} = 1 - \frac{58 \times 0.9}{110} = 53\%$$

$$D_{SS} = 1 - \frac{110 \times 0.9}{380} = 73\%$$

where

D_{FS} : First stage duty cycle,

D_{SS}: Second stage duty cycle.

B. Inductor selection:

An inductor is commonly used in boost converters which is connected in series as shown in figure 4-6 to smooth the current ripple of converter and store energy in each switching cycle. The value of inductor is usually selected from the data sheet but in our case since the voltage scale is very large, the inductor must be calculated from expression (10). However, before going through inductor calculation the inductor ripple current must be known which can be obtained from,

$$\Delta I_L = 1.75\% \times I_{OUT(MAX)} \times \frac{V_{OUT}}{V_{IN}} \qquad (9)$$

$$\Delta I_{L(FS)} = 0.175\times 28.65 \times \frac{110}{58} = 9.51\ A$$

$$\Delta I_{L(SS)} = 0.175\times 18\times \frac{380}{110} = 10.88\ A$$

Inductors' values for both stages can be calculated out of this expression [9].

$$L = \frac{V_{IN}\times(V_{OUT}-V_{IN})}{\Delta I_L\times f_S\times V_{OUT}} \quad (10)$$

$$L_{FS} = \frac{58\times(110-58)}{9.51\times 25000\times 110} = 115.25\ \mu H$$

$$L_{SS} = \frac{110\times(380-110)}{10.88\times 40000\times 380} = 179.64\ \mu H$$

MPPT is commonly used to increase the efficiency of PV systems. It operates in very high frequency, usually from 20 to 80 kHz. The reason behind that is it converts DC to DC to operate PV at MPPT. High frequency circuit works as a large transformer that allows boosting voltage and current to the desirable values, thus, meeting the voltage demand of water pump and a controller.

A boost converter has been modeled in Simulink as shown in figure 4-5; however, it has two stages of which have two control methods.

PV voltage and current regulated to MPP by P&O algorithm as shown in figure 4-7 and the flow chart in figure 4-6 as the first stage of converter which works as a battery charge controller. The voltage shall be adjusted to charge the batteries as well as boosted to the range of the second stage of the converter. For the second stage, as depicted in figure 4-6, the PID controller is proposed due to its simplicity since the reference was the desirable voltage and current.

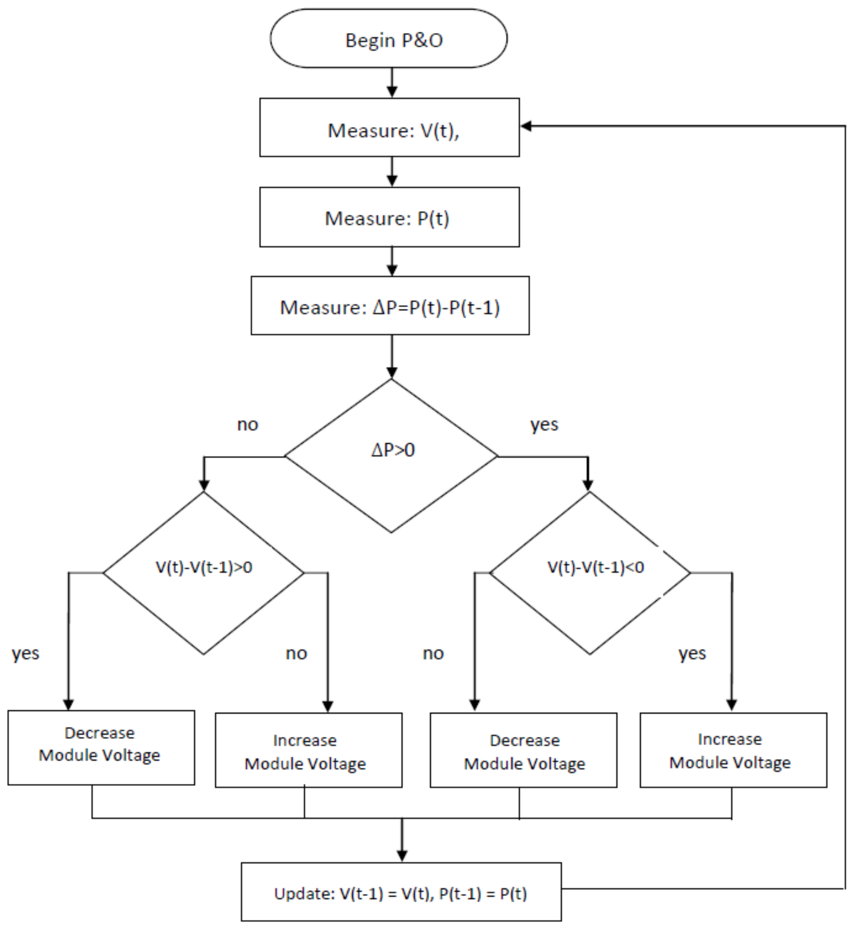

Figure 4-6 Perturbation and Observation algorithm.

Why P&O algorithm method for tracing the power points? Not the other methods?

As per a study conducted in this regard [41], it showed a comparison between the most known methods, the Perturbation & Observation and the Incremental Conductance methods. Their experimental performance results were relatively close where the efficiency for P&O was 99.3% and for the incCond was 99.4%. Yet the efficiency for the latter is little bit higher; however, it was concluded by choosing the P&O method for the cost matter.

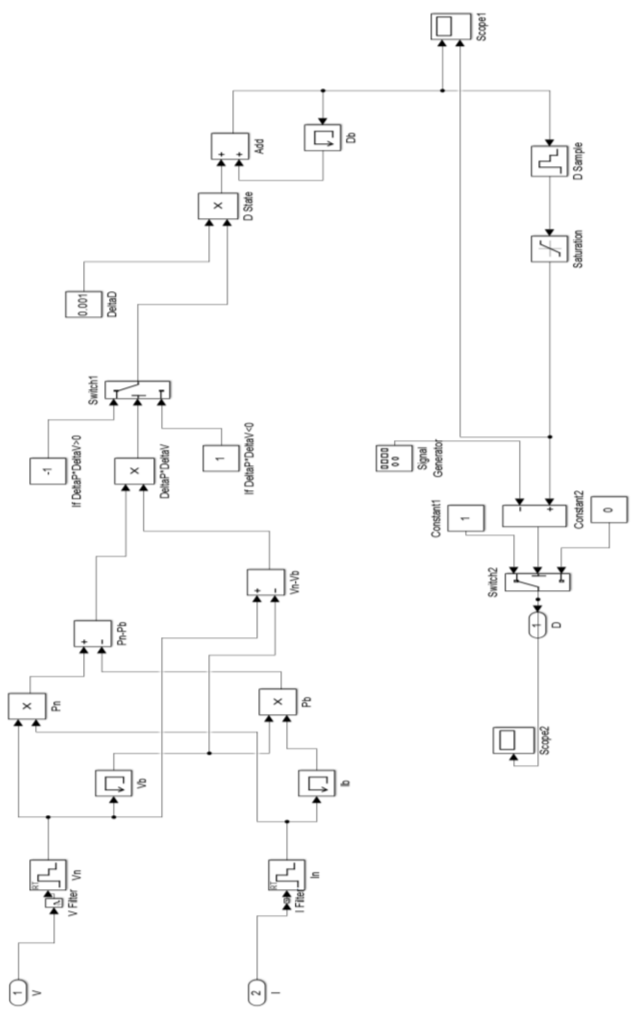

Figure 4-7 P&O algorithm implementation.

4.4 Energy Storage System Modeling

Nine batteries, lead acid, which have rating of 200A, 12 V each, have been chosen based on the battery sizing in chapter 3. They are connected in one string since they need to meet the bus voltage, 110 V (appendix b figure 1). The model of battery was already built in Simulink/ Matlab as shown in figure 4-8; however, there are some factors that have been modified such as the SOC, state of charge.

200A as a capacity for each battery was selected properly due to some aspects such as maintenance and size.

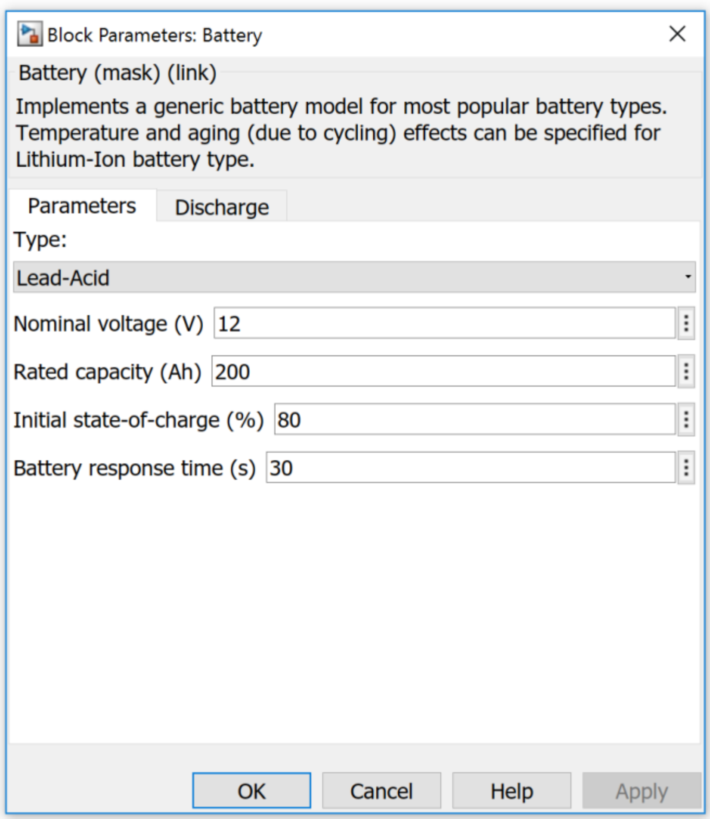

Figure 4-8 Battery model in Simulink.

4.5 DC Shunt Motor and Centrifugal Pump Modeling

A 5.5 kW DC shunt motor connected to a centrifugal pump has been designed by Simulink to deliver 245 m^3 of water per day. The DC motor and pump specifications are shown in table 4-3.

TABLE 4-3 MOTOR AND PUMP SPECIFICATIONS.

<table>
<tr><td colspan="7">DC PUMP SPECIFICATIONS</td></tr>
<tr><td>Model</td><td>Impeller</td><td>voltage (V)</td><td>Pump Power (W)</td><td>Max Flow (M3/H)</td><td>Max Head (M)</td><td>Outlet (IN)</td></tr>
<tr><td>4ZPC14/148-D380/5.5</td><td>Centrifugal (SS)</td><td>DC380</td><td>5500</td><td>10</td><td>120</td><td>4</td></tr>
<tr><td colspan="7">DC SHUNT MOTOR SPECIFICATIONS</td></tr>
<tr><td>Rated voltage (V)</td><td>Rated speed (RPM)</td><td>Rated current (A)</td><td colspan="2">Rated torque (N.M)</td><td colspan="2">Rotor inertia(Kg.cm²)</td></tr>
<tr><td>380</td><td>1700</td><td>15</td><td colspan="2">14.5</td><td colspan="2">0.01</td></tr>
</table>

The equivalent circuit of the DC motor has been modeled in Simulink as shown in figure 4-9. (simscape blocks)

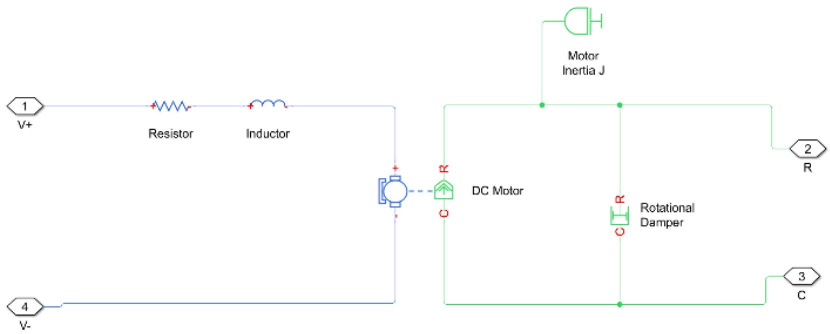

Figure 4-9 DC shunt motor simulation in Simulink.

Figure 4-10 shows the pump model in Simulink based on the specifications in table 3.

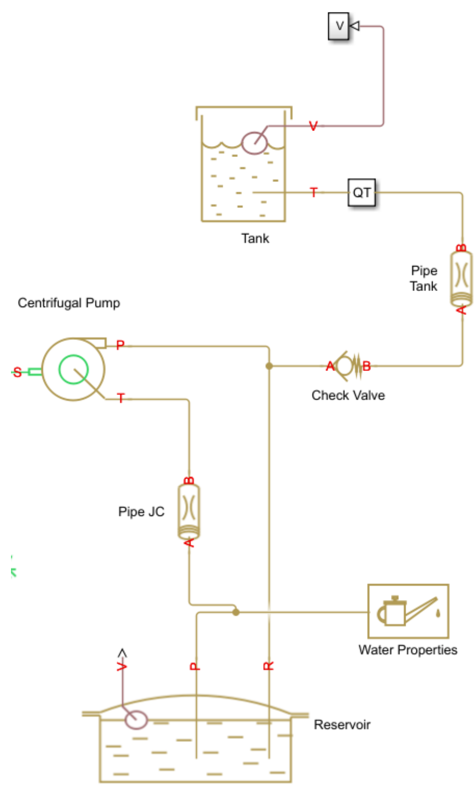

Figure 4-10 Centrifugal pump built in Simulink

4.6 Solar Water Pumping System Modelling

The complete model of solar water pumping system which is based on Simulink is shown below in figure 4-11. All the components modelling have been combined together to be set for simulation.

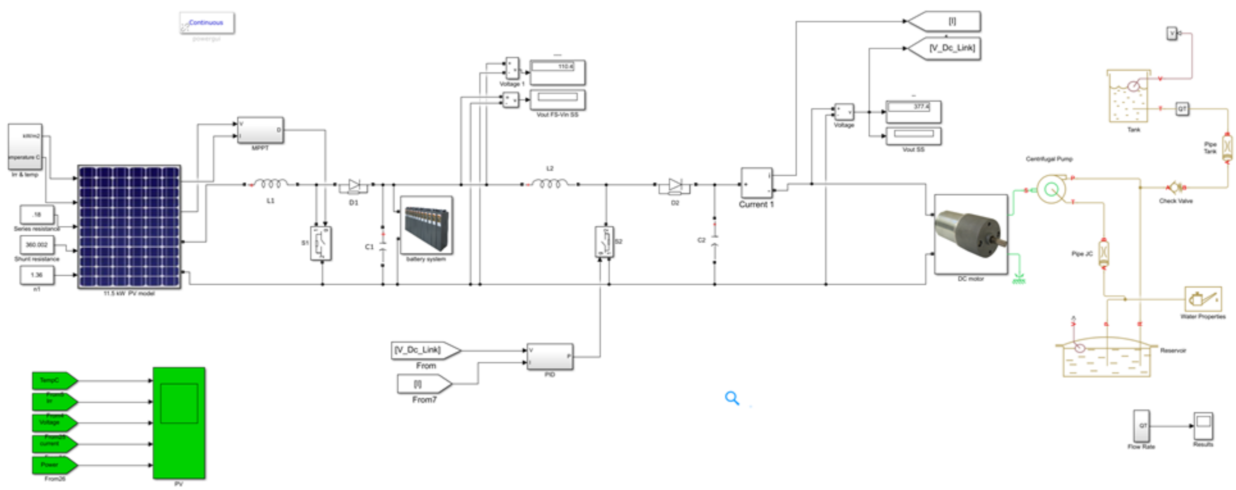

Figure 4-11 The proposed system model in Simulink.

Simulation results of such system model will be shown and explained in the next chapter (Chapter 5: Results and discussion)

Chapter 5

RESULTS AND DISCUSSIONS

5. RESULTS AND DISCUSSIONS

5.1 System sizing results

Comparable results were attained from the use of both Homer and PVsyst. A PV system rated at 11.6 kW (figure 5-1) was used for Homer, while a 11.5 kW system (figure 5-2) was used for PVsyst. As shown below, the energy production provided by PV system was sufficient to operate the water pumping system; moreover, there is 8% excess electricity that can be utilized for extra load such as small devices. Such system was designed without any tracking system, thus it is considered if there is any deficiency in energy delivery.

Figure 5-1 Screenshot of Homer for the energy production.

For storing the excess energy, Homer does not offer many choices in this regard, therefore, the only accessible choice was nominated. Nine (200A, 12V) batteries connected in series were enough to cover the power deficiency from PV array. Unlike Homer, PVsyst has a possibility of tank storage. In fact, it is the top choice for zones with elevated temperature levels, otherwise, it would disturb battery's life harmfully. Financially, the nine batteries which were nominated in Homer cost $11875 over the course of 20 years (including replacement and maintenance cost). Nevertheless, they were enough for covering power shortages for only 4 hrs as calculated in chapter 3, whereas the storage tank is sufficient for 2 cloudy days with 490 m^3 water capacity. The initial costs would settle around $6400. Therefore, if a comparison is made between the batteries and the storage tank, estimation should include the required number of batteries in same time duration. It is pretty obvious that more than 9 batteries would be required as shown and calculated in chapter 3, the required batteries are 27 batteries, costing $34,250 which is much more than the tank cost.

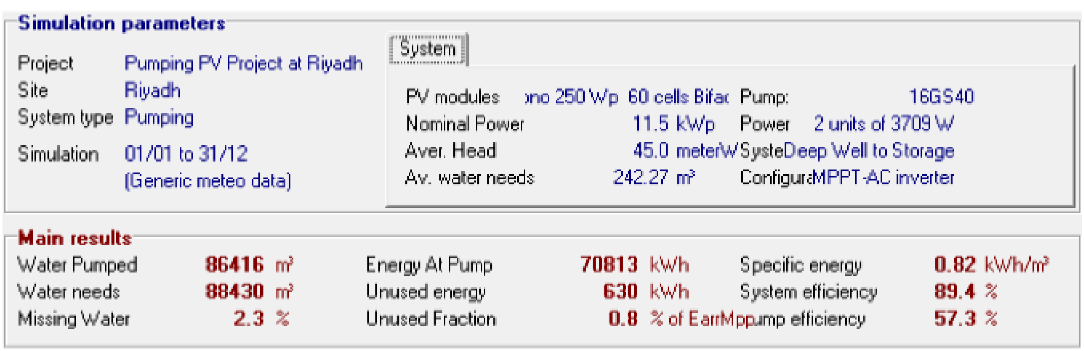

Figure 5-2 Screenshot of PVsyst the main results and the simulation parameters.

The pumps' sizes were somewhat different due to the limitations in PVsyst software, which only offers fixed sizes, however, the sizes were not too different. The selected pumps were 16GS40 with 250 V nominal voltage and 31A nominal current.

PV power outputs were changing every month. As shown in figure 5-3, the peak of power output happened in June, July, and August, while the least happened in January and December. Equally, the water demand showed almost the same variation on seasonal biases since the irrigation in summer requires more than other seasons.

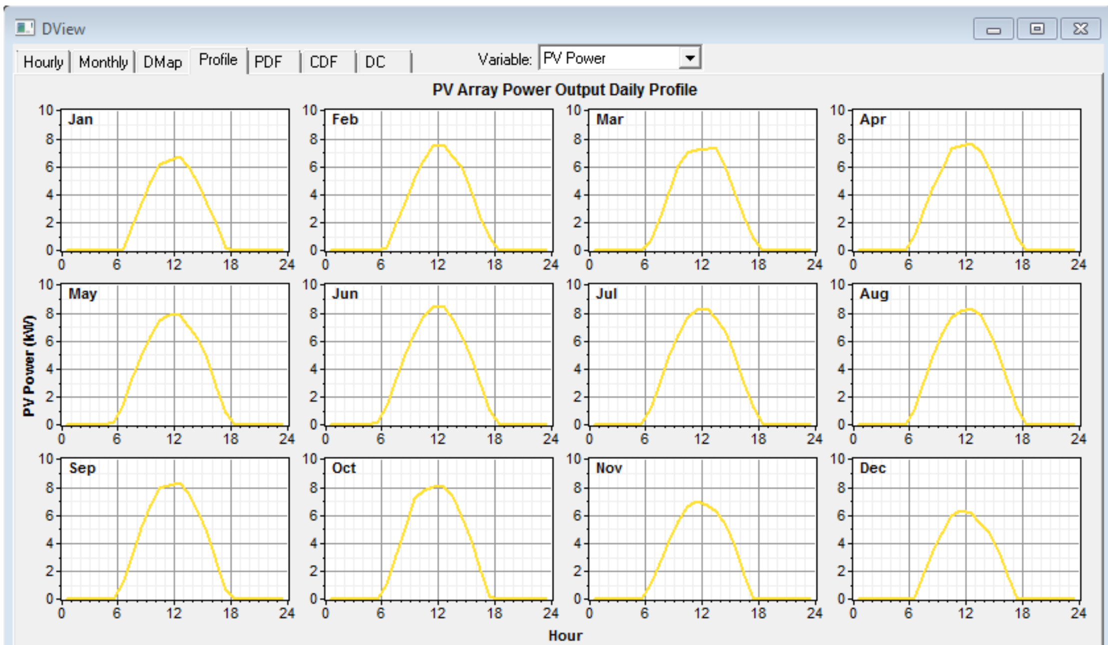

Figure 5-3 PV array power output daily profile (Homer).

Evidently, as simulation results from PVsyst show that most of the water production happened with the same ratio of PV array production and solar irradiation as shown in figure 3 in Appendix C. More than the required amount of water may be extracted in high intensive irradiation as depicted below.

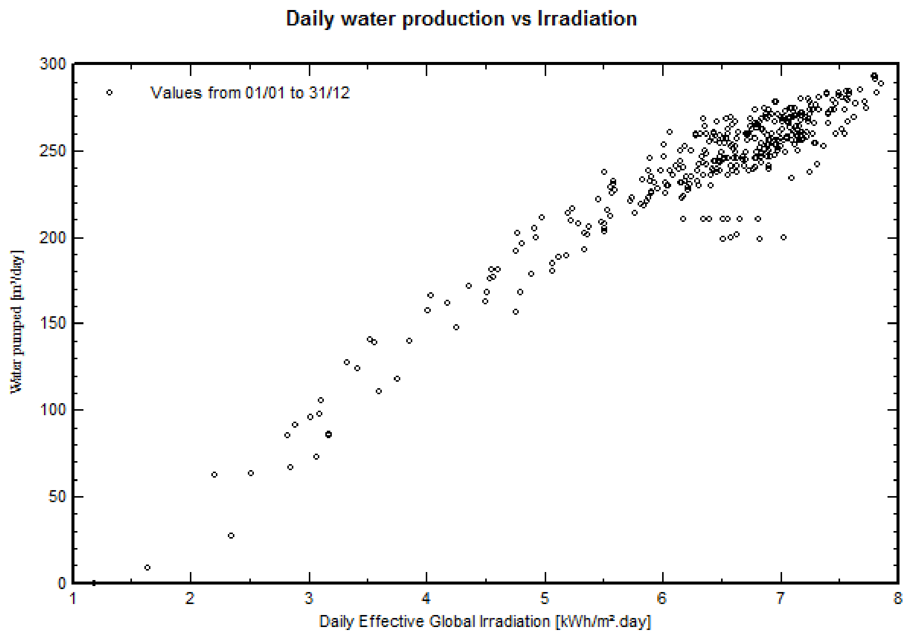

Figure 5-4 Water production versus input solar irradiation (PVsyst).

System cost:

System cost is reasonable when it is compared to conventional systems especially diesel generator which has high annual operational cost as shown in Appendix C, figure 1, which is almost the same as the initial cost of PV system. Even though the diesel generator initially costs $5,748, which is relatively low, the running costs are very high. For instance, diesel generator needs to be replaced every 5-7 years depending upon the quality of maintenance. However, PV solar water pumping system has quite high initial costs but the maintenance and operation costs are quite reasonable. The cost of PV, batteries and converter is $29,000, as shown in Appendix C, figure 2. In PVsyst, the cost is almost $36,000 including pumps, pipes, and wiring cost.

Water cost:

PVWPS is considered one of the best ways for drawing water out of a bore. Moreover, it is cheaper than conventional system despite the low diesel prices in Saudi Arabia. The cost of water, which depends on the results from Homer, as well as some calculations.

$$PVC = I + \sum_{n=1}^{N} \left(\frac{Cn}{(1+r)^{N}}\right) \qquad (1)$$

where *PVC* is the present value cost,

Cn is the annual cost,

r is the discount rate that will be assumed as 10% [10],

and *N* is the number of operational years.

The PV, batteries and inverter cost from Homer is $29,048 excluding the pump, pipes and set up costs. The cost of pipes and the pump is estimated to be $6000, which accumulates the total costs at $35,084.

I = $35,084

Operational and maintenance costs are assumed to be 2% of the initial cost:

O & M = 0.02 x 35,084 = $701.68

In this case, the annual operation and maintenance costs are only $701.68 for 25 years.

$$PVC = 35{,}084 + \sum_{n=1}^{25} \left(\frac{701.68}{(1+0.1)^{25}}\right) = \$36{,}703$$

The annual energy cost will be:

$$AEC = PVC\left(\frac{r(1+r)^N}{(1+r)^N-1}\right) \quad (2)$$

$$AEC = 36{,}703\left(\frac{0.1(1+0.1)^{25}}{(1+0.1)^{25}-1}\right) = \$4{,}043.5$$

Thus, the cost of each m^3 of water can be calculated:

$$\left(\frac{AEC}{WaterDemandPeryear}\right) \quad (3)$$

$$\frac{4043.5}{245m3/dayx365day} = \mathbf{\$0.045/m^3}$$

This value is exactly the same as the water cost estimated by PVsyst as shown in Table 1. Despite the cheap diesel costs, this value would be the cheapest cost of pumping water on a long run.

TABLE 5-1 WATER COST (PVSYST SCREENSHOT).

Water and Energy cost	
Energy used for pumping	19.7 MWh / year
Excess energy (tank full)	0.2 MWh / year
Cost of used energy	0.00 US$ / kWh
Water Pumped	86416 m³
Cost of pumped water	**0.04 US$ / m³**

5.2 System Modelling Results

As already shown and explained in the proceeding chapter, modeling of each component of such a large scale solar water pumping system. After that, all of these models were combined and connected as shown below.

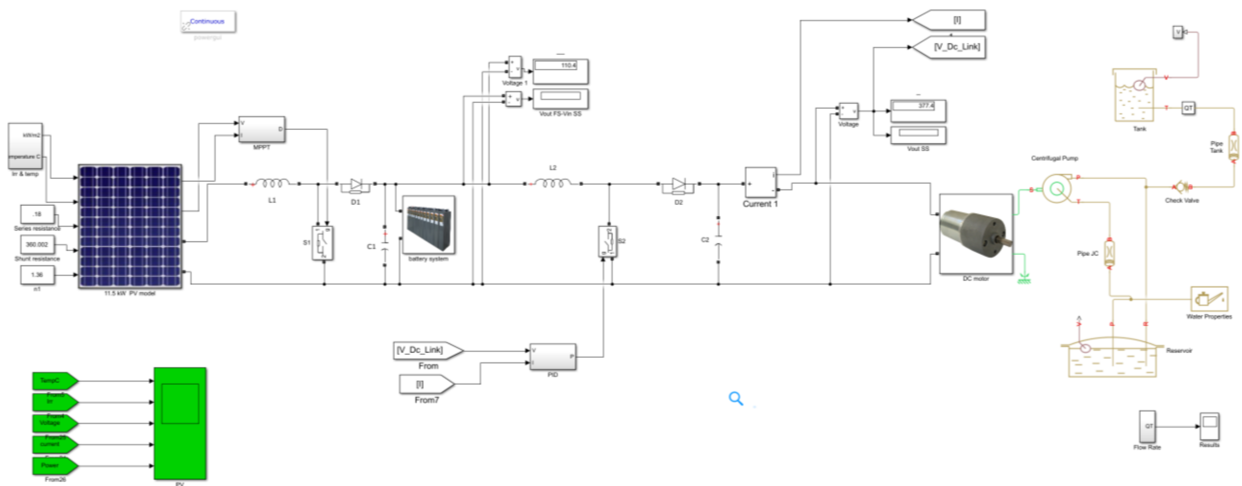

Figure 5-5 11.5 kW Solar water pumping system model in Simulink

Simulation results have shown that the output power is changing corresponding with the irradiation and temperature variation without the MPPT and boost converter as figure 5-6-c,d and e depict. Also, increasing in temperature directly affects the PV output as it goes down, while decreasing in temperature improves the performance of the PV array.

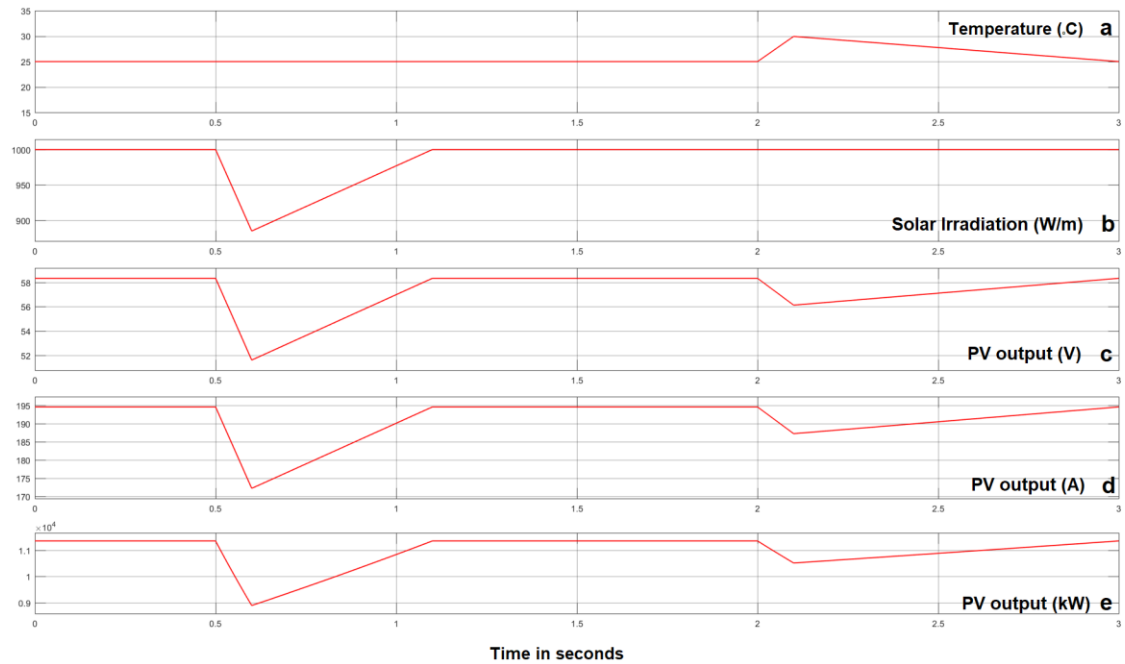

Figure 5-6 (a) Temperature. (b) Solar Irradiation W/m (c) PV output voltage, V. (d) PV output current, A. (e) PV output power, kW.

Controller performance simulation results

Two-stage boost converter helped stepping up voltage from 58V to the nominal voltage of the DC pump, 380V by using two controlling methods, O&P and a PID controller.

However, using MPPT has shown that efficiency of the system was slightly improved at the first stage (figure 5-7). At the second stage, it can be noticed that the voltage output is steady state and met the demand since the batteries voltage helped filling the voltage drop that occurred at the FS. (figure 5-8). Moreover, as figure 5-9 illustrates, the flow rate requirement which is the system output was being fulfilled.

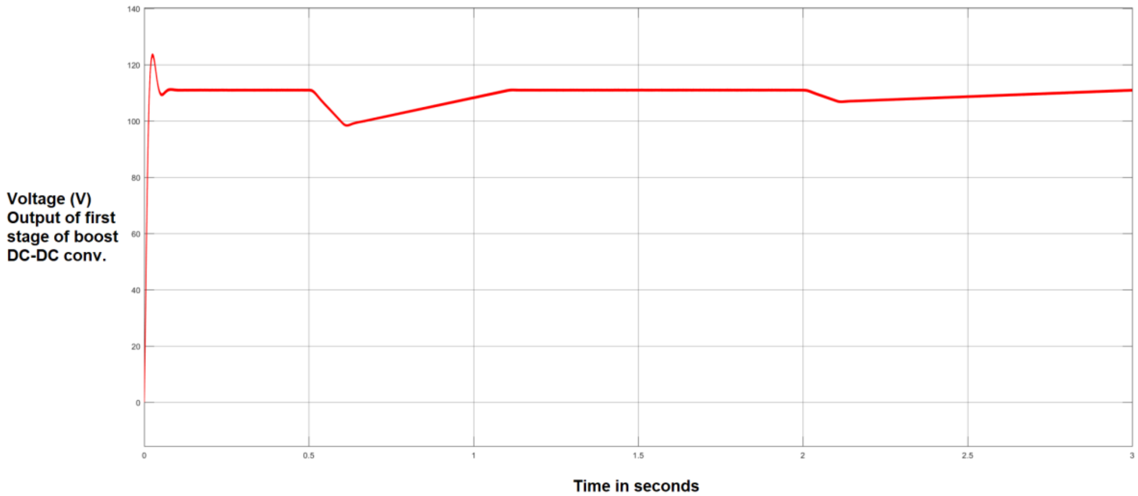

Figure 5-7 Output voltage of fixed DC-DC converter controller by a MPPT algorithm.

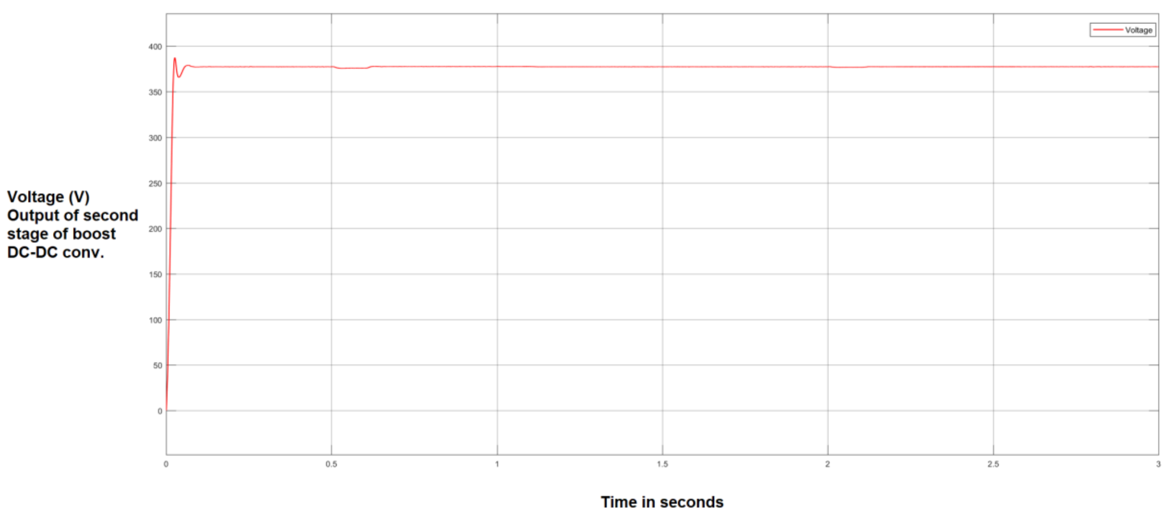

Figure 5-8 Output voltage of the second DC-DC converter stage.

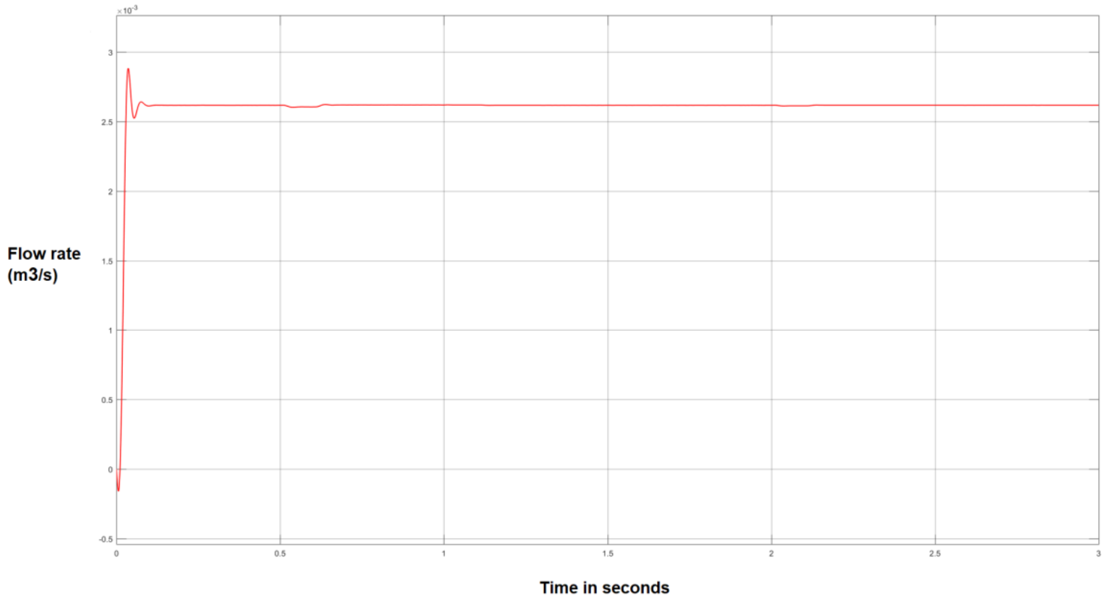

Figure 5-9 Flow rate, 0.0027 m^3/s.

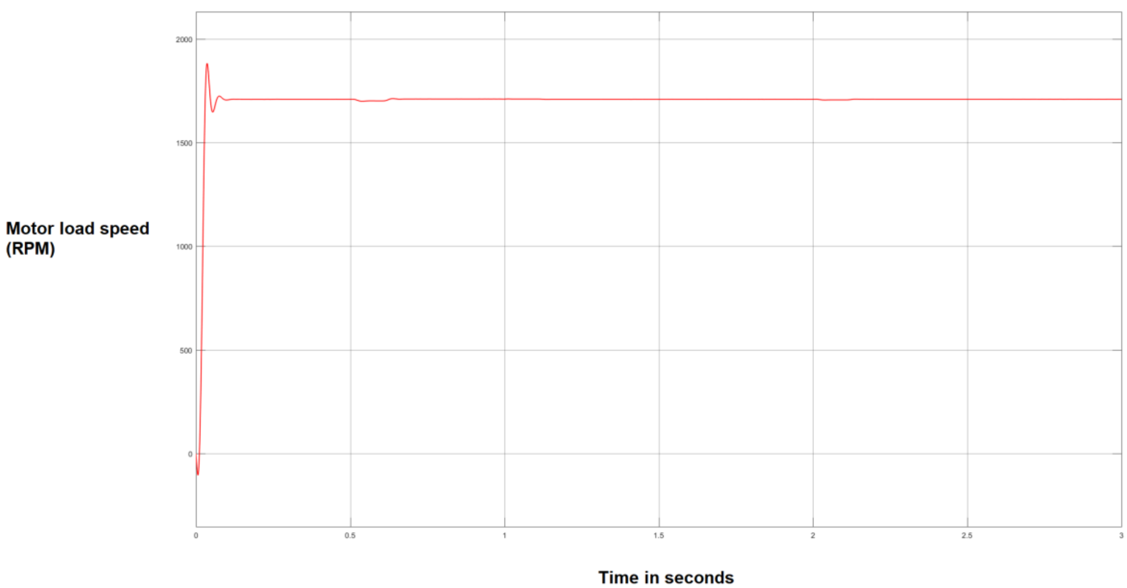

Figure 5-10 Motor load speed, 1700 rpm.

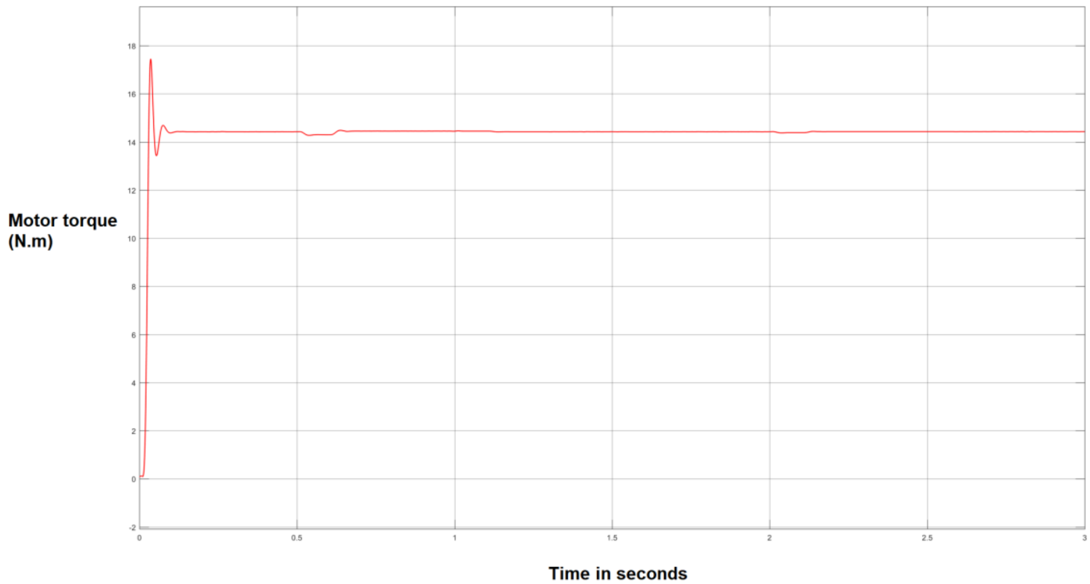

Figure 5-11 Motor torque, 14.5 N.m

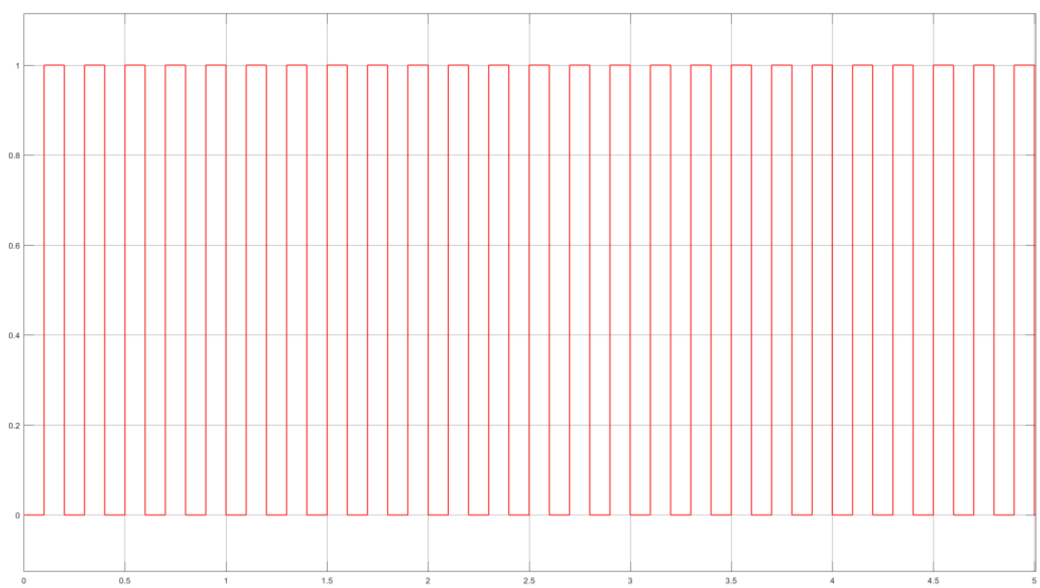

Figure 5-12 Duty cycle for a DC-DC converter.

5.3 Suggested System Data Logging System

There are many data loggers for PV systems in the market; however, they create high energy losses to feed themselves out of the energy production. To avoid these handicaps, a simple data logger can be built using Arduino. Current sensors and voltage divider are needed to be installed along with Arduino as well as LCD display.

To monitor the system remotely, there are various websites providing this service such as Xively, but the code should be developed along with that. Also, for storing the data, SD card needs to be installed as well, needing a written code.

Chapter 6

CONCLUSIONS AND RECOMMENDATIONS

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Sizing a large scale solar powered water pumping system has been carried out and economically analyzed; helping to understand the whole concept of using renewable energy over conventional energy. It was obvious that PVWPS is very suitable and recommended in sunny spots like Saudi Arabia. Exploiting such systems in a place like Saudi Arabia yields, to some extent, the lowest water extraction cost with \$0.04 for each m^3. Moreover, Saudi government already announced that oil prices will be raised up to 30% within this year. This would encourage farmers to look for alternative solutions such as PVWPS. Consequently, it would make water cost cheaper than ever.

The dynamic modeling of a large scale solar powered water pumping system which is fed by 11.5 kW PV source has been investigated and tested using Simulink. Thus, the system simulation has, shown satisfactory results. Dynamic results indicate that MPPT algorithm for the first DC-DC stage and PID controller for the second DC-DC stage are able to achieve the objective for a variation in the input temperature and input solar irradiance. Moreover, the feasibility of using such system in Saudi Arabia is much higher than any elsewhere since there is an enormous solar resources available. Even though the study only focused on one location which is Riyadh which is a moderate spot, there are some regions in KSA have higher total solar radiation such as southern area [10].

6.2 Research contributions

- Solar water pumping system has been focused to be an economical solution for Saudi Arabia.

- Saudi Arabia is blessed with high intensity of solar irradiation; however, it is not being effectively utilized.
- Commercial Solar water pumping system kits are typically designed for small-scale applications; nevertheless, most of farms in the region are considered large-scale.
- Data for an average farm in Saudi Arabia was collected for a case study in this thesis.
- Water pump size was estimated based on TDH, flow rate, and pump efficiency.
- HOMER and PVsyst were used for sizing such system and results were compared to each other.
- The possible energy storage methods (batteries and water tank) were presented based on economical analysis.
- Dynamic model of a large scale solar water pumping system has been built in Simulink/Matlab.
- Two stages boost converter was developed and modelled in Simulink.
- This research shows that large scale solar water pumping system is a good solution for countries like Saudi Arabia.

6.3 A list of resulting publications

1. Abdulhamid Alshamani, Tariq M. I qbal, “Sizing and Modelling of a large deep water Solar Water Pumping System for irrigation in Saudi Arabia” presented at IEEE NECEC 2016 conference, St. John’s, Canada.

2. Abdulhamid Alshamani, Tariq M. I qbal, "Feasibility of using a Large Deep Water PV Water Pumping System A case study for an average farm in Riyadh, Saudi Arabia" presented at IEEE IEMCON 2017 conference, Vancouver, Canada.
3. Abdulhamid Alshamani, Tariq M. I qbal, "Modelling of a large-scale Solar Powered Water Pumping System for irrigation in Saudi Arabia" presented at IEEE IEMCON 2017 conference, Vancouver, Canada.

6.4 Recommendations and future work

Using a water storage tank over batteries is highly recommended for Saudi Arabai for many reasons. First and foremost, it costs around 25% of the batteries expenses on the course of 20 years. Second, it is not affected by high temperature, unlikely to the batteries which could add up more maintenance and operational cost. Some water loss due to leakage and evaporation is expected.

Irrigation distribution has different methods in Saudi Arabia as it is in other countries; however, this study suggests using drip irrigation which is considered the best method for water distribution. It has been compared to other irrigation methods and comes as the most efficient way with 85% efficiency (appendix d). Open channel, which is popular in Saudi Arabia, comes as a second; however, it's still not efficient in terms of water conservation, which losses more than 40% of water until to reach the chosen spot, resulting in high water consumption as well as running water pump for an abnormal long time. Both of them are compatible with solar pump, but the former is more suitable for irrigation in Saudi Arabia especially, nowadays, the government encourages people to be more aware of water conservation. SPWPSs could raise the availability of fresh water from underground; equivalently, Saudi Arabia would abandon the desalination (converting saltwater to freshwater) ,which comes in the top of the list with approximately 5.2 million cubic meters in daily basis [42], or at least minimize the production through this process.

The future work needs to be related to the modeling and controlling of the system. Developing an experimental work and comparing the performance of both approaches under many scenarios is one of the strategies that could be followed. This would help understanding the behaviour of such systems in different ways. Also, the data logging system should be developed based on experimental work such as writing cods for Arduino and configuring the monitoring system.

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APPENDICES

APPENDICES

Appendix A:

Table 1: the equivalent length of straight pipe for valves and fittings (Engineering ToolBox)

Equivalent Length of Straight Pipe for Valves and Fittings (meter)														
Flanged Fittings		Pipe Size												
		1/2	3/4	1	1 1/4	1 1/2	2	2 1/2	3	4	5	6	8	10
Elbows	Regular 90 deg	0.3	0.4	0.5	0.6	0.7	0.9	1.1	1.3	1.8	2.2	2.7	3.7	4.3
	Long radius 90 deg	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.3	1.5	1.7	2.1	2.4
	Regular 45 deg	0.1	0.2	0.2	0.3	0.4	0.5	0.6	0.8	1.1	1.4	1.7	2.3	2.7
Tees	Line flow	0.2	0.3	0.3	0.4	0.5	0.5	0.6	0.7	0.9	1.0	1.2	1.4	1.6
	Branch flow	0.6	0.8	1.0	1.3	1.6	2.0	2.3	2.9	3.7	4.6	5.5	7.3	9.2
Return Bends	Regular 180 deg	0.3	0.4	0.5	0.6	0.7	0.9	1.1	1.3	1.8	2.2	2.7	3.7	4.3
	Long radius 180 deg	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.3	1.5	1.7	2.1	2.4
Valves	Globe	11.6	12.2	13.7	16.5	18.0	21.4	23.5	28.7	36.6	45.8	58.0	79.3	94.6
	Gate	0.0	0.0	0.0	0.0	0.0	0.8	0.8	0.9	0.9	0.9	1.0	1.0	1.0
	Angle	4.6	4.6	5.2	5.5	5.5	6.4	6.7	8.5	11.6	15.3	19.2	27.5	36.6

Table 2: Water tank cost breakdown.

Material	**Each 4 m (diameter) x 1 m (height)**	**Cost in Saudi Riyal**	**Cost in US$**
Concrete bag	30 bags	30 bags x 13.5 SR x 12.5/4 x 4 m = 5062.5 SR	
Sand	One small truck	12.5/4 x 4 x 1 x 200 SR = 2500 SR	
Rebar	1/16 ton	2 ton = 2 x 1850 = 3700 SR *	
Labor	1000 SR	1000 x 12.5/4 x 4 = 12500 SR	
Total		**23762.5 SR**	**6337 US$**

* https://www.metalbulletin.com/Article/3738062/Saudi-Arabias-Sabic-increases-rebar-price-on-materials-costs.html 13/10/2017

Appendix B:

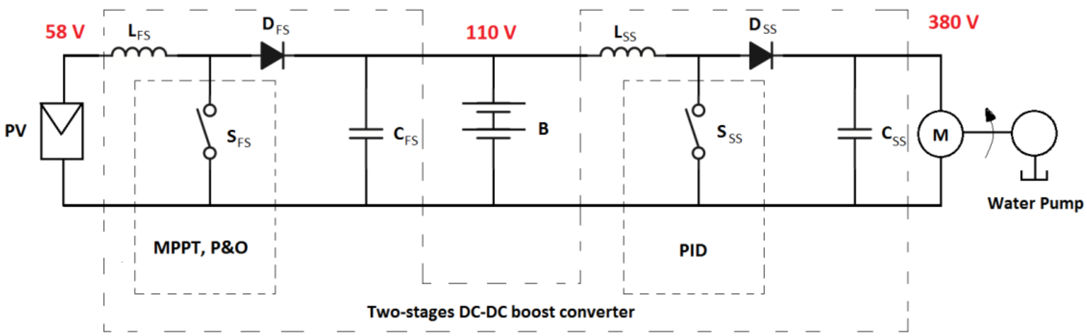


Figure 1: Proposed system voltage bus levels

Appendix C:

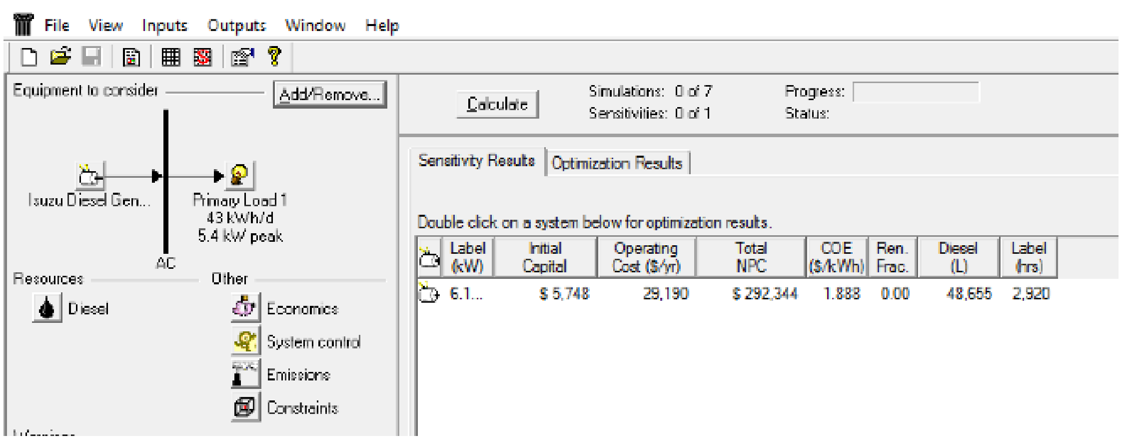
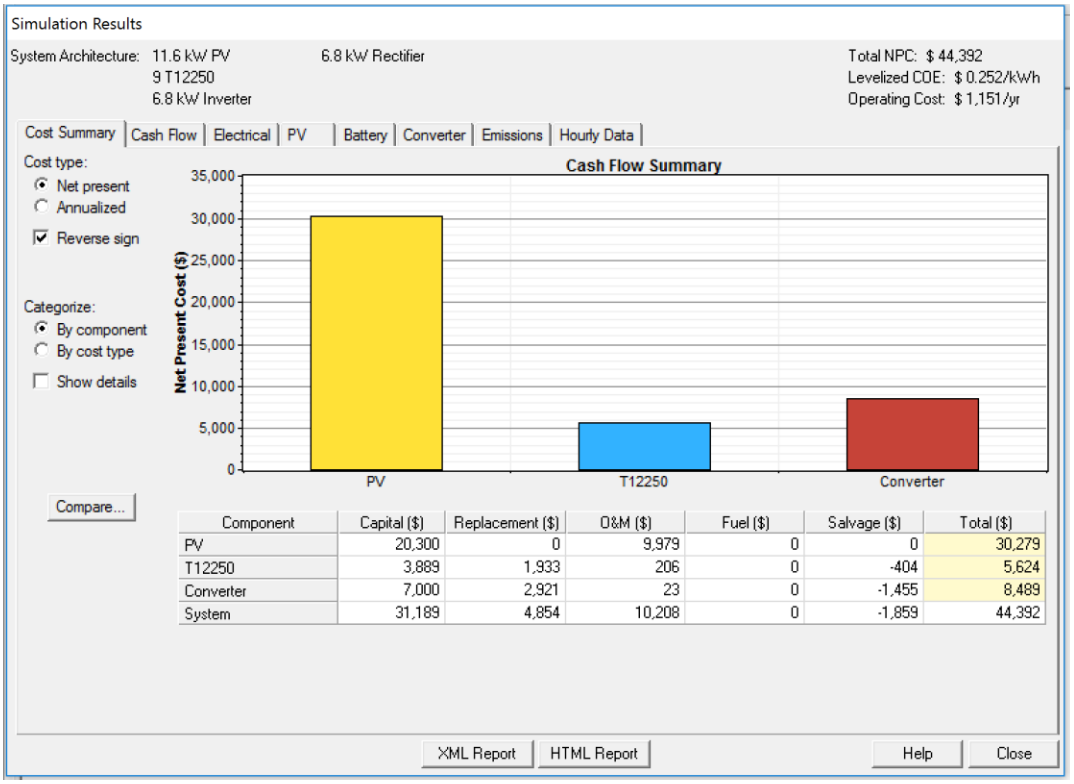


Figure 1: Screenshot for diesel generator optimized system.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	20,300	0	9,979	0	0	30,279
T12250	3,889	1,933	206	0	-404	5,624
Converter	7,000	2,921	23	0	-1,455	8,489
System	31,189	4,854	10,208	0	-1,859	44,392

Figure 2: Screenshot for the PV system cost summary.

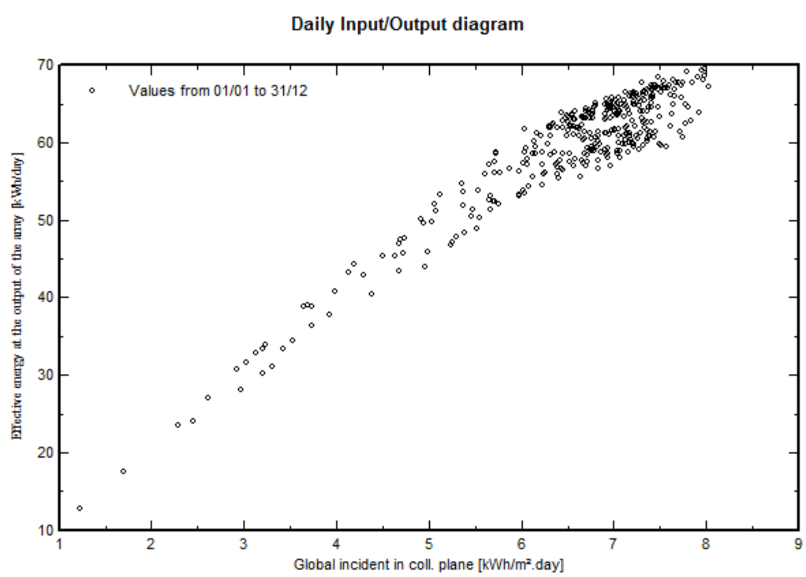


Figure 3: PV production versus input solar irradiation (PVsyst).

Appendix D

Table 1: Irrigation methods and its applicability to solar pumps.

Irrigation method	Typical application efficiency	Typical head	Solar pump applicability
Open Channels	50-60%	0.5-1m	Yes
Sprinkler	70%	10-20m	No
drip	85%	1-2m	Yes
Flood	40-50%	0.5m	No