BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY

A Thesis

On

DESIGN OF AN EFFICIENT PHOTOVOLTAIC PUMP FOR IRRIGATION

By

Md. Mizanur Rahman Sarkar

Roll no. 100506125P

Supervised By

Dr. Shahidul Islam Khan
Professor, Department of Electrical and Electronic Engineering
Bangladesh University of Engineering and Technology, Dhaka

Co-supervised by
Prof. Dr. Quamrul Islam
Professor, Department of Mechanical Engineering
Bangladesh University of Engineering and Technology, Dhaka

This Thesis is submitted to the Department of Electrical and Electronic Engineering in Partial Fulfillment of the requirements for the Degree of Master of Science (M. Sc.) in Electrical and Electronic Engineering

March 2011

ACKNOWLEDGEMENTS

I would like to take this opportunity to thank my thesis supervisor Prof. Dr. Shahidul Islam Khan for his valuable guidance and support throughout my postgraduate program. I would also like to thank my thesis co-supervisor Dr. Md. Quamrul Islam, Professor, Department of Mechanical Engineering, BUET, Dhaka who permitted me to use his Solar Panels and Water Pumps for this thesis. I am grateful to Dr. Mohammad Ali Choudhury, Professor, Department of Electrical and Electronic Engineering, BUET, Dhaka for his suggestions and valuable time to complete this thesis work. I would also convey my thanks to the academic and administrative staffs in the Department of Electrical and Electronic Engineering and Department of Mechanical Engineering. Besides I would like to pay my special thanks for the laboratory assistants in the Power Electronics, Fluid Machinery and High Voltage Laboratory. I express my warm wishes for the people in Center for Energy Studies (CES), BUET who helped me with their instruments to make this work easy.

Finally, I would like to thank my family and friends for their support throughout my postgraduate school experience.

The thesis titled “Design of an efficient photovoltaic pump for irrigation” submitted by Md. Mizanur Rahman Sarkar, Roll no. 100506125P of session October 2005 has been accepted as satisfactory in partial fulfillment of the requirement for the degree of M. Sc. in Electrical and Electronic Engineering.

BOARD OF EXAMINERS

1.

-- Chairman

Dr. Shahidul Islam Khan (Supervisor)

Professor, Department of Electrical and

Electronic Engineering, BUET, Dhaka.

2.

--- Member

Dr. Md. Quamrul Islam (Co-Supervisor)

Professor, Department of Mechanical

Engineering, BUET, Dhaka.

3.

--- Member

Dr. Md. Saifur Rahman (Ex- Officio)

Professor and Head of the Department of Electrical and

Electronic Engineering, BUET, Dhaka.

4.

--- Member

Dr. Mohammad Ali Choudhury

Professor, Department of Electrical and

Electronic Engineering, BUET, Dhaka.

5.

--- Member

Dr. Md. Ashraful Hoque (External)

Professor, Department of Electrical and

Electronic Engineering, Islamic University of technology

(IUT), Gazipur, Dhaka.

DECLARATION

This thesis work has been done by the author under the supervision of Dr. Shahidul Islam Khan, Professor, Department of Electrical and Electronic Engineering and under the co-supervision of Dr. Quamrul Islam, Professor, Department of Mechanical Engineering, Bangladesh University of Engineering and Technology (BUET), Dhaka and has not been submitted elsewhere for any Degree or Diploma.

Signature of the Author

....

(Md. Mizanur Rahman Sarkar)

ABSTRACT

Bangladesh is a country where energy crisis seems to be the major problem. This country is blessed with abundant solar irradiation (~4.5KWh/m^2-day). The country has very limited success to harness solar energy to provide electricity for remote people in rural areas. As a promising renewable alternative to conventional water pumping system for large, medium, and small applications, solar water pumping system has a potential to contribute significantly. Solar photovoltaic pumping is a means to mitigate energy crisis for irrigation in Bangladesh. This thesis deals with the design and performance analysis of a DC photovoltaic water pumping system. It provides theoretical and practical studies of Solar Photovoltaic and modeling techniques using equivalent electric circuits. A DC solar water pump is built and experimented to observe the results with a direct connection from solar array. Various methodologies to increase the efficiency of the system have been discussed to implement in the system. A DC-DC buck converter is designed and constructed to provide current boosting to the DC pump for having a better performance from the system. Battery and inverter is avoided in the system which allows a lower cost. All components in the system are procured locally except the solar panels. DC water pumping system has a good prospect to solve the energy crisis in the irrigation season as well as it can be used to cultivate lands throughout the year. Also solar water pumping may enhance pure drinking water availability in remote areas of Bangladesh.

TABLE OF CONTENTS

Page Number

Page Number

PAGE NUMBER

LIST OF TABLES Page Number

LIST OF FIGURES Page Number

Page Number

Chapter 1

INTRODUCTION

1.1 Introduction

Energy crisis is an important issue in today's world. Availability of Power supply is an important factor for a country's socio-economic development. Bangladesh is a third-world country where only 47 percent of the entire population has access to power supply and the per capita power consumption is only 220 kWh [1]. From Table 1.1, it is seen that compared to per capita electricity consumption of BRICS countries (Brazil, Russia, India, China, and South Africa) and SAARC (South Asian Association for Regional Cooperation countries such as Pakistan, Srilanka) the per capita consumption of Bangladesh is very low.

Table 1.1: Per Capita Electricity Consumption of Bangladesh in 2009 (KWh) [1]

Bangladesh	220
Brazil	2023.76
India	443.54
Nepal	79.68
Pakistan	388.10
Srilanka	388.09
Vietnam	552.85
Indonesia	504.43
China	2443.57

In Bangladesh most of the power plants run by conventional energy resources like natural gas, coal and other fuels. These Conventional energy resources are not only limited but also the prime cause for environmental pollution. The consumption of fossil fuels has an environmental impact, in particular the release of carbon dioxide (CO_2) into the atmosphere. CO_2 emissions can be greatly reduced through the use of renewable energy technologies.

Use of Renewable energy gained popularity among the people in Bangladesh from the late 1990s. Solar, Wind, Biomass and Hydro energy are some of the Renewable

Energy resources used in the country. Among all these, solar energy is a promising one for Bangladesh due to its location. Bangladesh is situated between 20.30 -26.38 degrees north latitude and 88.04- 92.44 degrees east with abundant solar radiation in a clear day. Solar energy is rapidly gaining the focus as the location of Bangladesh is ideal to harness the Sun's energy. The daily average solar radiation in Bangladesh is 4 to 6.5KWh/m^2 which is better compared to many European nations working on solar energy in a large scale [2]. Solar panel is the basic part of Solar Energy system, which is mainly made from semiconductor materials to generate electricity from the radiation of Sun. The major component of solar panels is Silicon, which has maximum 24.5% efficiency [3].

Energy, water and agriculture together form a formidable synergy, which when appropriately utilized and managed, can drive a nation way forward. Despite having fertile soil for agriculture, Bangladesh's food and agricultural production is low due to the gaps between demand and supply of energy. Especially for diesel fuel and electric power, irrigation suffers drastically in the rural areas. Applying solar photovoltaic panels for irrigation can change the energy scenario of the country. Integration with the conventional electric pumps can be made to convert those pumps into solar water pumps.

In this thesis, a simple but efficient photovoltaic water pumping system is presented. It provides the operation of a DC solar water pump in direct-coupled method and pump-controller connected method. The solar water pumping system is built in the Laboratory of Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh. A pump-controller in Buck topology is designed and implemented to increase the overall efficiency of pumping system.

1.2 Conventional Water Pumping Systems in Bangladesh:

Agricultural productivity holds the key to any country's overall economic growth. Bangladesh has fertile agricultural land, abundant water in wet season but limited water in dry season (January to May). Due to limitation of water in dry season, irrigation plays the vital role to expand cultivable area and improve agricultural production in Bangladesh. Water is pumped from ground and surface water level for irrigation in Bangladesh. LLPs (Low Lift Pumps) are used to lift water from surface water level and STWs (Shallow Tube-wells), DTWs (Deep Tube-wells), HTWs (Hand Tube-wells) are used to lift water from ground water level. LLP, STW and DTW are operated by electrical or mechanical power. Electricity and diesel are the sources of electrical and mechanical power respectively [4].

1.2.1 Low Lift Pumps (LLPs)

Approximately 0.15 million LLPs were in operation in the year 2008-09 Boro season to irrigate 1 million hectare of land in Bangladesh. 7% of the LLPs were electric and remaining 93% were diesel pumps. Fig 1.1 shows the distribution of power source uses for LLPs in 2008-09 Boro seasons [4].

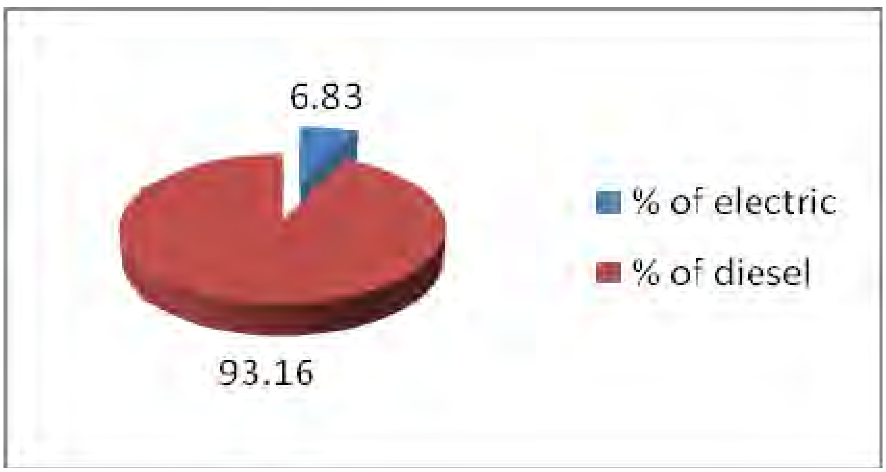


Figure1.1: Power source wise LLPs used in Bangladesh in 2008-09

1.2.2 Shallow Tube-Wells (STW)

Approximately 1.4 million STWs were in operation in the year 2008-09 in the Boro season to irrigate 3.5 million hectare of lands in Bangladesh. 15% of the STWs were run by electricity and remaining 85% were run by diesel. Fig 1.2 shows the distribution of STW power sources in 2008-09 in the Boro season [4].

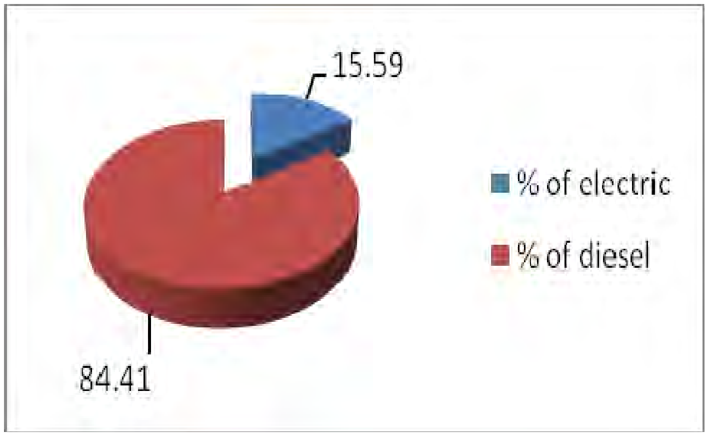


Figure 1.2: Power source wise STW used in Bangladesh in 2008-09

1.2.3 Deep Tube-Wells (DTWs)

Approximately 32000 DTWs were in operation in the year 2008-09 in the Boro season to irrigate 0.8 million hectare of lands in Bangladesh in which ~10% of the DTWs were run by diesel and remaining 90% were run by electric supply. Fig 1.3 shows DTW distribution of power source in 2008-09 Boro seasons [4].

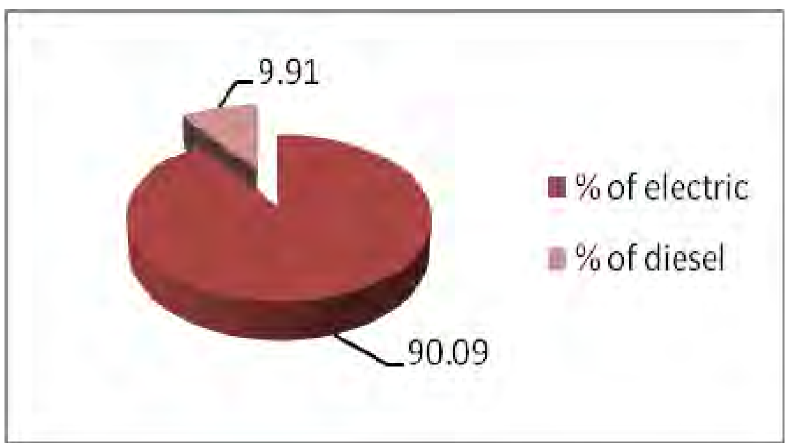


Figure1.3: Power source wise DTWs used in Bangladesh in 2008-09

1.3 Scope of the Thesis

The use of renewable energy has risen considerably in the recent times in developed and developing countries. In Asia, India and China have achieved considerable success in innovating and using the technology of renewable energy. Although the initial installation cost of renewable energy is higher now, in near future it will gradually decline and will come down within the purchasing capacity of the people.

The long-term economics will make PV pumps suitable over other watering options, except where gravity feed is available. One study completed by the Bureau of Land Management (USA) compared solar water pumping systems to generator systems. For one 3.8 gpm system with a 275 foot design head, the PV system cost only 64% as much over 20 years as the generator system did over only 10 years. This remote solar site also used only 14% as many labor hours. Inexpensive diesel or gas generators have low initial costs but require consistent maintenance and have a design life of approximately 1500 hours. Small to medium sized solar pumping systems often cost less initially than a durable slow speed engine driven generator.

As in other Renewable Energy systems, initial installation cost is the main disadvantage of Solar Water Pumping system. History of solar water pumping technology dates back to four hundred years (when Solomon de Caux of France raised water from a mountain by the expansion of solar-heated air). Presently, approximately 50,000 solar pumps are in operation worldwide [5].

Bangladesh already achieved limited success to harness solar energy to provide electricity especially to remote area people in rural areas. Now it is time to introduce solar energy into irrigation system which demands major electricity supply during the BORO season. Bangladesh has 1.55 millions units of mechanized (diesel and electric) irrigation pumps [4]. Among these pumps, 16.30% of pumps are electric and 83.70% of pumps are diesel pump [4].

1.3 million Diesel pumps consume 10 billion litres of high speed diesel fuel annually. Government has to give subsidy on diesel price every year, which is around BDT 55 billion yearly [6]. Diesel has to be imported from that makes the diesel price and its availability highly vulnerable. 0.25 Million electric pumps require 1100 megawatts of electric supply daily during the irrigation season. Power companies have to load-shed in a large scale during irrigation season to provide continuous electricity to the farmers. Natural gas reserve of our country is decreasing every year and it hinders the electricity generation.

This thesis presents a means to mitigate energy crisis through solar water pumping system. A solar water pumping system has been designed and built to comprehend the irrigation with solar photovoltaic panels and locally available electric pumps. All components in the system design have been procured locally except solar panels. A DC-DC Buck converter is built to integrate with the solar water pumping system to operate it efficiently. Automatic solar tracking system has also been designed and constructed to apply in the water pumping system in future.

Chapter 2

SOLAR ENERGY

2.1 Introduction

The history of PV dates back to 1839 when a French physicist, Edmund Becquerel, discovered the first photovoltaic effect when he illuminated a metal electrode in an electrolytic solution. Thirty-seven years later British physicist, William Adams, with his student, Richard Day, discovered a photovoltaic material, selenium, and made solid cells with 1~2% efficiency [7]. In 1954 the first generation of semiconductor silicon-based PV cells was fabricated with efficiency of 6%. Then these were used in space applications. Presently the production of PV cells is following an exponential growth curve since technological advancement of late ‘80s. The development has started improvement of efficiency and reduces cost. Today’s PV cells convert only about 10 to 20 percent of the radiant energy into electrical energy. Fossil fuel plants, on the other hand, convert 30 to 40 percent of their fuel’s chemical energy into electrical energy. Research to increase the efficiency will continue to achieve a good conversion rate compared with the conventional energy resources.

2.2 Basics of Solar Energy

The most abundant and convenient source of renewable energy is solar energy, which can be harnessed by photovoltaic cells. Photovoltaic cells are the basis of a solar system. The word photovoltaic comes from “photo” means light and “voltaic” means producing electricity. Therefore, the photovoltaic process is “producing electricity directly from sunlight”. The output power of a photovoltaic cell depends on the amount of light projected on the cell. Time of the day, season, panel position and orientation are the factors behind the output power. Photovoltaic cells are also called PV cells or solar cells. Solar-powered calculators, toys, and telephone call boxes use solar cells to convert light into electricity.

Photons of light with energy higher than the band-gap energy of PV material can make electrons in the material break free from atoms that hold them and create holeelectron pairs, as shown in Figure 2.1 [7]. These electrons fall back into holes causing charge carriers to disappear. If a nearby electric field is provided, those in the conduction band can be continuously swept away from holes toward a metallic contact where they emerge as electric current. The electric field within the semiconductor itself at the junction between two regions of crystals of different type, called a *p*-*n* junction.

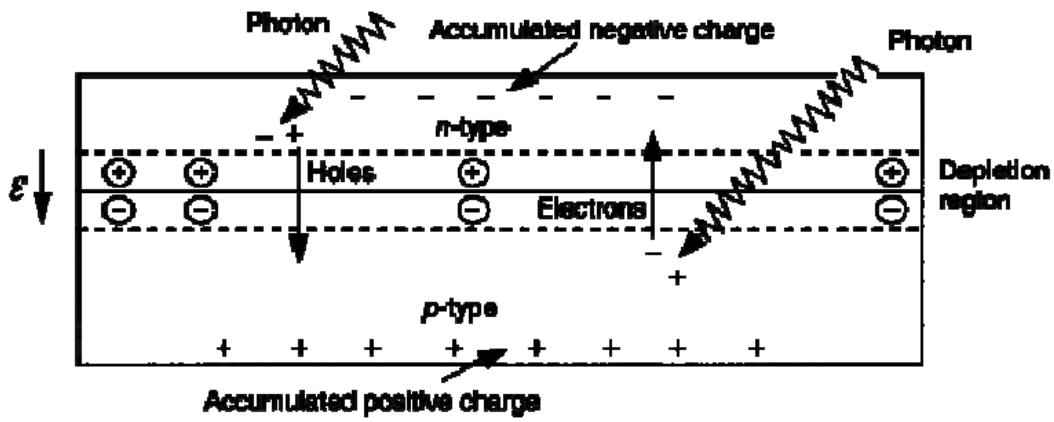


Figure 2.1: Typical Solar cell consisting of a p-n junction [7]

The PV cell has electrical contacts on its top and bottom to capture the electrons, as shown in Figure 2.2 [7]. When the PV cell delivers power to the load, the electrons flow out of the *n-side* into the connecting wire, through the load, and back to the *p-side* where they recombine with holes. Conventional current flows are in the opposite direction from electrons.

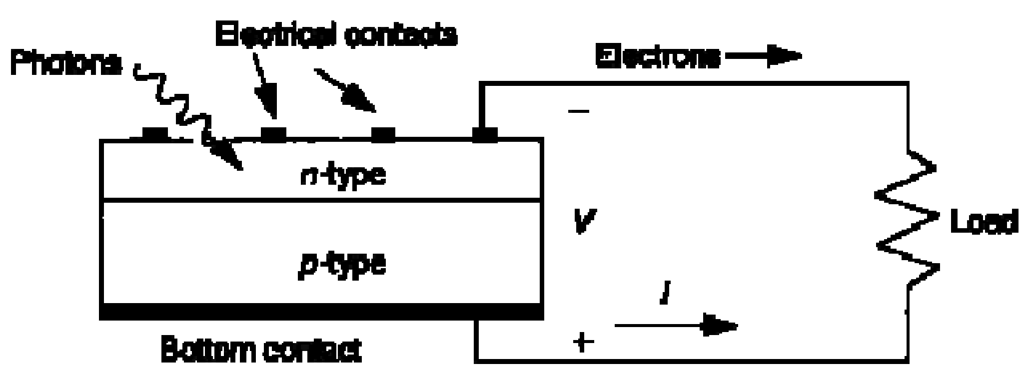


Figure 2.2: Conversion of Light energy to Electrical Energy [7]

The electrical equivalent circuit of a solar cell is shown in Fig. 2.3 [7]. It has a current source I_{ph}, a diode and two resistors (R_s and R_{sh}). Upon incidence of light on the solar cell, current I_{ph} is generated and part of the current can be delivered to load.

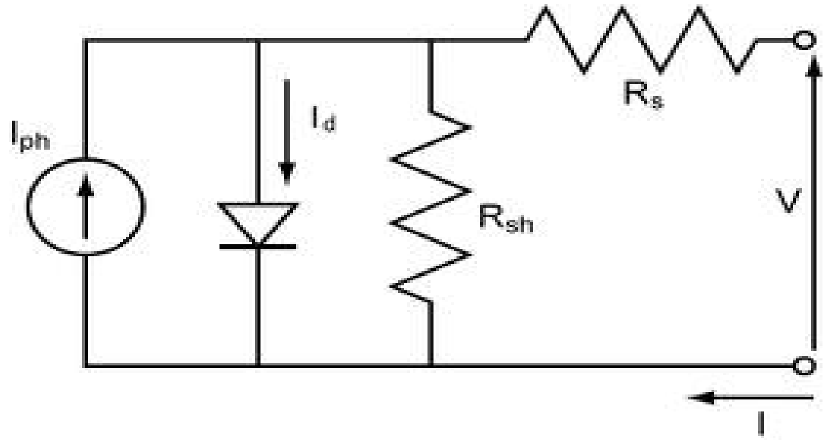


Figure 2.3: Electrical equivalent circuit of a Solar Cell [7]

The Current of the solar cell is given by the following equation:

$$I = Iph - Io\{\exp[\, q(V + IRs)/nKT\,] - 1\} - (V + IRs)/Rsh$$

Where,

I = output current (amperes)

I_{ph} = photo-generated current (amperes)

I_d = diode current (amperes)

V = voltage across the output terminals (volts)

R_S = series resistance (Ω)

I_0 = reverse saturation current of diode (amperes)

n = diode ideality factor (1 for ideal diode)

q = elementary charge

k = Boltzmann's constant

T = absolute temperature

R_{sh}= shunt resistance (Ω)

The current-voltage and power-voltage characteristics of a photovoltaic cell are shown in Fig. 2.4 [7].

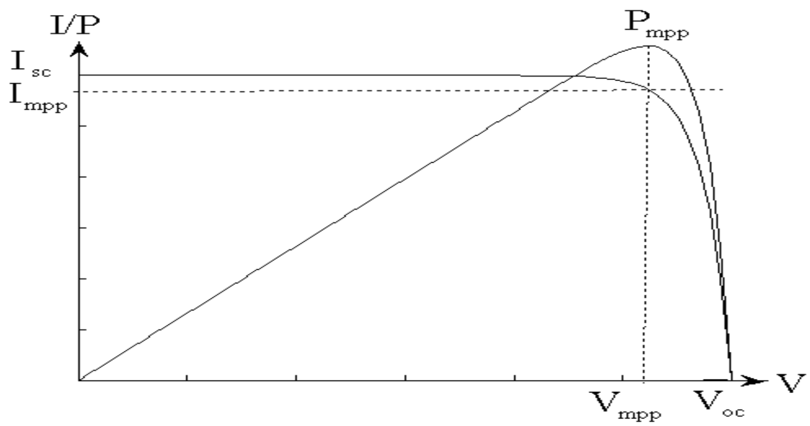


Figure 2.4: I-V and P-V characteristics curve of a Solar Cell [7]

2.3 Present Applications of Solar Energy in Bangladesh

In the last decade, solar PV as an alternative source of energy has gained popularity and has been used to generate energy in different forms. Grid connected solar PV and Solar Home System (SHS) are the two most popular models used throughout the world. In remote areas of the developing world, SHS has become very popular as the over all system is relatively simple, easy to handle and reliable. During the last 5 years, Bangladesh has seen a significant growth in SHS. Bangladesh Infrastructure Development Company Limited (IDCOL) has established 454,000 SHS installation up to January 2010 [2]. IDCOL has a revised target of 1million SHS within the year 2012. IDCOL has also financed other solar programs in Bangladesh [6].

2.4 Future Applications

2.4.1 Solar Power Station

Solar Power Station is mini power station with solar power, battery backup, diesel or natural gas generator as a secondary power generation source. The system consists of high quality photovoltaic (PV) modules, mounting structures to secure modules on the roof, warranties and instructions. These systems are suitable for schools, government offices, hospitals, military check post points and other important installations where the electrical load is light. This type of system can mitigate energy crisis of

Bangladesh by making smaller load systems capable to maintain their own power supply.

2.4.2 Grid Tied Solar System

2.4.2.1 Grid-tie - No battery backup

Most commonly used systems in the industrialized world are grid tied solar systems. These systems produce electricity and sell it to the grid when there is excess electricity. Battery is not required for this system and hence the overall system cost reduces. This system will only operate when the sun light is available. Daytime electricity usage from the grid can be reduced dependency on conventional generators by this system. In Bangladesh this type of system can be integrated in the industrial area where heavy electrical loads are operated during the peak day hour.

2.4.2.2 Grid-tie – With battery backup

Grid-tie with battery backup system is the costliest system among the various types of solar power systems. Specialized grid interactive inverters and other system components are required to be imported for these kinds of system. Integration of net metering with this system can sell excess energy to the Grid.

2.4.3 DC Solar irrigation Pump

Given the energy crisis and rising price of petroleum products, it is important to explore alternative energy sources for irrigation to ensure both food and energy security. It is appropriate time that Bangladesh should concentrate to diversify the applications of solar energy to areas of agriculture. One of the choices is to introduce solar photovoltaic pumping for irrigation. Solar photovoltaic pumping can be introduced in Bangladesh in two ways. Existing pumps can be retrofitted or replaced by solar pumps directly. STW diesel pumps should be replaced by DC solar pumps. The DTW electric pumps should be retrofitted into AC solar pumps at initial stage.

2.4 Summary

Solar cells internal characteristics along with P-V and I-V curves are described in this chapter. Then the prospects of solar energy in Bangladesh have been discussed. Also various types of Solar PV based application are briefed in this chapter.

Chapter 3

SOLAR WATER PUMP

3.1 Introduction

Water pumping is one of the attractive and appropriate usages of solar energy. From crop irrigation to stock watering to domestic uses, water pumps are used extensively throughout the world. Operation of water pumps requires electricity supply or diesel. Solar energy can mitigate electricity demand or diesel requirement to run water pumps by using Solar Water Pumping System.

3.2 Solar Water Pumping

Solar-powered pumping systems meet a broad range of water needs. In principle they may be used virtually anywhere, but the most compelling needs and opportunities are found in the fuel-poor but sun-rich rural areas of the third world country like Bangladesh. Solar pumps may be of any size. Small farms, villages, and animal herds in developing countries require hydraulic output power of less than a kilowatt. Many of these potential users are too far from an electrical grid to economically tap that source of power, and engine-driven pumping tends to be prohibitively expensive as well as unreliable due to the high cost of purchased fuel and insufficient maintenance and repair capabilities. Usually electric water pumps that are plugged into an outlet using alternating current (AC) are generally not built to operate very efficiently because there is no limitation to the amount of power available. A solar-powered pumping system generally costs more initially than a gas, diesel, or propane-powered generator but requires far less maintenance and labor. Comparing installation costs (including labor), fuel costs and maintenance costs over 10 years, it is observed that solar is an alternate choice. These systems have the added advantage of storing water for use when the sun is not shining, eliminating the need for batteries, enhancing simplicity and reducing overall system costs. Solar water pumps are designed to use the direct current (DC) provided by a PV array, although some newer versions use a variable frequency AC motor and a three-phase AC pump controller that enables them to be powered directly by the solar modules. Because PV is expensive and its power production can be variable, solar pumps need to be as efficient as possible i.e. they need to maximize the gallons of water pumped per watt of electricity used.

The key to PV's choice is the low labor and maintenance costs relative to the other options. The long-term economics make PV pumps comparable to most other remote watering options in the rural areas. The lifetime of solar water pump is usually 20 years, which ultimately is lower than the life span period cost compared to the conventional pumps. Bangladesh is a potential place for implementing solar water pumping due to lack of electricity supply in the rural areas needing irrigation. By using photovoltaic pumps, load on the grid system can be reduced and the subsidy on the diesel can be lowered .The advantages of solar water pumping system over the conventional pumping are tabulated in the Table 3.1.

Table 3.1: Comparison between Solar water pump and Conventional Water Pump

Attributes	Solar Water Pump	Conventional water Pump
Grid Electricity Needed?	No	Yes
Maintenance	Low Maintenance and unattended operation. Simple and reliable	Need maintenance and replacement
Fuel	No fuel cost or Spill	Fuel often expensive and supply intermittent
Upfront Cost	Upfront cost higher but last longer	Moderate capital cost
20 years total cost	Lower	Higher

3.3 Types of Solar Water Pumps

Solar Water pumping System can be divided into two basic types.

1. According to the storage system.
2. According to the types of the motor used.

Again, there are two types of solar-powered water pumping systems according to the storage system.

1. Battery-coupled
2. Direct-coupled.

3.3.1 Battery- coupled Solar Water Pump

Battery-coupled water pumping systems consist of photovoltaic (PV) panels, charge control regulator, batteries, pump controller, pressure switch and tank and DC water pump (Figure 3.1 [7]). The electric current produced by PV panels during daylight hours charges the batteries, and the batteries in turn supply power to the pump anytime water is needed. The use of batteries spreads the pumping over a longer period of time by providing a steady operating voltage to the DC motor of the pump [8].

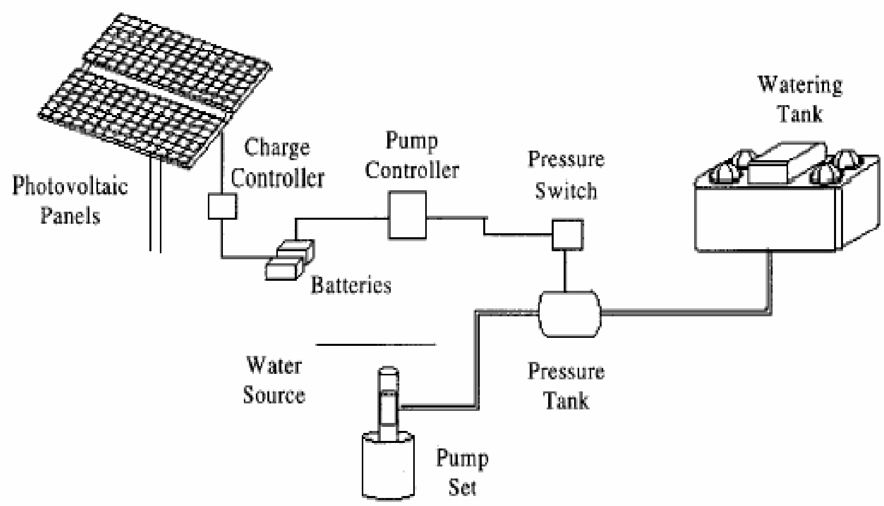


Figure 3.1: Battery coupled solar water pumping system [7]

3.3.2 Direct- coupled Solar Water Pump:

In direct-coupled pumping systems, electricity from the PV modules is sent directly to the pump, which in turn pumps water through a pipe to where it is needed (Figure 3.2 [7]). This system is designed to pump water only during the day time. The amount of water pumped is totally dependent on the amount of sunlight hitting the PV panels and the type of pump. Because the intensity of the sun and the angle at which it strikes the PV panel changes throughout the day, the amount of water pumped by this system also changes throughout the day. Direct-coupled pumping systems are sized to store extra water on sunny days so it is available on cloudy days and for the night. Water can be stored in a larger-than-needed watering tank or in a separate storage tank and then gravity-fed to smaller watering tanks [8].

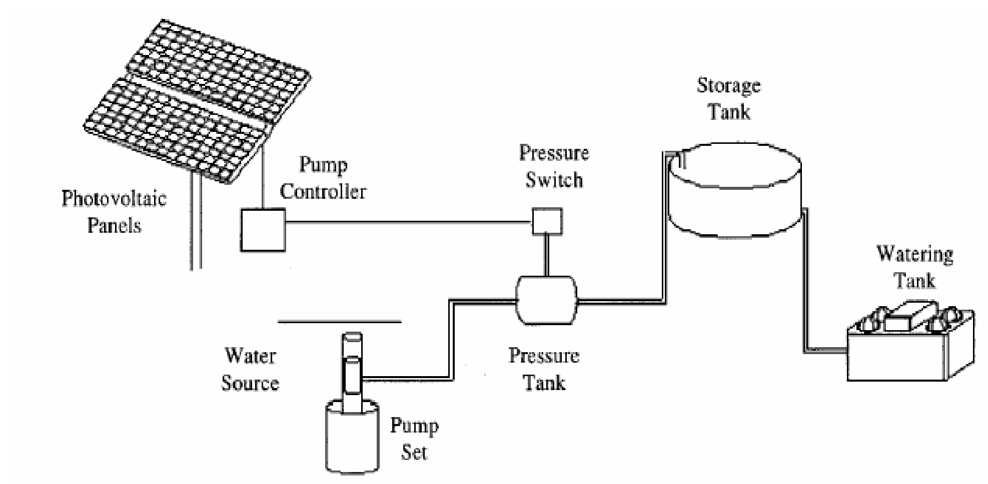


Figure 3.2: Direct coupled solar water pumping system [7]

Solar water pumps can be segmented into two categories according to the motor used.

1. AC Solar Pump
2. DC Solar Pump

3.3.3 AC Solar Pump

AC solar pump is the modification of existing electric pumps by retrofitting some components. Usually, the electric pumps are driven by AC supply but the power output from the solar panel is DC. To use the DC power to run the AC system, an inverter is required additionally. Figure3.3 [8] represents the basic diagram of AC solar pump (ACSP).

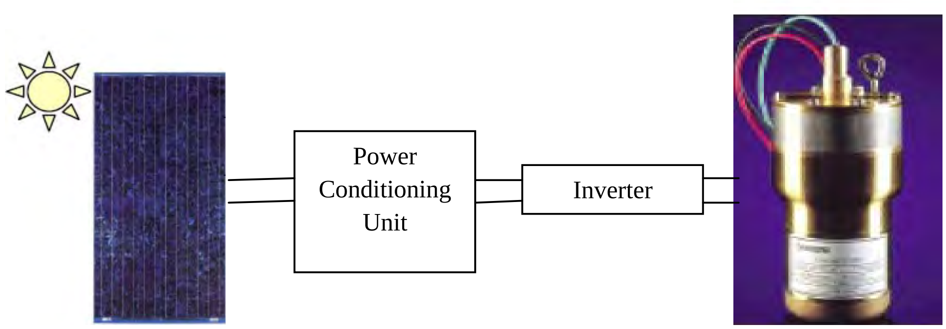


Figure3.3: AC solar water pump [8]

3.3.4 DC Solar Pump

DC solar pump is widely used throughout the world today. DCSP operates in a very simple mechanism. Figure3.4 [8] shows the basic connection diagram of a DCSP.

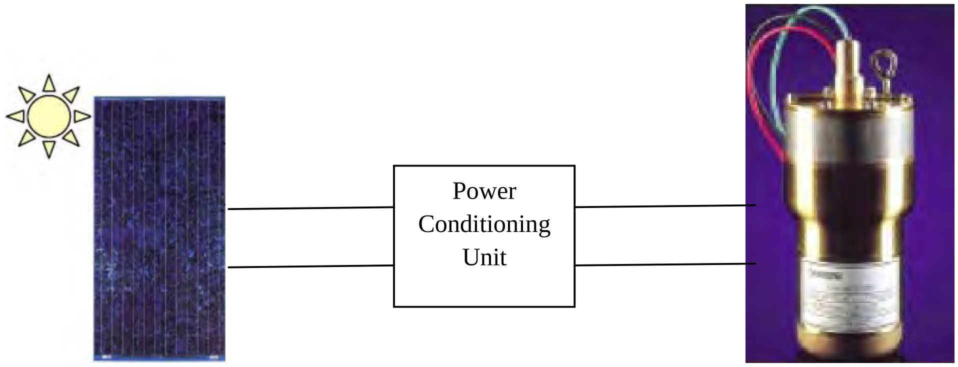


Figure3.4: DC solar water pump [8]

3.4 Summary

Solar photovoltaic pumping can be introduced in Bangladesh in two ways. Existing pumps can be retrofitted or replaced by solar pumps directly. STW diesel pumps should be replaced by DC solar pump where as the DTW electric pumps should be retrofitted into AC solar pumps at initial stage. AC solar pumps require sine wave inverter to convert solar panel's DC supply to AC supply. On the other hand, DC solar pump operates in very simple mechanism. A DC pump is easy to be maintained and operated by non-technical people of the rural areas. Considering the aspects of Bangladesh, a DC direct-coupled solar water pump is designed and then the performance of the designed system is studied to complete the thesis.

Chapter 4

DESIGN AND CONSTRUCTION OF DC SOLAR WATER PUMP SYSTEM

4.1 Introduction

Designing of a photovoltaic water pumping system has two important aspects:

1. Selection of the suitable system components requiring low maintenance, long life system and reliability of operation.

2. Matching of system components responsible for efficient operation of the system [7].

4.2 Construction of a DC solar Pump system

In the proposed photovoltaic water pumping system, the solar panels are directly connected to a DC motor that drives the water pump. For such simplified systems, DC motors and centrifugal pumps are required, because of their ability to be matched to the output of the solar panels. Volumetric pumps, often referred to as (positive) displacement pumps, have completely different torque-speed characteristics and are not well suited to being directly coupled to solar panels.

Similarly, a range of motor types is used for water pumping systems, including DC series motors, DC permanent magnet motors, DC permanent magnet brushless motors, AC asynchronous induction motors and AC synchronous motors. For AC motors, an inverter is to be included between the solar panels and the motor.

A DC motor and a centrifugal pump is used in developing this system. Initially this system is implemented without Power Conditioning Unit (PCU) to observe the performance of the pumping system. Later a Buck converter is designed to supply initial high current to the motor for starting. Components are sized accordingly and then connected directly with the panels to examine the converter design.

4.3 Solar panel

There are different sizes of PV modules commercially available (Appendix A); SIEMENS SP-75WP Solar panels are used in the proposed system [9]. The specifications of the solar panels are provided below:

Rated Current : 4.4 A.

Rated Voltage : 17 V

Short Circuit (SC) Current : 4.8 A

Open Circuit (OC) Voltage : 21.7 V

Temperature Co-efficient (SC) : 2.06mA / ºC

Temperature Co-efficient (OC) : .0777V / ºC

Twelve (12) 75wp solar panels have been used to provide DC power supply for the water pumping system. The ambient condition to have the highest output power from this type of solar panel is 25˚C and 1000watt/m^2. Such 12 solar panels supply 900Wp power during the ambient condition. Unfortunately the ambient condition is not always found in the environment. The highest irradiance level was found 400watt/m^2 during a typical winter day when the test results were taken. It was found that average 400 to 450 watts of power from these 12 solar panels at an irradiance level of 400 watt/m^2.

4.3.1 Solar Array

Available solar panels have been connected in three arrays. The first and second array, 5 panels are put together and at the top array other 2 panels are kept. All twelve panels are connected in parallel to provide power supply to the pumping system.

Figure 4.1 Solar Array consisting twelve solar panels

4.3.2 Solar Panel Sizing and Wiring

Parallel connections from all the panels are brought to a combiner point, named as combiner box. Combiner box is designed with a simple terminology. Two bus bar conductors of current carrying capacity of 100amps are used to construct the combiner box's main frame. Each bus bar has 13 holes to screw 12 input strings from solar panel and 1 output string to provide power at the circuit breaker. The combiner box is attached with the pillar at the roof with the help of ceramic bars. Single string of a solar panel meets at the combiner box with the string of the other panels. Each positive string of the panel enters at the combiner box through a power diode. The forward bias voltage drop of the power diode is 0.6 volt. All the strings are bolted with screw at the combiner box's hole. Total short circuit current that gathers at the bus bars is 57.6 amps and open circuit voltage is 21 volts.

An output string is drawn from the bus bars to the circuit breaker to provide the power supply. The circuit breaker is a single phase breaker where a auto cutoff switch is provided. Turning on the breaker ON, supply solar panel's power into the input of the motor-pump set.

Figure 4.2: Combiner Box connection from Solar Array

4.4 DC motor and pump set

A centrifugal AC pump is selected to be used in the water pumping system. The configuration of the pump is:

Shallow tube well pump, TOYO; Model: TJ-10M;

Power: 0.50 hp; Voltage: 220V; Frequency: 50 Hz;

Suction lift: 5 m; Max^{m} head: 7 m; Single impeller; Made in China.

The centrifugal pump has an AC induction motor connected with the pump. To construct a DC pump set from the AC pump, the AC motor is detached from the pump. Then a Permanent Magnet DC motor (PMDC) is coupled with the pump to make a DC pump set from the conventional AC pump. The specification of the DC motor is:

Power: 0.9 hp; Type: Permanent Magnet;

Operating Voltage : 12 volts; SAWAFUJI

Made in Japan

The features of the constructed DC pumps are:

1. Direct DC power supply from solar panel runs the system.
2. No inverter is required to convert solar panel's DC supply into AC supply.
3. The coupling of the DC motor with the pump is done with an iron ring.
4. The alignment of the system is not perfect and there exists considerable friction losses.
5. The characteristics of the constructed DC pump set do not match perfectly with the given data of the AC pump's specifications.
6. The pumping system can be operated without any operator.
7. There is no maintenance or dependence on Grid electricity for the system.
8. It is useful to operate in the household water supply.
9. Small Scale irrigation can be done throughout the day time when the sun light available.
10. No storage material (e.g. Battery) is required.

Figure 4.3: DC motor and Pump Set

4.5 Direct System of Solar Pump

Power supply from the combiner box passes to the DC pump set through a circuit breaker. At the beginning, this simple mechanism is connected to observe the performance of the system. After observing the performance of the system, power electronics device is integrated into the system to increase the overall efficiency of the system. The block diagram of the direct system is given in the Figure 4.4.

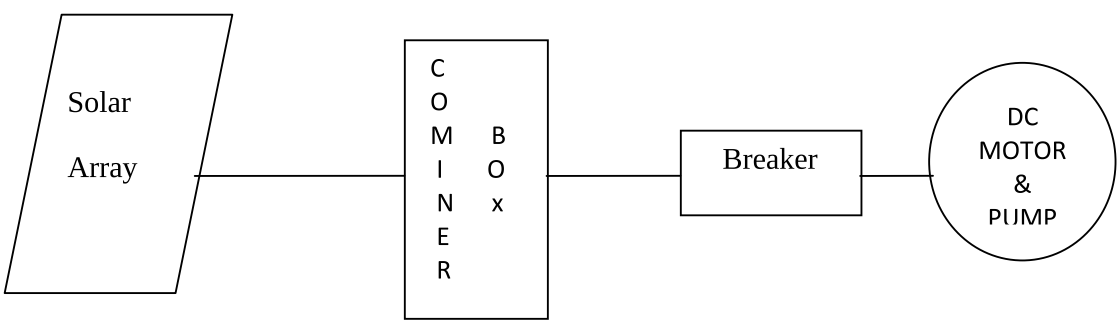


Figure 4.4: Direct Coupled Solar Water Pump

The observed performance with the direct coupled system has been analyzed and the ways of improving the overall system performance are tabulated in the Table 4.1.

Table 4.1: Performance Chart of Direct Coupled Solar Water Pump

Attributes	**Directly Connected Solar Water Pump**	**Ways of Improvement**
System Voltage	4 to 6 volts	Increasing the supply current will build up the system operating voltage
RPM	900-1100 RPM	Increasing armature current will raise the speed of the DC pump system gradually.
Discharge Capacity	35-45 Lit/min	Depends on the RPM of the system.
Armature Current	20-28 amps.	Conversion of input voltage to increase current.

4.6 Efficiency Improvement of DC Solar Pump

The efficiency of the direct coupled solar pump can be increased in various ways. Some of those ways are described briefly in the following section.

4.6.1 Maximum Power Point Tracking (MPPT)

MPPT technology deals with the operating curve of the solar system. Maximum power point tracking (MPPT) is the process to maximize the output power from solar panel by keeping the solar panel's operation on the knee point of *P-V* characteristics (Fig. 4.5 [10]). A number of MPPT algorithms have been developed and employed around the world. MPPT technology only offers the maximum power that can be received from a stationary array of solar panels at a particular time; it cannot, however, increase the power generation when the sun is not aligned with the system [10].

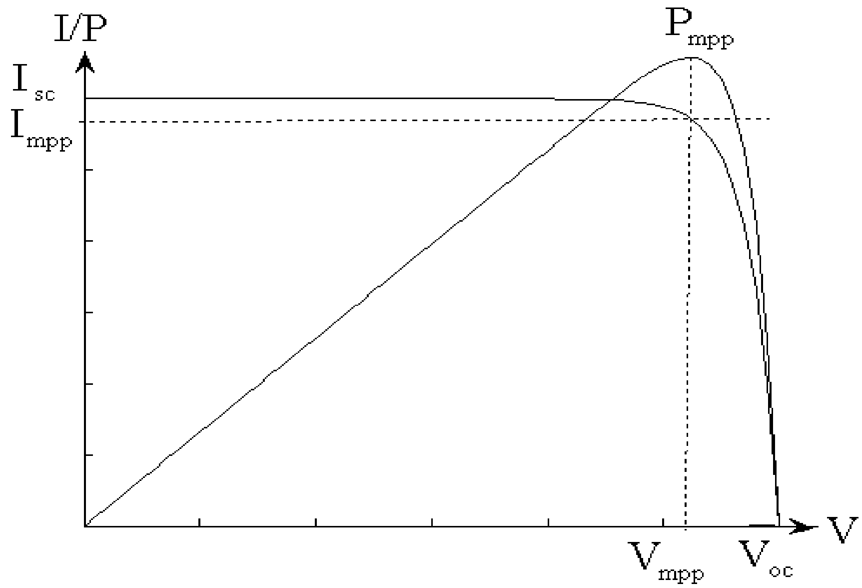


Figure 4.5: MPPT operational Curve for a Solar System [10]

Maximum Power Point tracking technology can improve the overall efficiency of solar water pumping system, by matching the load line of the pump with the characteristic curve at different irradiance level. MPPT technology has not been tried in the proposed system to increase the efficiency.

4.6.2 Battery Coupled System

Battery coupled system can be integrated with water pumping to stabilize the power supply to DC motor. Battery provides constant voltage supply to the load until the deep-discharging point. The system operates at the highest efficiency in the battery coupled system sacrificing some other obstacles. The main disadvantage of a battery coupled system will be the additional cost and the maintenance of battery. The system will be costly as well as the battery needs to be replaced after every 3 to 5 years. Integration of battery in the system will also require some other power electronics equipment to be introduced. Charge controller will be required to protect the battery from over charging and deep discharging. The voltage output from the solar panel also varies with the temperature and to stabilize the voltage charge controller is required too. A typical battery coupled system's configuration is given below.

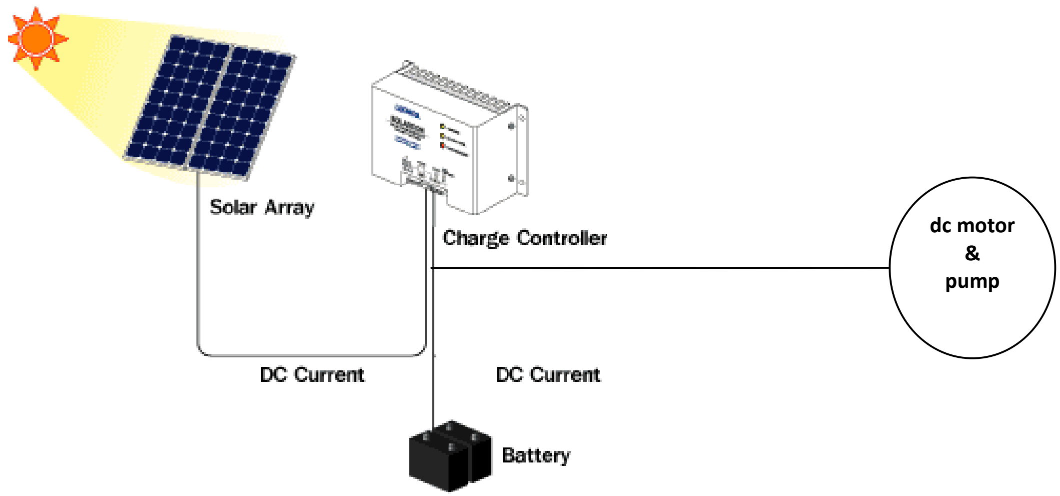


Figure4.6: Battery Coupled System [10]

4.6.3 Thin Film Solar Panel

Thin film amorphous solar panels gained popularity for solar water pumping system recently. Thin film solar panel is effective when low sun hour and variation of sun energy is inevitable. This type of solar panel can generate power from the panel even in the dark light condition that assures to run the pump in bad light too. By increasing the effective operating time of solar panel, the power supply to the motor increases and the overall efficiency improves. The specification of a 50Wp thin film solar panel is given below:-

- Open circuit voltage (V_{oc}) =78.5 volts
- Short circuit current (I_{sc}) =1.16 amp
- Power output from a single panel = 50 watts
- Rated voltage = 60.2 volts
- Rated current = .83 amp

It is observed clearly that the rated current of the thin film solar panel is lower than the mono-crystalline panel that have been used in the proposed system. So when the irradiance level of sunlight decreases, it has less impact on the power generation of thin film solar panel than the crystalline panels. The current of a solar panel solely depends on the irradiance level and voltage level depends on the temperature of the atmosphere. Two 50Wp thin film solar panels' picture is given in the Figure 4.7 [10].

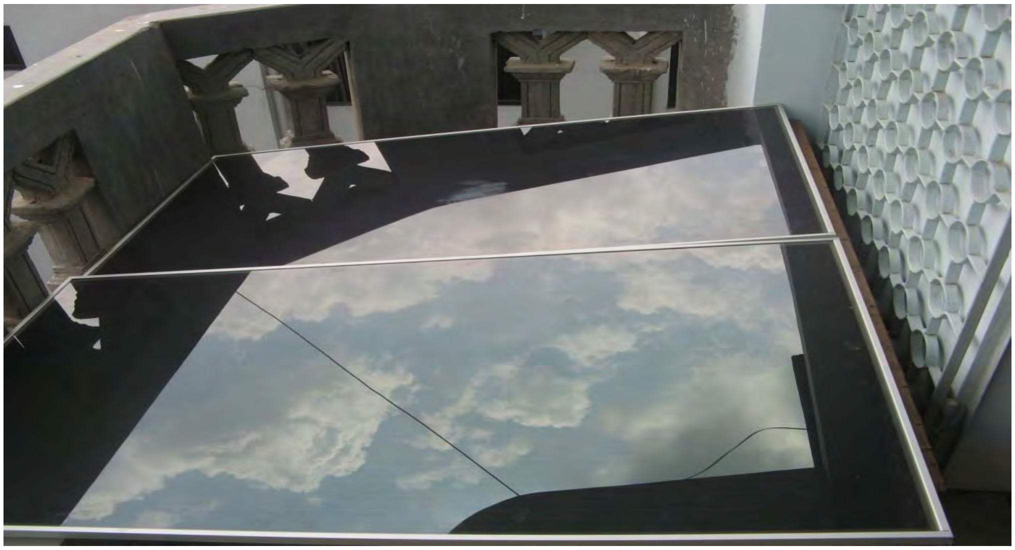


Figure 4.7: Two 50Wp thin film Solar panel [10]

4.6.4 Solar Tracking System

Automatic solar tracker increases the efficiency of the solar panel by keeping the solar panel aligned with the suns position change. Solar tracking is a mechanized system to track the sun's position that increases power output of solar panel by 30% to 60% than the stationary system [11]. Many methodology of solar tracking system have been proposed in recent days. From the literatures it is evident that sensing of sun light, providing initial position of the solar panel and power consumption of the motor for the tracker are the major challenges of the solar tracking system [12]. Solar tracking system can be used in two ways, Dual-axis tracking and Single-Axis Tracking. A small scale solar tracker has been designed and constructed to find out the feasibility of the designing process of the solar tracker [13]. To integrate solar tracking system with the existing fixed mounted solar panels could not be done, but a small scale solar tracker has been built as a part of the thesis.

4.6.5 DC-DC Converter

A DC-to-DC converter is a device that accepts a DC input voltage and produces a DC output voltage. Typically the output produced is at a different voltage level than the input. In addition, DC-to-DC converters are used to provide noise isolation, power bus regulation, etc. Switching DC-DC power supplies are compact, lightweight and more efficient than ordinary linear regulated power supplies. Besides there are SMPS configurations which can step up, step down voltages with precise voltage regulation. DC-DC converters those are operated under high frequency can be classified into four categories [14].

i. Buck Converter
ii. Boost Converter
iii. Buck-Boost Converter
iv. Ĉuk Converter

In this thesis the Buck topology is adopted for current boost (by voltage step down) required for the DC motor. Hence a simplistic analysis of the Buck converter is provided only with next subsection.

4.6.5.1 Buck converter, step-down converter [Fig 4.8 [14]]

In this circuit the transistor turning ON will put voltage V_{in} on one end of the inductor. This voltage will tend to cause the inductor current to rise. When the transistor is OFF, the current will continue flowing through the inductor but now through the diode. We initially assume that the current through the inductor does not reach zero, thus the voltage at Vx will now be only the voltage across the conducting diode during the full OFF time. The average voltage at Vx will depend on the average ON time of the transistor provided the inductor current is continuous.

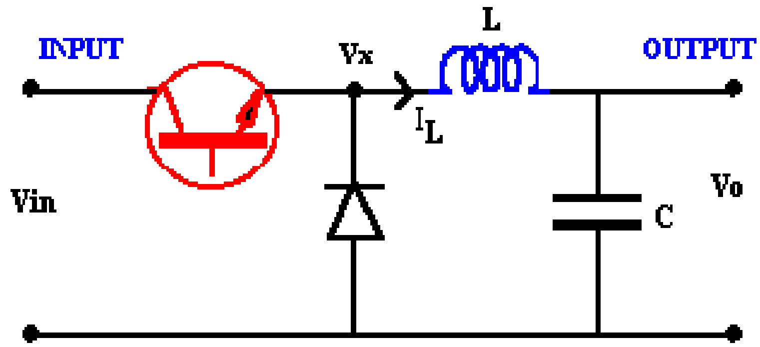


Figure 4.8: Buck Converter [14]

To analyze the voltages of this circuit let us consider the changes in the inductor current over one cycle. From the relation

$$Vx - Vo = L\frac{di}{dt} \tag{4.1}$$

The change of current satisfies

$$di = \int_{ON} (V_X - V_O)dt + \int_{OFF} (V_X - V_O)dt \tag{4.2}$$

For steady state operation the current at the start and end of a period T will not change. To get a simple relation between voltages we assume no voltage drop across transistor or diode while ON and a perfect switch change. Thus during the ON time $V_x=V_{in}$ and in the OFF $V_x=0$. Thus

$$0 = di = \int_0^{T_{ON}} (V_{IN} - V_O)dt + \int_{T_{ON}}^{T_{ON}+T_{OFF}} (-V_O)dt \tag{4.3}$$

This simplifies to,

$$(V_X - V_O)T_{ON} - V_O T_{OFF} = 0 \tag{4.4}$$

$$\frac{V_O}{V_{IN}} = \frac{T_{ON}}{T} \quad (4.5)$$

Defining "duty ratio" as-

$$D = \frac{T_{ON}}{T} \quad (4.6)$$

The voltage relationship becomes $V_o = D*V_{in}$ Since the circuit is assumed lossless and the input and output powers must match on the average $V_o*I_o = V_{in}*I_{in}$. Thus the average input and output current must satisfy $I_{in} = D*I_o$. These relations are based on the assumption that the inductor current does not reach zero.

4.7 Designing device to increase the efficiency of the Solar Water Pumping system

4.7.1 Solar Tracking System

Development of solar panel tracking system has been ongoing for many years. As the sun's position changes across the sky during the day, it is advantageous to have the solar panels track the location of the sun, such that the panels are always perpendicular with the position of the sun. Available solar trackers in the market are costly to integrate with solar panel system [15]. In the developing countries where cost is one of the major issues to integrate technologies and solar tracking prototype presented at this section can provide a solution. The major components are used in the prototype are given below:-

- Photo resistor
- Microcontroller
- Stepper motor

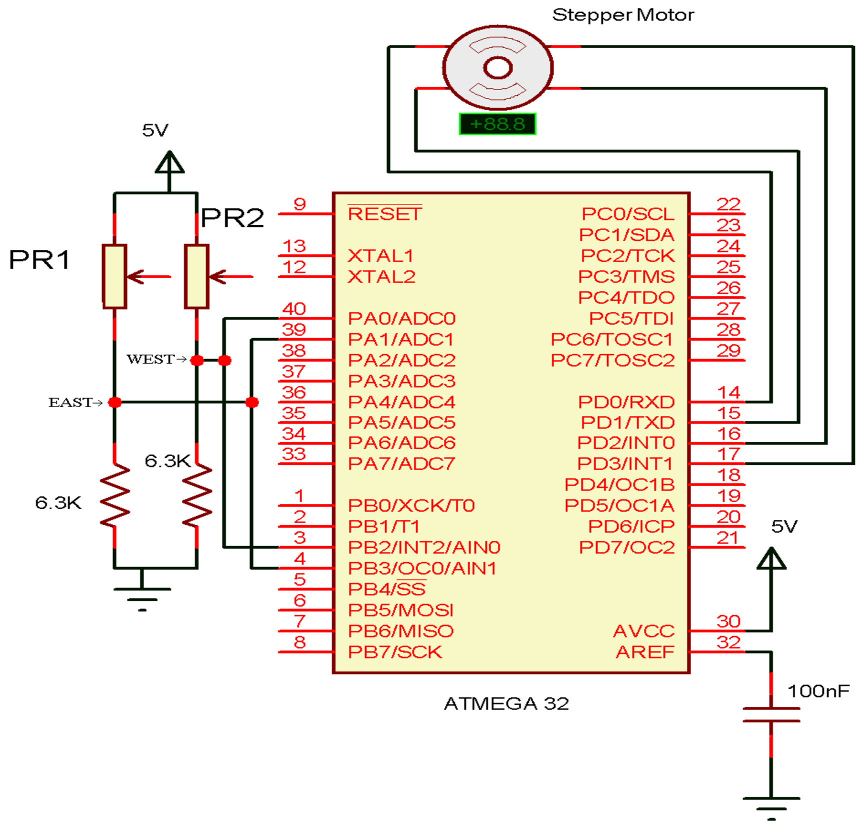


Figure 4.9: Schematic design of Solar Tracker [15]

Cadmium sulphide (CdS) photo resistor is used in the designed prototype. The CdS photo resistor is a passive element that has a resistance inversely proportional to the amount of light incident on it. To utilize the photo resistor, it is placed in series with another resistor. A voltage divider is thus formed at the junction between photo resistor and another resistor; the output is taken at the junction point to pass the measured voltage as input to microcontroller. In the solar tracker prototype, it is desired that output voltage at junction point will increase as the light intensity increases and so the photo resistor is placed at the top position in series connection with resistor.

The ATMEGA32 microcontroller has been used in the prototype [16]. Microcontroller is the heart of overall system. ATMEGA32 microcontroller requires a 5 volt regulated voltage supply. ‘7805’ voltage regulator IC is used to provide fixed 5 volts supply to the microcontroller [17]. ATMEGA32 has features such as analog comparator (AC), analog to digital converter (ADC), universal synchronous asynchronous receiver transmitter (USART), times etc (Appendix B). Utilization procedure of these features is given below in the following section.

4.7.2 Analog comparator

There are two pins which are known as analog input 0 (AIN0) and analog input 1 (AIN1). Two analog voltage signals coming from two junctions of photo resistor circuit are fed to these pins. There is a bit called analog comparator output (*ACO*) which is set to either '1' or '0' and can be defined as:-

$$ACO = \begin{cases} 0 & V_{AIN1} > V_{AIN0} \\ 1 & V_{AIN1} < V_{AIN0} \end{cases} \tag{4.16}$$

4.7.3 Analog to digital converter

Among 8 analog to digital converter input pins ADC0 and ADC1 have been used; where $V_{ADC0} > V_{ADC1}$ is expected. Differential input is converted into digital value and the most 8 significant bits are defined as *ADC_result* to compare with threshold.

$$ADC\_result = [V_{ADC0} - V_{ADC1}]_{\text{digital}} \tag{4.17}$$

This threshold value, set according to the photo resistor response against the solar radiation intensity, is provided, since *ADC_result* alone might be insufficient for rotation of motor.

And if *ADC_result* > *Threshold*; motor rotates one step.

4.7.4 Timers

The built-in timer of ATMEGA32 is utilized to create delay. The Earth rotates on its own axis, with respect to the Sun 360˚ in a day and so it rotates, (360˚/24=) 15˚ an hour or 3.75˚ in 15 minutes. Delay for 1.5 minutes and 15 minutes are required. These delays are mentioned as *short delay* and *moderate delay* respectively.

4.7.5 Algorithm

In the proposed algorithm two variables *I* and *Count* have been used. *I* represent total number of rotation the motor must make to track the sun from dawn to dusk. First hour after the sunrise and last hour before the sunset is not considered for the tracking, as in the first hour after sunrise the west sensor does not have sufficient light than the east one; the tracker remains off. The last hour before sunset will provide additional energy to rotate the panel in the initial position and so the tracker no more rotates to the west rather it will rotate reversely. As 2 hours in day time are not considered for tracking, (2X15˚=) 30˚ of rotation is not required to be done by the solar tracker. Half stepping of stepper motor is considered which gives 3.75˚ rotation in each stepping; approximately ((180˚-30˚)/3.75˚=) 40 rotations are required in each day to track the Sun at daylight. *Count* is used for counting the number of '*wait*' states when weather is cloudy and ADC does not permit to rotate the motor.

A small scale prototype of the solar tracker has been made to check feasibility of the design methodology. At initial stage a small plastic board, considered as the solar panel, is mounted on an aluminium shaft. Figure 4.10 [17] illustrates the dummy panel along with other circuitry of the prototype.

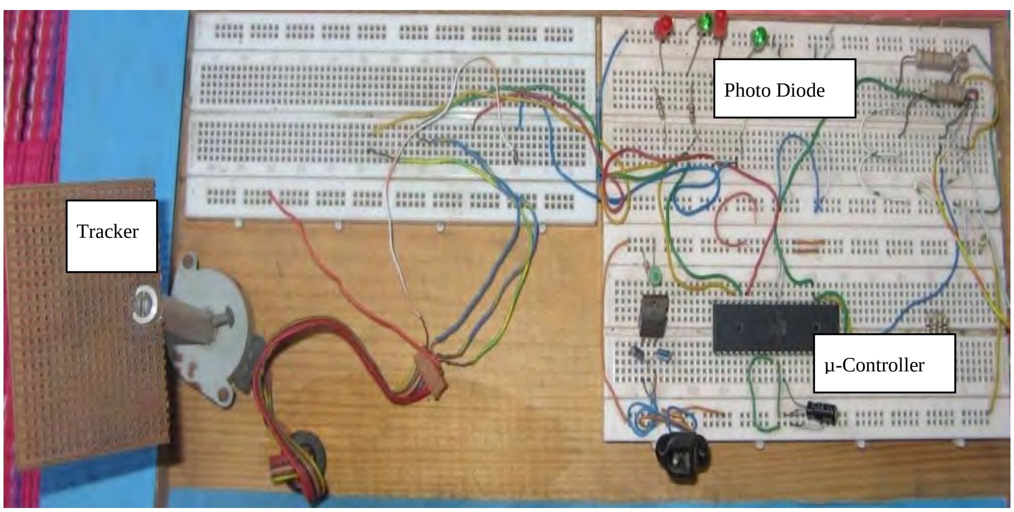


Figure 4.10: Prototype of Solar tracker [17]

4.7.6 Operation of the solar tracker

Solar tracker provides three ways of operation and control mechanism through the programme written in microcontroller (Appendix D).

4.7.6.1 Normal day light condition

Two photo resistors are used in the solar tracker to compare the output voltages from two junctions. As the sun's position changes from east to west in the day time, AIN0 needs to provide higher voltage than AIN1 to sense the rotation of the sun. This condition is considered as normal day light condition and tracker rotates the panel 3.75˚ after every 15 minutes.

4.7.6.2 Bad weather condition

When the sky gets cloudy, there will be less striking of light on both the photo resistors and so sufficient voltages might not be available at junction point. The difference of voltage at junction point will not be greater than the threshold value to rotate the tracker. At the mean time, sun continues change position in the western direction. To solve this problem, a *short delay* is provided which will check for voltage input from junction point in every 1.5 minutes. Microcontroller will use the variable *Count* to check for consecutively 10 times to make the '*wait*' state equal to 15 minutes (*moderate delay*) to rotate the stepper motor one step.

4.7.6.3 Bidirectional rotation

At day time, the solar tracker will rotate in only one direction from east to west. Variable *I* will count the total rotation in day time and that is approximately calculated as 40 rotations considering 150˚ rotation in a single day. When the sun sets, no more rotation is needed in western direction. For the next day, the solar panel needs to go to the initial position in the morning to track the sun's position again. To do so, the variable *I* that counts the number of rotation in the day time will work out.

When the variable (*I*) shows value greater than 40, the tracker stops rotating in the western direction and rotates reversely in the eastern direction to set the tracker to the initial position for the next day. When it goes to initial position, power supply to the tracker will be turned off and the tracker will be in stand by till sunlight in the next morning.

4.8 Designing the buck converter for pump controller [Fig 4.11 [17]]

The most challenging and difficult part of the system are to design & construct the DC-DC Buck converter. Designing process of the converter requires extensive knowledge on Power Electronics. The following steps have been followed to construct the Buck converter.

1. **Calculation of the required inductor**
2. **Calculation of the capacitor**
3. **Selection of the diode**
4. **Selection of the MOSFET**

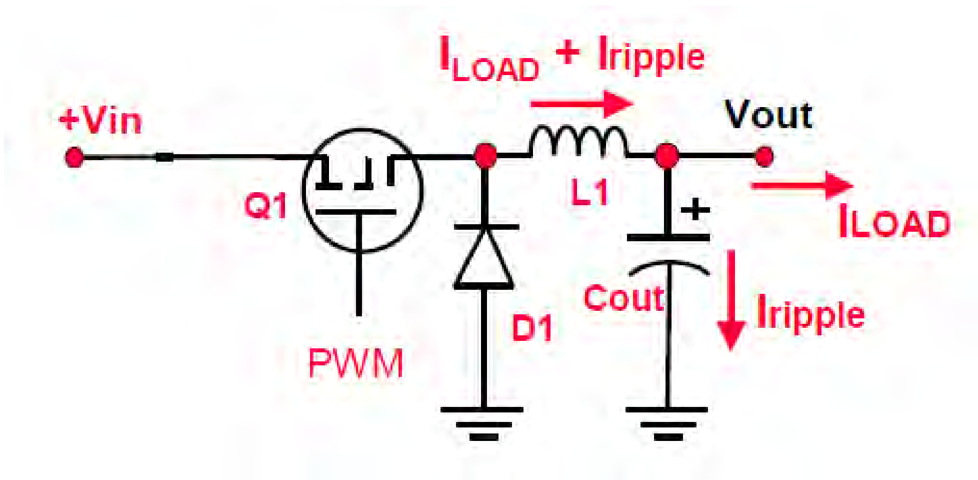


Figure 4.11: Typical BUCK converter [17]

Input and output voltage values as well as the switching frequency needs to be fixed at the very first of the designing process. Assumptions are:

V_{In} = 17 volts

V_{Out} = 12 volts

$F_{switching}$ = 30 KHz

Duty Cycle, D= 12/17= 0.705

Ripple Current, I_{ripple}= 0.117 amps.

4.8.1 Calculation of the required inductor

Starting with the basic equation for current flow through an inductor:

V = L di/dt **(4.18)**

Rearranging the terms to calculate “L” and the equation changes to:

L = V dt/di **(4.19)**

Rearrange and substitute:

L = (Vin – Vout) · (D / Fsw) / Iripple **(4.20)**

Calculation:

:

L = 5 V · (0.705 / 30 KHz) / 0.117A

L = 1.004 mh.

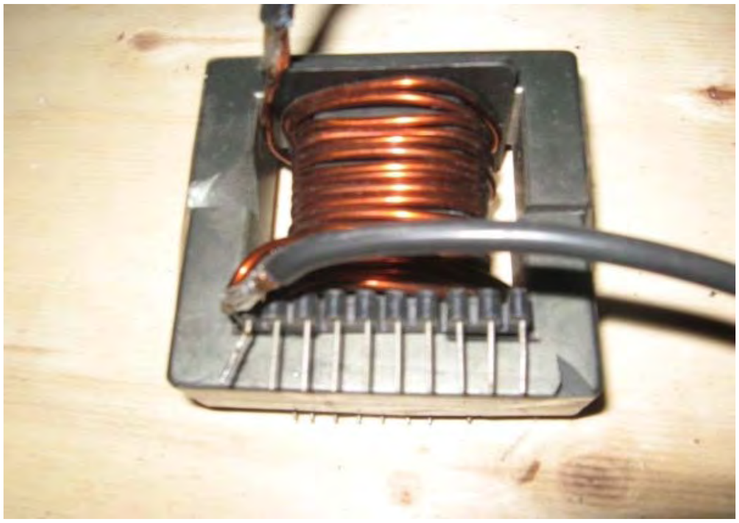


Figure 4.12: Inductor of 1.01mh

4.8.2 Calculation of the capacitor

The peak-to-peak ripple voltage of the capacitor is defined as:

$$dV_c = di / (8 * Fsw * C_{out}) \qquad (4.21)$$

Rearranging the terms to calculate "C_{out}" and the equation changes to:

$$C_{out} = di / (8 * Fsw * dV_c) \qquad (4.22)$$

Assuming dV_c = 2.3 mV, the value of C_{out} is obtained as:

$$C_{out} = .117 / (8 * 30\ KHz * 2.3\ mV)$$

$$C_{out} = 211\ \mu F$$

Figure 4.13: One of the Capacitor Banks

4.8.3 Selection of the diode

Maximum Diode Current needs to be analyzed first:

$$I_d = (1-D) \cdot I_{LOAD}$$

$$I_d = (1.0 - 0.705) \cdot 51.42 = 15.1689\ A$$

Five (5) amps, 12 volts ten (10) diodes are connected in parallel to provide the required I_d for the designed DC-DC converter.

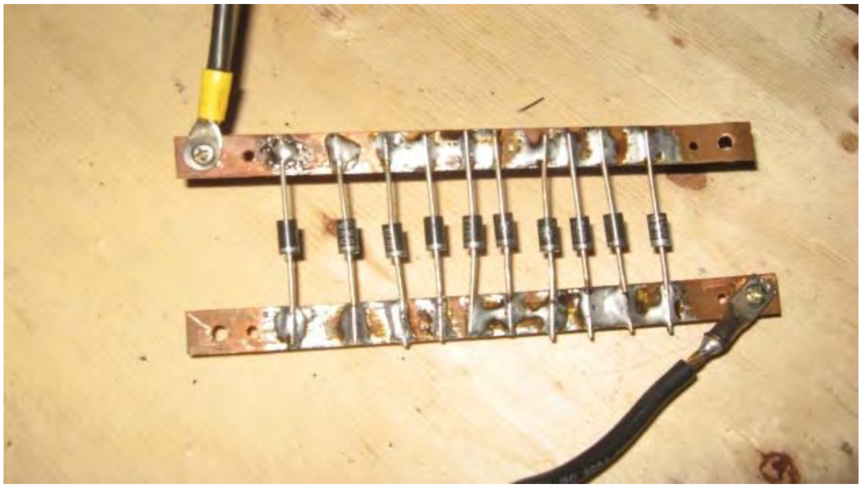


Figure 4.14: Diode Paralleled Bus bars

4.8.4 Selection of the MOSFET

Traditional Power MOSFETs are chosen to provide the Gate pulse from SMPS circuit. 6 power MOSFETs are connected in Parallel to operate under a high current. The MOSFETs are switched synchronously from the pulse of SMPS.

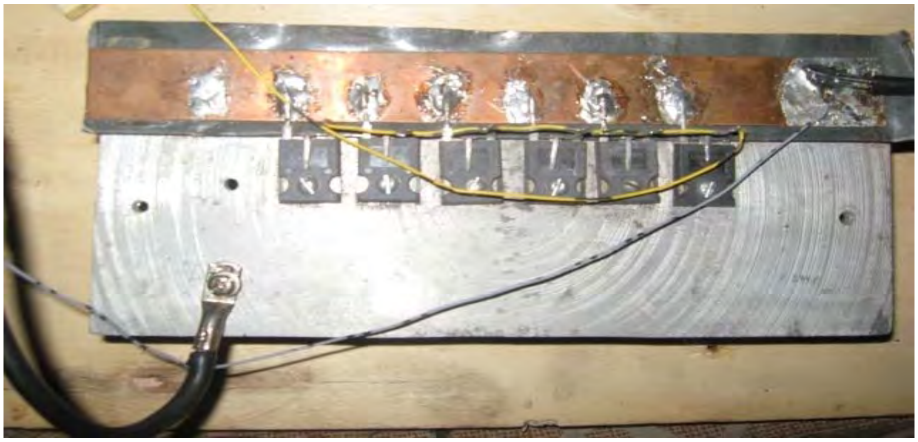


Figure 4.15: MOSFET gate

4.8.5 SMPS circuit

In a Switch Mode Power Supply (SMPS), pulse is provided at the MOSFET gate to turn on/off to control voltage regulation of the DC-DC converter. SG3524 IC is used as to make SMPS. This IC can be used for switching regulators of polarity, transformer-coupled DC-to-DC converters, transformer less voltage doublers and polarity converters, as well as for other power control applications. The system frequency of the SMPS is kept at 30 KHz. High frequency switching is expected in the converter design to make the system audible noise free as well as to provide better sensitivity to the system. The SG3524 is designed for commercial applications of 0°C to +70°C (Appendix C). The test circuit diagram of the SMPS IC is given in the Figure 4.21.

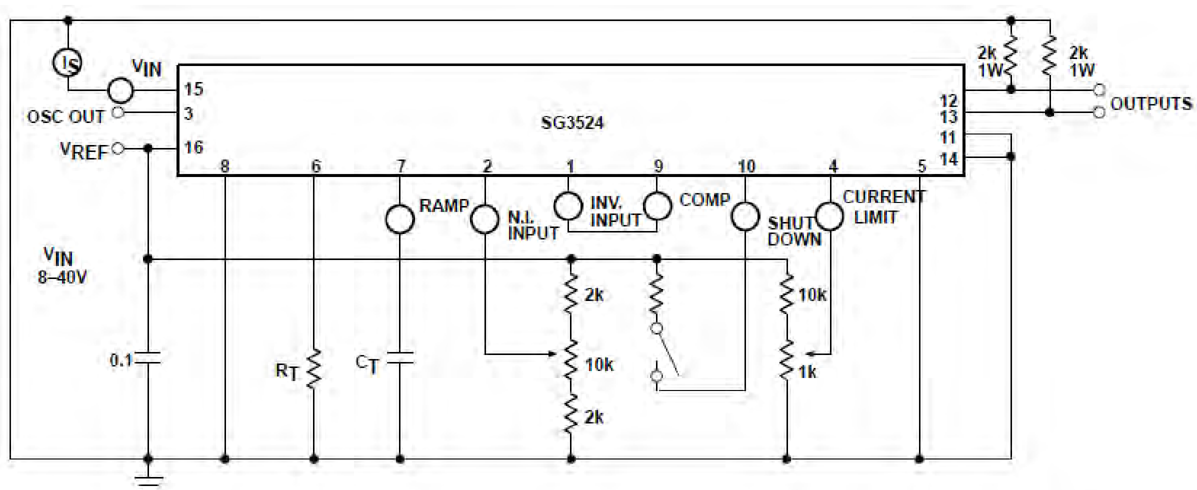


Figure 4.16: SMPS circuit connection

4.9 Solar water PUMP with DC-DC buck converter

Figure 4.17: Solar Water Pump with BUCK converter

Following assessments were made on the Direct coupled Solar water pump before connecting the DC-DC buck converter:

1. The system works well and can lift water from a tank of 10 to 50 feet height when the sun light is sufficient for the system.
2. The DC motor operating voltage is 12 volts but it requires a high current of 40 to 60 amps to work in full speed of 3000 rpm.
3. Due to insufficient light, the system cannot run at full speed throughout the day time. As the BACK emf of the DC motor is related with speed of the motor, it shows a lower value than the actual value expected at the motor input terminal.

After integrating the BUCK converter with the solar pumps, improvements have been observed on the described criteria. The improvements are enlisted below:

1. Converter keeps the DC motor operating voltage at 12 volts but it increases the load current. The increasing load current improves the speed of the system to 1200- 1500 RPM at half load.

2. BACK emf of the DC motor is also improved as the speed of the system increases after the conversion of voltage and current though the BUCK converter.

4.10 Summary

The designing procedure of the solar water pumping system has been discussed in this chapter. Direct coupled system is built initially and then the ways of the improvements have been described briefly. Solar tracking system and DC-DC buck converter have been chosen to improve the performance of the system. Finally, DC-DC buck converter is implemented in the water pumping system to have better results than the direct coupled system.

Chapter 5

DATA COLLECTION AND RESULT

5.1 Introduction

Data Collection from the designed solar water pump system has been done in three steps to observe the variation of output results from the system. The steps are:

1. No Load System
2. Direct Coupled System
3. Solar Water Pump with BUCK converter

5.2 No Load System

The DC pump system that has been used for the process is built from a AC pump by modification. To check the performance of the pump after integration with the DC motor, no load test has been done. In the no load test, the system was supplied from DC power supply in the laboratory without any load on the system. Supplied voltage, current and speed of the system were recorded as shown in Table 5.1.

Table 5.1: Data Collection on No load system

Voltage (Volts)	Current (Amps)	Speed (RPM)
10	11.5	2400
11	12	2560
12	12	2850
13	12.5	3060
13	14	3200

The highest no load speed goes up to 3000-3200 rpm at no load. The result from the no load test reveals that the integration of the DC motor with the centrifugal pump is matched satisfactorily.

5.3 Direct Coupled System

Direct coupled system stands for the direct connection from solar panel to the DC motor-pump. No power electronics conditioning unit have implemented in the system. The performance of the direct coupled solar water pump was not satisfactory. The data has been collected considering all the drawbacks. The observed data is tabulated in the Table 5.2.

Table 5.2: Data Collection on Direct Coupled System

Voltage (Volts)	Current (Amps)	Speed (RPM)	Discharge (Lit/Min)
5	20	880	10
5	22	920	13
6	25	950	14
6	28	1000	22
6.1	30	1020	24

The reasons for not having expected result from the direct coupled system are,

1. DC motor requires a high current to start up; in direct coupled system there was no way to increase the starting current to the DC motor.

2. In absence of initial high current, voltage does not build up in the system which leads to operation of the system at a lower torque.

3. The speed of the system relates directly with the torque of the motor and so the speed in RPM was found quite low.

4. The coupling of DC motor with the pump has not been done perfectly as alignment of the DC motor with the Centrifugal pump mismatched. Due to misalignment, frictional losses existed in the system which eventually decreased the speed.

Under the load the highest speed of the system has been observed as 1020 rpm which indicates poor overall efficiency of the system. To improve the efficiency, further studies have been done to develop solar tracking system and DC-DC buck converter. The prototype of solar tracking system has been built and constructed successfully. Though solar tracker was not incorporated in the system, as it requires power to rotate the panels. The tracker is designed and tested only, but not integrated in the system.

DC-DC converter design and topology have been studied and the BUCK converter has been chosen to be adopted. The basic principle of the BUCK converter is to lower the voltage and raises the current. As high current is required to operate the system at a better efficiency, BUCK converter has been designed and integrated with the direct coupled system to observe the improvement.

5.4 Solar Water Pump with BUCK converter

DC-DC BUCK converter is placed in between the circuit breaker and the supply point of the DC motor. Data has been collected for a day long time at various irradiance level of sun. Irradiance is measured at W/m^2 with the help of Pyrometer. Other than measuring the voltage, current and speed of the system, measurements are also taken for discharge capacity, discharge height, and speed control. The collected data for the system voltage, current and the speed for various irradiance levels are provided in the Table 5.3.

Table 5.3: Data collection with converter connection

Date	Irradiance (W/m^2)	Time (hrs)	Voltage (Volts)	Current (Amps)	Speed (RPM)
25.01.11	250	10.00	5.5	25	1020
	300	11.00	5.8	30	1050
	330	11:45	7	32	1100
	336	12:30	7.15	35	1175
	365	13:00	7.36	42	1245
	313	13:30	7.31	30	1173
	299	14:30	6.87	29	1123
	233	15:00	5.10	22	875
	189	15:30	5.05	20	860
26.01.11	290	10.00	5.8	26	1040
	300	11.00	5.8	30	1050
	320	11:45	6.8	30	1080
	360	12:30	7.35	37	1200
	375	13:00	7.5	43	1265
	300	13:30	7.00	28	1154
	285	14:30	6.70	28	1130
	220	15:00	5.50	24	905
	200	15:30	5.25	20	820
29.01.11	245	10.00	6.25	25	990
	320	11.00	6.8	30	1070
	330	11:45	7.1	33	1120
	356	12:30	7.33	35	1155
	360	13:00	7.4	41	1255
	305	13:30	6.92	30	1103
	300	14:30	6.67	29	1083
	260	15:00	5.10	22	915
	180	15:30	5.05	20	840
30.01.11	230	10.00	5.3	25	1050
	330	11.00	6.9	31	1110
	350	11:45	7.3	39	1156
	380	12:30	7.8	44	1290
	375	13:00	7.66	40	1245
	323	13:30	7.11	33	1167
	299	14:30	6.77	30	1121
	256	15:00	6.00	26	1000
	215	15:30	5.70	23	975

Data has also been collected by controlling the speed of the pump. The collected data provides various values of discharge capacity for different speed. The suction head (also called datum head) of the pump is taken as 18 inch. The collected data of Irradiance, discharge time, discharge water, discharge capacity, pump speed and discharge pressure at various speeds is tabulated in the Table 5.4.

Table 5.4: Speed Control Data with Converter Connection

Date	Irradiance (W/m^2)	Discharge Time (Sec)	Discharge water (Liter)	Discharge Pressure (Psi)	Speed (RPM)	Discharge Capacity (Lit/min)
25.01.11	365	10	9.7	4	1240	58.2
	356	45.3	8.3	6	1274	10.99
	345	67.4	7.9	7	1225	7.03
26.01.11	375	9	9.7	4	1260	64.66
	360	43.3	8.3	6	1285	11.5
	340	67.4	7.9	7	1235	7.04
29.01.11	360	10.5	9.7	4	1230	55.42
	346	46.7	8.3	6	1263	10.66
	335	69.2	7.9	7	1198	6.84
30.01.11	380	8.9	9.7	4	1268	65.39
	375	40.3	8.3	6	1288	12.35
	350	64.4	7.9	7	1240	7.36
01.02.11	278	67.4	7.9	7	1260	7.0
	330	45.3	8.3	6	1285	11.0
	294	39.5	13.8	5	1235	21.0
	336	30	14.1	4.7	1230	28.2
	345	10	6.5	4.2	1263	39.0
	356	21	13.1	4.1	1198	37.4
	365	10	9.7	4	1268	58.2

5.5 Characteristics of Solar Pump and Motor

Combined characteristics of pump and motor of the solar pumping system is presented next.

5.5.1 Head , Discharge and Efficiency Calculation

Head , H(ft) = Discharge pressure in Psi × 2.31 + datum head(ft)

Discharge, Q = Discharge Water/Discharge time

Maximum useful power from array = Conversion efficiency of panel × Irradiance × Area of panels = Electrical input

Hydraulic Output= Q γ H/550

Where Q = Discharge in ft^3/s

γ = Density of water in lb/ft^3

H = Head of pump in ft

$$\% \text{ Efficiency}(\eta) = \frac{\text{Hydraulic Output}}{\text{Electrical Input}} \times 100$$

$$= \frac{Q \gamma H/550}{\text{Electrical Input (hp)}} \times 100$$

Electrical input (hp) is considered in two ways which is given below:

a. Maximum useful power from array =conversion efficiency of panel (here 12% from panel data) x sun's Irradiance x number of panels x Area of panels.

b. power absorbed by pump = multiplication of voltage and current (VI)

Using the above formula and data of Table 5.3 and Table 5.4, Table 5.5 is prepared.

Table 5.5: Prepared and derived data from Table 5.3 and Table 5.4

Discharge Pressure (Psi)	Discharge water (Litre)	Discharge Time (S)	Head, H (ft)	Discharge, (ft^3/min)	Voltage (V)	Current (A)	Power absorbed by pump(hp)	Efficiency (pump & motor) (%)	Irradiance (W/m^2)	Useful power from Array (hp)	Approx. Useful Efficiency (pump& motor (%)
4.7	14.1	30	12.3	1	6.8	32	0.3	7.7	336	0.41	5.67
5	13.82	39.5	13.4	0.75	6.1	31	0.25	7.5	330	0.4	4.7
4	9.7	10	10.7	2.04	7.36	42	0.41	10.1	365	0.445	9.3
6	8.3	45.3	15.4	0.39	5.6	28	0.22	5.14	300	0.366	3.1
4.2	6.5	10	11.3	1.375	7	35	0.33	8.8	345	0.42	6.96
7	7.9	67.4	17.7	0.25	5.3	25	0.18	4.6	278	0.34	2.45
4.1	13	20	10.9	1.75	7.15	38	0.36	9.9	356	0.435	8.25

5.5.2 Characteristic curves of solar water pumping system

The results of Table 5.5 are presented graphically in Fig 5.1 -5.5.

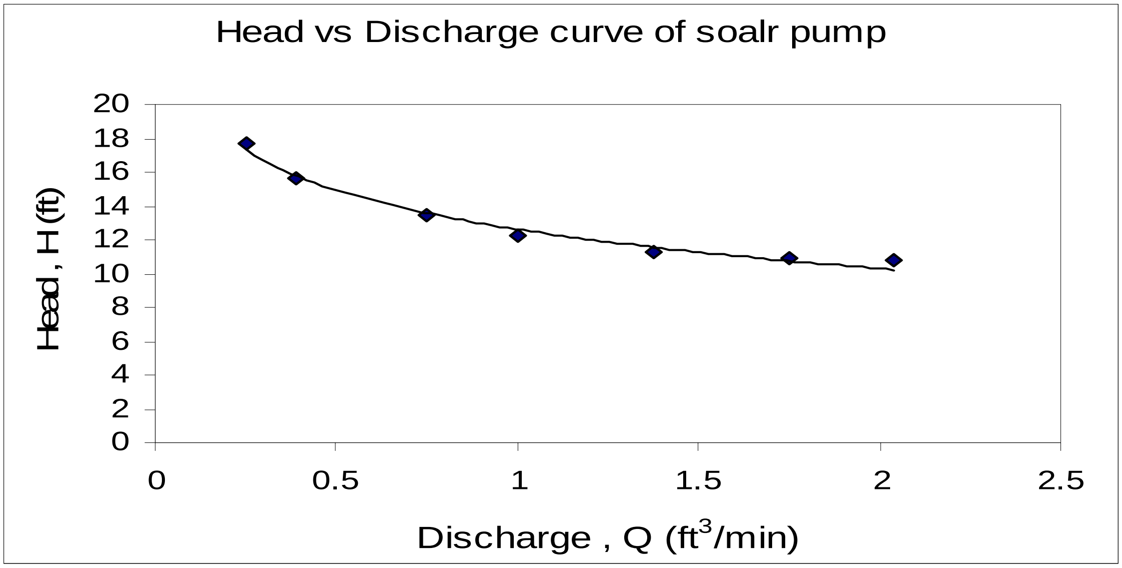


Fig 5.1: Head vs Discharge curve of solar water pump

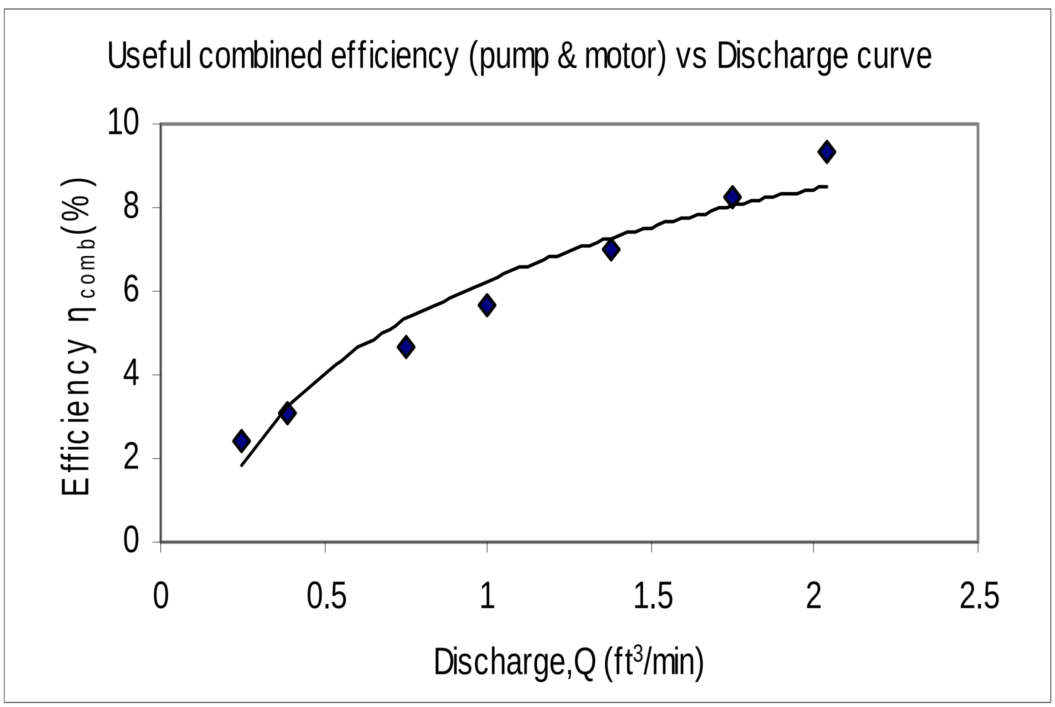


FIG 5.2: USEFUL COMBINED EFFICIENCY (PUMP & MOTOR) VS DISCHARGE CURVE

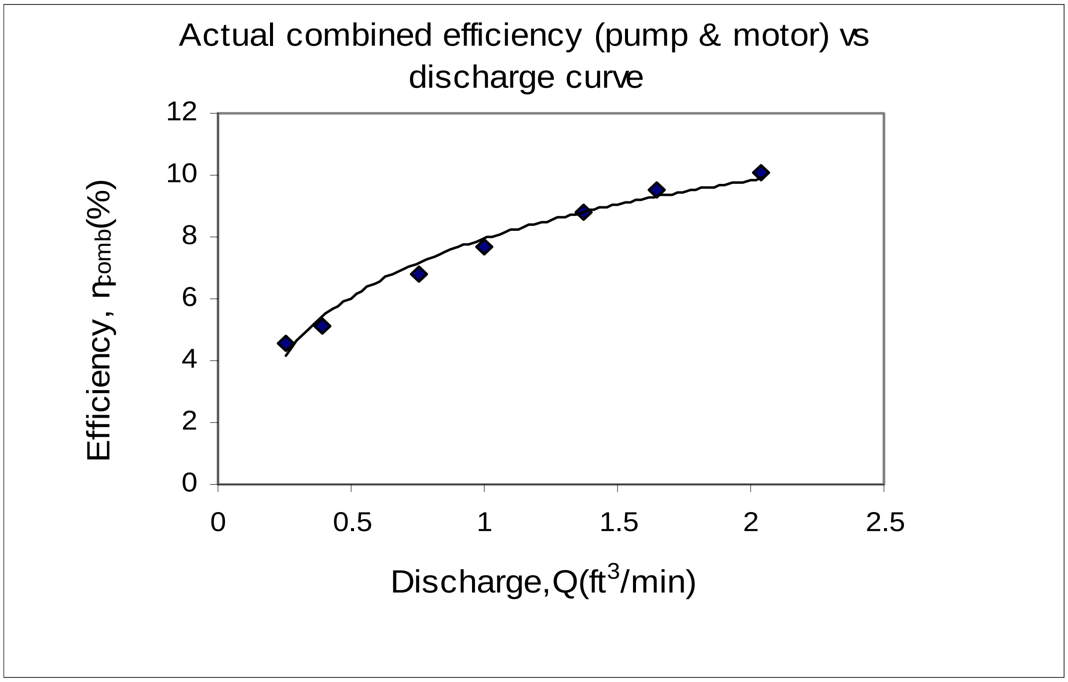


FIG 5.3: ACTUAL COMBINED EFFICIENCY (PUMP AND MOTOR) VS DISCHARGE CURVE

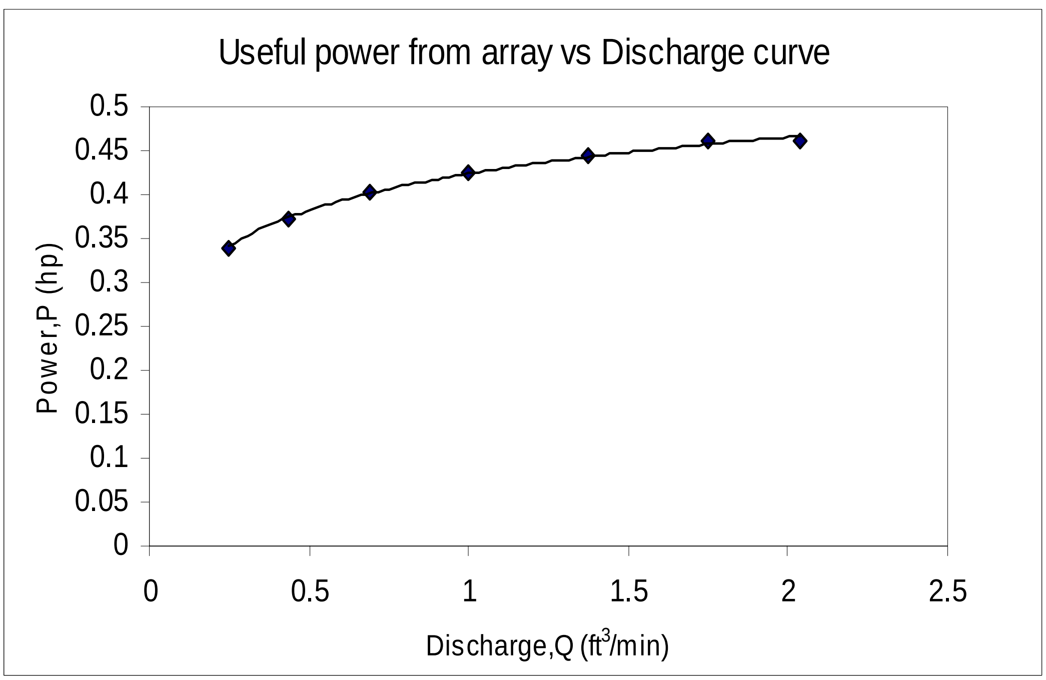


FIG 5.4: USEFUL POWER FROM ARRAY – DISCHARGE CURVE

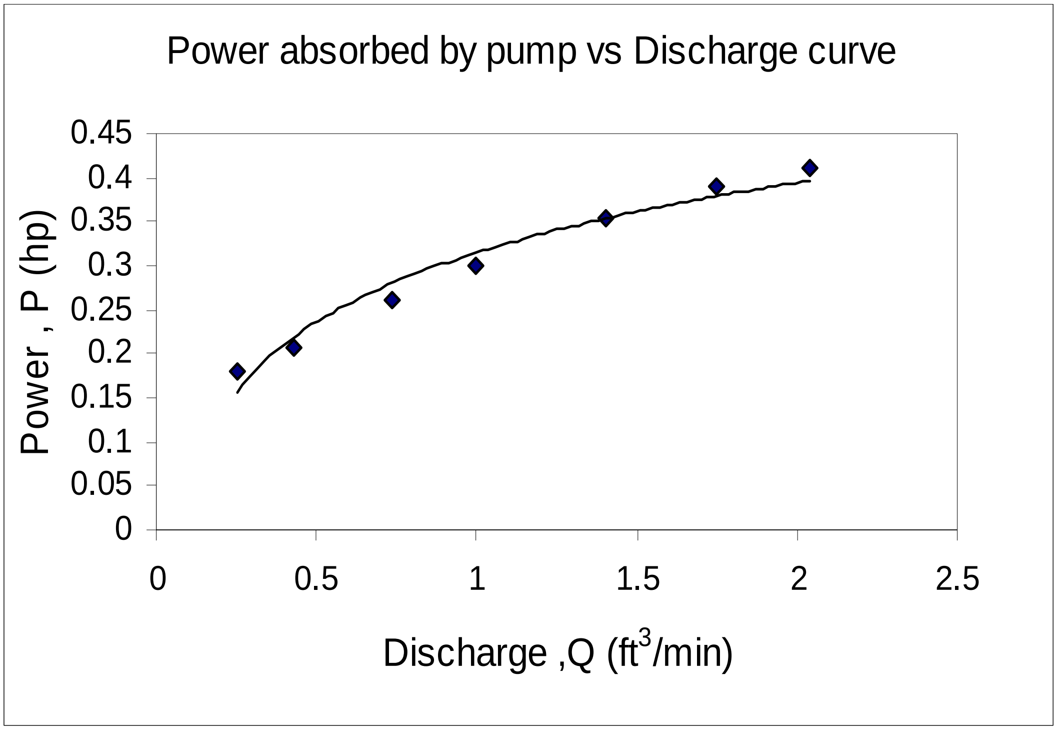


FIG 5.5: ABSORBED POWER BY PUMP – DISCHARGE CURVE

The characteristics of solar pump and motor make conformity with the original characteristics of pump and motor. In Fig 5.1 with increases of the head, discharge of pump decreases. In Fig5.4 with increases of combined efficiency (pump and motor) discharge of pump increases.

5.6 Summary

Data has been collected from the designed water pumping system for three different cases. Firstly, data has been taken for no load condition, then data from direct-coupled connection has been tabulated and finally data has been recorded after connecting DC-DC Buck converter with the solar water pump. Data from the last observation provides acceptable good results. Improvement of the performance was also found in the last system compared to other connections**.** Head - Discharge curve of solar pump and combined efficiency (pump and motor) - Discharge curve have been drawn from the data collected and the characteristics was found to meet the actual characteristics of pump - motor .This project was carried out throughout the winter and the average discharge capacity was found in the range of 35-56 Liter/min. This discharge capacity is expected to increase in the summer season with increased irradiance of sunlight.

Chapter 6

Installation Cost, Assessment of water requirements and Irrigation

6.1 Introduction: A solar pump is designed and implemented using locally available technologies to investigate a way to reduce dependency of diesel – and electricity - driven water pumps in agricultural land in Bangladesh. Solar irrigation pumps can play a vital role in reducing demand for electricity from grid, diesel and make possible to irrigate a vast portion of lands that are devoid of irrigation facilities. Main applications of solar pumps in rural areas of developing countries like Bangladesh may be water supply for drinking and irrigation. Also end uses such as water pumping in fish breeding centers, salterns, drainage, poultry and cattle farms may be benefited from such systems.

6.2 Installation Cost

The installation costs of this proposed system is tabulated in Table 6.1.

Table-6.1: Typical present installation cost of the solar water pumping system.

Sl.no.	**List of materials**	**Costs at this project (TK)**	**Remarks**	**Costs at fields (TK)**	**Remarks**
01	12 x 75 W solar panel	---	free of cost.	12 x 10500/= =126000/=	12 numbers of 75 W 12 V each solar panels required.
02	12V 1hp dc motor	7000/=		7000/=	
03	1hp centrifugal pump	6000/=		6000/=	
04	Controller(DC-DC buck converter)	9000/=		9000/=	
05	2 core 10 rm BYM cables(200 ft)	40000/=	As distance between panels and pump sets is very high so it requires more cables.	3000/=	In fields panels and pump sets will be close to each other. Hence fewer cables require.
06	Connectors, busbars, and Accessories	5000/=		5000/=	
	Total =	67000/=	Total =	156000/=	

The costs of installing these locally developed solar pumps will be less than the imported ones as the imported solar pumps are expensive. Repair and maintenance costs will also be lower than the imported solar water pumps. Since these pumps will run without battery and inverter, maintenance costs will be lower than any other types. Farmers can easily install and change the pumps whenever necessary because it is made using local pumps without battery and inverter. These one horse power solar pump system will cost about TK.156000 /=, whereas, Dhaka University Scientists' developed one horse power solar pump costs about TK. 375000/= [18]. Following these procedures one can construct solar pumping system of higher capacity to irrigate large area farms.

6.3 Assessment of water requirements

Water requirements for irrigation depend on a number of factors, which need to be analyzed in order to optimize solar water pumping system to the given situation. Factors which have the most direct influence on the assessment of water requirements are;

i. Cropping system followed by the farmer,

ii. Crop water requirements under given climate conditions,

iii. Type and condition of soil;

iv. Topology of the area.

The annual cropping system followed by farmers reflects the seasonality of the agricultural practices as well as the crop mix during each season. The choice of cropping system would be mainly governed by the market considerations of the product. Some typical cropping systems followed in Bangladesh are presented in Table-6.2 [19]. Solar water pumping system can be used for irrigation throughout the cropping season.

Once the cropping is identified, the net water supply for irrigation can be estimated from the data on crop water requirements. These are obtained from the Directorate of Agricultural Extension (DAE) in Bangladesh (Table-6.3[19]). The gross water supply, which is also the desired solar water pumping output depends on the efficiency of water conveyance through the field, which in turn depends primarily on the field canal network and soil conditions.

Table-6.2: Some Typical Medium Highland cropping system in Bangladesh [19]

Sl. No.	Crop	Season	
1.	Pulses Chilly Soyabean	October February July	January July September
2.	Chilly Vegetables	November May	May October
3.	Mustard Potato Vegetables	October December June	February February October
4.	Wheat Chilly	November March	February September
5.	Onion Vegetables Soyabean	October March July	January July September
6.	Garlic Chilly Vegetables	September February June	January May August
7.	Potato Rice(Boro) Chilly	November February May	January May September

Source: Irrigated Crop Production Manual, DAE, Bangladesh.

Table-6.3: Irrigation water requirements of Medium Highland Crops Grown in Bangladesh [19]

Crops	Crop duration(days)	Number of Irrigation	Irrigation frequency(days)	Water requirement per irrigation(m^3/ha)	Daily water requirement per irrigation on rotation basis
Chilly	150	19	8	184	23
Onion	95	11	7	273	39
Garlic	90	15	6	200	33
Soyabean	110	4	28	750	27
Wheat	120	5	24	700	29
Rice(Boro)	120	5	24	2150	90
Potato	100	10	10	350	35
Mustard	96	4	24	750	31
Vegetables	100	17	6	176	29

Source: Irrigated Crop Production Manual, DAE, Bangladesh.

6.3.1 Drinking water supply

In general, drinking water requirements can be estimated as the product of the per capita consumption and the human or animal population as the case may be. Domestic water requirements per capita vary markedly in response to the actual availability of water. If there is home supply the consumption may be five or more times greater than if water has to be collected from various water points. Where ground water is scarce, the per capita allocation of water will be determined more by supply constraints than by the demand. Subject to availability of water, it seems reasonable to assume a consumption rate of 40 liters per capita per day for the purpose of designing village drinking water supply schemes[19]. Typically daily water requirements for a range of livestock are presented in Table-6.4[19].

Table: 6.4: Typical Daily water requirements of Livestock [19].

Species	Liters of water per day
Camels	40-90
Horses	30-40
Cattle	20-40
Milch cow	70-100
Sheep and Goats	1-5
Swine	3-6
Lactating	25
Poultry	0.2-0.3

For example, population at one small village of Patenga, where, water to be supplied by the solar pump to 500 peoples, 100 cattle, 200 goats and 1000 chickens, the demand can be estimated as,

Then present daily water demand is:

500 people	= 500 x 40 L	=20000	Litrtes
100 cattle	= 100 x 40 L	= 4000	Litres
300 Goats	= 300 x 5 L	= 1500	Litres
2000 Chickens	= 2000 x 0.1 L	= 200	Litres

Total Demand = 25,700 Litres

$= 25.7 \ m^3$

Considering that the average discharge of this designed solar pump is

= 50 Litre/min

= 50 x 60 Litre/h

and considering the pump will run for 8 hours in a day, The Discharge Capacity = 50 x 60 x 8 Litre /day

= 24,000 Litres

= 24 m^3

It can be inferred that this designed solar pump will meet the water requirements of the one small village of Patenga. Once the water requirements are established, the capacity of solar pump requirements can be estimated.

6.4 Irrigation:

By far 35% [18] of our arable land falls under various irrigation projects. Energy used in irrigation is electricity and diesel. The total estimated number of deep tube-well installed is 31302 and the number of small and medium irrigation pump are 14,15000. In irrigation 75% of the pumps are run by diesel and the remaining 25 % are operated by electricity [18]. The electricity requirement for the irrigation pumps at present is 1200 MW. In contrast supplied power stands at 750 MW [20]. On the other hand 65% of arable land could not be brought under irrigation system. Under these circumstances the solar water pump can play a significant role. To solve this problem we have developed a solar pump model using locally available pumps. Implementation of this model solar pump can save a good amount of subsidy in electricity and diesel by shifting to these pumping systems. 65% of arable land that is outside the irrigation coverage can also be included within irrigation network using solar water pumping system. As a consequence the production of crops can be increased. It is expected that the solar water pumping system based on local technology will facilitate the effort to bring more and more land within irrigation network.

Advantages of the locally developed solar water pumping system are,

1. Installation cost of indigenous solar water pumping systems will less than imported ones,
2. Dependence of the demand of diesel and electricity will reduce,
3. Maintenance cost will be less because imported systems after passing of one year period take longer time and higher cost for repairing and

4. Due to use of local pump farmer can easily install and change the pumps whenever necessary.

6.5 Summary

To popularize the solar pumping system following recommendations are proposed,

1. Encourage the locally developed solar pumping technology in all sectors,
2. Through piloting of region based solar water pumping installation of more such project should be undertaken,
3. Subsidy in this field like that of diesel, electricity and fertilizer may be provided,
4. All over the world the price of solar panels are decreasing but in contrast the prices are not decreasing according to that in Bangladesh. Effort to fabricate solar panels and DC motors at low cost in Bangladesh should be undertaken,
5. Installation of mini-grid should be encouraged to provide electricity to nearby villages, and
6. Additional funding should be provided for experimentation for similar projects.

Chapter 7
FUTURE SCOPE OF SOLAR PUMP IN BANGLADESH

7.1 Introduction

Future works that can be undertaken in the designed and fabrication of solar water pump is discussed in this chapter. The developed solar pumping system was experimented in winter season, where, irradiance were low. Similar types of projects in larger scale can be taken for further study in summer season.

7.2 Micro grid System with Solar Water Pump

The micro-grid energy strategy offers society a critical path towards energy independence and environmental restoration. In technical terms a micro-grid (µ Grid) is "a grouping of generating sources and loads operating semi-independently of the large grid power system". In the solar context, a micro-grid would be a collection of multiple solar panels that produce thousands of watts at a time rather than the 40-50 watts produced by one conventional SHS (Solar Home System). These panels combined with batteries and small generators can power homes in a village, operate irrigation pumps, provide electricity to schools, clinics, small industries and shops etc. Energy conversion, heat recovery, renewable energy harvesting and energy storage may all take place simultaneously within a micro-grid [21].

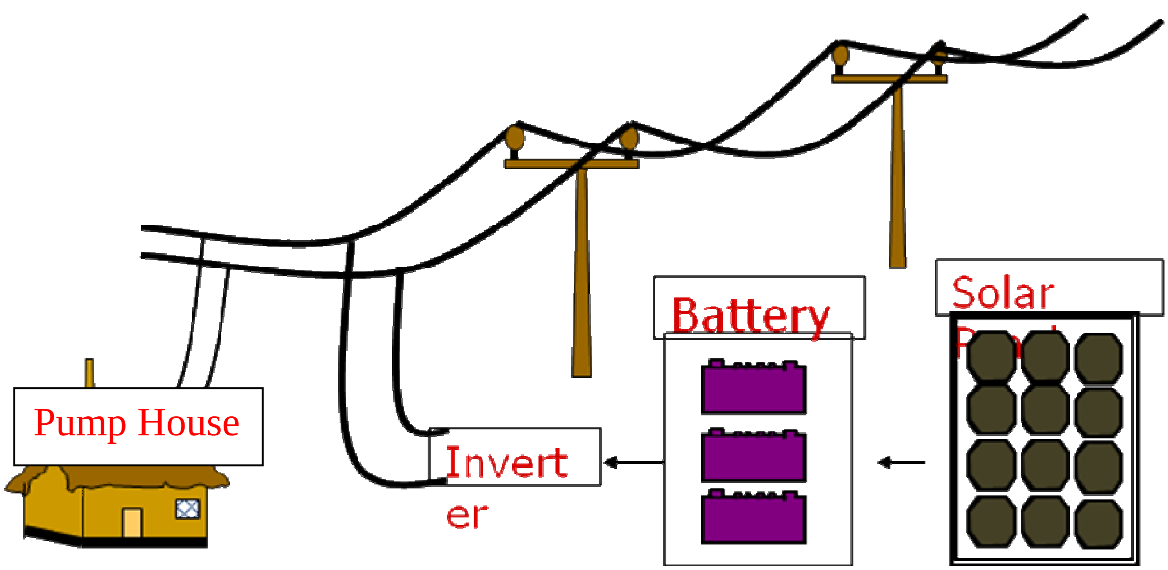


Figure 7.1: Micro Grid system with Solar Water Pump [21]

A micro-grid has the capability to intelligently prioritize loads so that important loads can be served during supply shortages. Micro-grids can be operated in isolation (islanded) or as an interconnected subset of the bulk (macro-grid) power system. To maximize efficiency, a micro-grid typically blends or 'hybridizes' multiple generation and distribution technologies with particular emphasis on maximum utilization of thermal energy. The energy flow in a micro-grid supports a very high overall efficiency. Battery requirement is relatively small in micro grid systems.

7.3 Closed loop Converter with MPPT

A Microcontroller based closed loop control can be integrated in between the input and output of the Buck converter. The output voltage can be sampled and matched with the input voltage. The gate pulse can be produced from the microcontroller instead of external timer circuits and gate pulses will be logically changed to control the output of the converter. The logical calculation would be such that the maximum power point could be tracked. So it will control the output and track the maximum point simultaneously. Typical components of a MPPT based control is shown in Fig-7.2 [21]

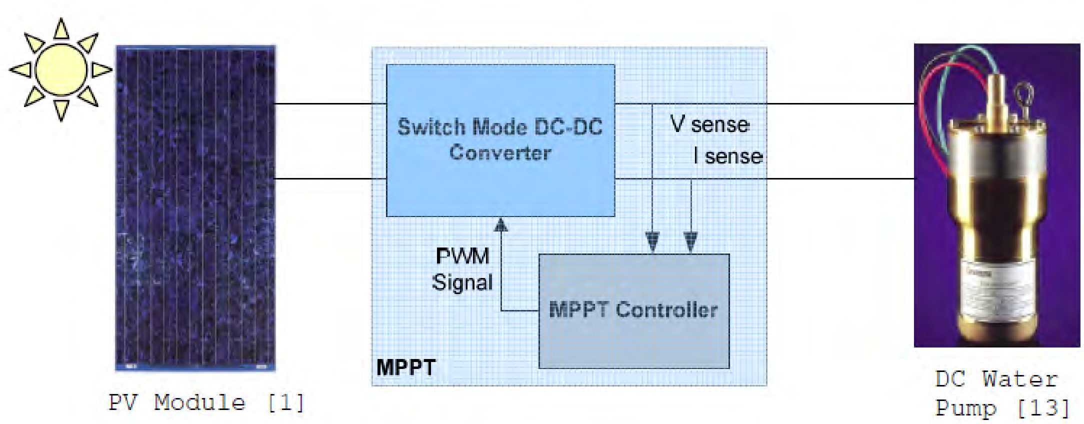


Figure 7.2: Closed Loop control of DC-DC converter [21]

The control system performance can be improved by combining the closed-loop control of a PID controller with feed forward open-loop control. Knowledge about the system (such as the desired voltage and current) can be fed forward and combined with the PID output to improve the overall system performance [22]. The feed-forward value alone can often provide the major portion of the controller output. The PID controller can be used primarily to respond to whatever difference or error remains between the set point (SP) and the actual value of the process variable (PV) [23]. Since the feed-forward output is not affected by the process feedback, it can never cause the control system to oscillate, thus improving the system response and stability.

7.4 Solar Tracking System

The proposed Solar Tracking system that has been designed and constructed as a part of the thesis cannot be implemented in the final design. A large solar tracker can be built using the same logic that has been proposed in the prototype design. Medium sized solar tracker can also be installed to rotate twelve solar panels separately. Solar tracking system is acting as an essential part of the solar water pumping system to increase the operation efficiency of the system. Further improvements can be done on solar tracker by modifying the system into Dual axis tracker from Single axis tracker. A dual axis tracker tracks the position of earth's rotation as well as the sun's position. A typical solar tracker based water pumping system is shown in Fig 7.3 [22].

Figure 7.3: Solar water pumping with Solar Tracker [22].

7.5 Summary

The proposed solar water pumping system can be modeled for micro grid supply as well as the performance of the system can be improved by integrating closed loop control with the DC-DC buck converter. Large scale solar tracking system can also be made from the proposed solar tracker to implement with photovoltaic water pumping system to get better efficiency.

Chapter 8

CONCLUSION

Solar photovoltaic pumping offers a way out to the people of Bangladesh from the energy crisis. This thesis demonstrated that solar photovoltaic technology can be integrated to pumping systems in Bangladesh. Some technological challenges were overcome through engineering solutions and showed a representative model can be implemented. Upfront cost of the solar pumping systems potentially hinder to popularize the systems in rural areas but private companies, bank and govt. can come forward for a solution that can fit to rural people of Bangladesh.

Generally, the proposed Solar Water Pumping system briefly tenders the following opportunities:

- Long lasting and free maintenance.
- No dependency on electricity connection and diesel price.
- Satisfactory performance on water pumping.
- User and environment friendly.
- Invariant of any natural calamities.

Issues of energy and global warming are some of the biggest challenges for humanity in the 21st century. The world is getting divided into two groups: the countries that have access to oil and natural gas resources and those that do not have. In contrast, renewable energy resources are ubiquitous around the world. Especially, PV has a powerful attraction because it produces electric energy from a free inexhaustible source, the sun, using no moving parts, consuming no fossil fuels, and creating no pollution or green house gases during the power generation. Together with decreasing PV module costs and increasing efficiency, PV is getting more pervasive than ever.

REFERENCES

[1]. “Towards Revamping Power and Energy Sector: A Road Map” report by Finance Division Ministry of Finance, Government of the People's Republic of Bangladesh.

[2]. Renewable energy and environmental information network, web page available: http://www.reein.org/solar/index.html.

[3]. Green, Martin A. Solar Cells; Operating Principles, Technology, and System Applications Prentice Hall Inc., 1982

[4]. “Minor Irrigation Survey Report 2008-09,” Bangladesh Agricultural Development Corporation, Survey and monitoring project for development of minor irrigation, June-2009.

[5]. C. J. Swet, Paul E. Dorvel, John D. Furber, and Daniel Ingold, “Understanding solar water pumps,” Vita, 1600 Wilson Boulevard, Suite 500, Arlington, Verginia 22209 USA

[6]. The Daily Prothom Alo, 4th November, 2009, web page available: http://www.prothom-alo.com/detail/date/2009-11-04/news/17114

[7]. Stuart R. Wenham, Martin A. Green, Muriel E. Watt, and Richard Corkish, Applied Photovoltaics, 2nd ed., London, UK : Earthscan, 1997. Copyright: ARC centre for Advanced Silicon Photovoltaics and photonics

[8]. Hahn A., Resource-conserving Irrigation with Photovoltaic Pumping Systems, 16th European Photovoltaic Solar Energy Conference, 1-5 May 2000, Glasgow.

[9]. Siemens Solar, SP 75- 75 wp Mono Crystalline Photovoltaic Datasheet.

[10]. C. Hua and C. Shen, “Comparative study of peak power tracking techniques for solar storage system,’’ Applied Power Electronics Conference and Exposition, vol. 2, pp. 679-685, Feb. 15-19, 1998.

[11]. M.A. Panait and T Tudorache, “A Simple Neural Network Solar Tracker for Optimizing Conversion Efficiency in Off-Grid Solar Generator” Intl. Conf. on Renewable Energy and Power quality, no. 278, March, 2008.

[12]. O. Bingol, A. Altinta, and Y. Oner, “Microcontroller based solar- tracking system and its implementation,” Journal of Engineering Sciences, vol. 12, pp. 243–248, 2006.

[13]. M. F. Khan and R. L. Ali, “Automatic sun tracking system,” All Pakistan Engineering Conference, Islamabad, Pakistan, 2005.

[14]. Rashid, Muhammad H. Power Electronics - Circuits, Devices, and Applications 3rd Edition Pearson Education, 2004

[15]. WATTSUN™ SOLAR TRACKER RETAIL PRICE AND DATA SHEET. [Online]. Available: http://www.wattsun.com/prices.html

[16]. “Microcontroller” datasheet. [Online]. Available: http://www.datasheetcatalog.com/datasheets_pdf/A/T/M/E/ATMEGA32.shtml.

[17]. “7805’’ datasheet. [Online]. Available: http://www.electrokits.com/ Datasheets/ 7805-Datasheet

[18]. Bhowmik, Prof. Dr.N.C and others “Development of solar water pumping using indigenous technology for irrigation”, Renewable energy research centre, Energy park, University of Dhaka,Dhaka-1000,Bangladesh,September 2009.

[19]. Ahmed Sultan, “Investigation And Analysis of Wind Pumping System for Irrigation In Bangladesh,” Department of Mechanical Engineering, BUET, Dhaka, Bangladesh, February 2002.

[20]. Power Supply Activities, Irrigation Scenario 2010, Power Division, Ministry of Power, Energy and Mineral resources, Bangladesh

[21]. A. Engler, D. Georgakis N. Hatziargyriou C. Hardt S. Papathanassiou “Operation of a prototype Microgrid system based on micro-sources equipped with fast-acting power electronics interfaces”, in Proc. 35th Annual IEEE Power Electronics Specialists Conference, 20.-25.06.2004, Aachen.

[22]. Anonymous Solar Powered Livestock Watering System, http://www.utextension.utk.edu

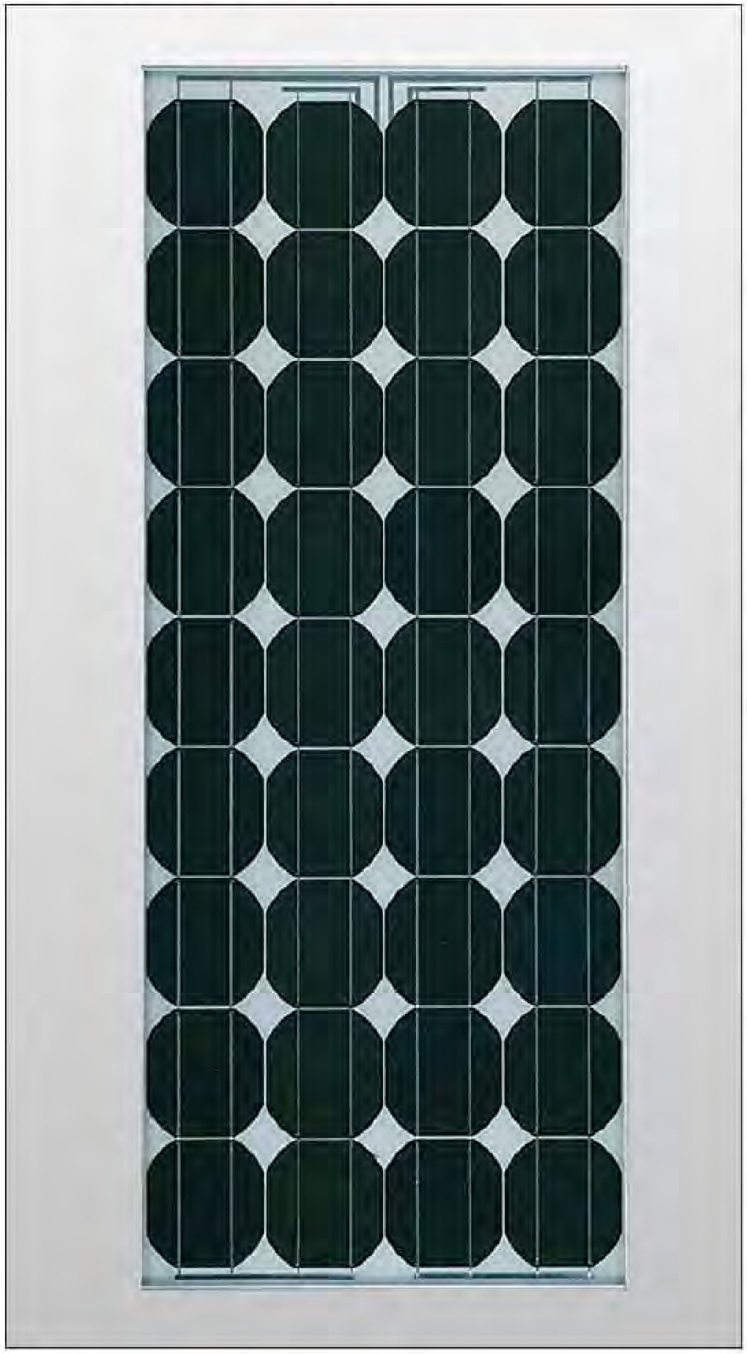
[23]. Helikson,H.J and Others, Pumping water for irrigation using solar energy, University of Florida, USA, 1995.

APPENDIX- A

Datasheet of Solar panels

A .1 Specification of Solar Panel- Siemens SP75

Solar module SP75



When it comes to reliable and environmentally-friendly generation of electricity from sunlight, solar modules from Siemens provide the perfect solution. Manufactured in compliance with the most stringent quality standards, Siemens Solar modules are designed to withstand the toughest environmental conditions and are characterized by their long service life. Siemens Solar modules are covered by a 25-year limited warranty on power output – your guarantee of trouble-free solar power generation.

PowerMax® technology

Siemens' proprietary PowerMax® technology optimizes the energy production of individual cells and solar modules for all types of environmental conditions. PowerMax® process optimization includes a special refining technique for ingots, a clean room semiconductor grade production process, and a multistage proprietary TOPS™ (Texture Optimized Pyramidal Surface) process. The TOPS process incorporates the formation of textured pyramids on the surface of the solar cell. These pyramids are then specially treated to passivate the surface. The cell's optical properties are optimized for maximum absorption of photons from the sun's light. TOPS also maximizes photon absorption from direct and diffused light (typical under cloudy conditions). This means that light absorption is especially high, even at low light levels. Siemens PowerMax® solar cells deliver maximum energy throughout the day.

Solar module

Model:	**SP75**
Rated power:	**75 Watts**
Limited Warranty:	**25 Years**

Certifications and Qualifications

- UL-Listing 1703
- TÜV safety class II
- JPL Specification No. 5101-161
- IEC 61215
- CE mark
- FM Certification

Intelligent module design

- All cells are electrically matched to assure the greatest power output possible.
- Ultra-clear tempered glass provides excellent light transmission and protects from wind, hail, and impact.
- Torsion and corrosion resistant anodized aluminum module frame ensures dependable performance, even through harsh weather conditions and in marine environments.
- Built-in bypass diodes (12V configuration) help system performance during partial shadowing.

High quality

- Every module is subject to final factory review, inspection and testing to assure compliance with electrical, mechanical and visual criteria.
- 36 PowerMax® single-crystalline solar cells deliver excellent performance even in reduced-light or poor weather conditions.
- Cell surfaces are treated with the Texture Optimized Pyramidal Surface (TOPS™) process to generate more energy from available light.
- Fault tolerant multi-redundant contacts on front and back of each cell provide superior reliability.
- Solar cells are laminated between a multi-layered polymer backsheet and layers of ethylene vinyl acetate (EVA) for environmental protection, moisture resistance, and electrical isolation.
- Durable back sheet provides the module underside with protection from scratching, cuts, breakage, and most environmental conditions.
- Laboratory tested and certified for a wide range of operating conditions.
- Ground continuity of ≤ 1 ohm for all metallic surfaces.
- Manufactured to exacting Siemens quality standards.

Easy installation

- ProCharger™-CR junction box accepts conduit, cable or wire and is designed for easy field wiring.
- Lightweight aluminum frame and pre-drilled mounting holes for easy installation.
- Factory configured for 12V operation and may be reconfigured in the field for 6V operation.
- Modules may be wired together in series or parallel to attain required power levels.

Performance warranty

- 25 Year limited warranty on power output.

Further information on solar products, systems, principles and applications is available in the Siemens Solar product catalog.

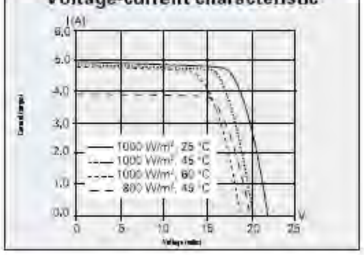
Siemens modules are recyclable.

Solar module SP75

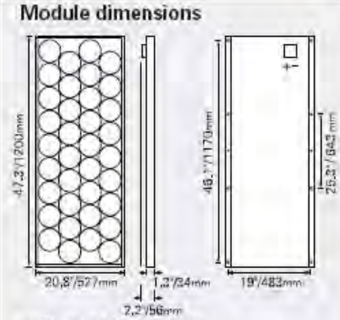
Electrical parameters			12 V/6 V
Maximum power rating P_{max}		[Wp] 1)	75
Rated current I_{MPP}		[A]	4.4/8.8
Rated voltage V_{MPP}		[V]	17.0/8.5
Short circuit current I_{SC}		[A]	4.8/9.6
Open circuit voltage V_{OC}		[V]	21.7/10.9
Thermal parameters			
NOCT 2)		[°C]	45 ±2
Temp. coefficient: short-circuit current			2.06 mA / °C
Temp. coefficient: open-circuit voltage			-.077 V / °C
Qualification test parameters 4)			
Temperature cycling range		[°C]	-40 to +85
Humidity freeze, Damp heat		[%RH]	85
Maximum system voltage		[V]	600 V per UL (1000 V per ISPRA)
Wind Loading	PSF	[N/m²]	50 [2400]
Maximum distortion 3)		[°]	1.2
Hailstone impact	Inches	[mm]	1.0 [25]
	MPH	[m/s]	52 [v=23]
Weight	Pounds	[kg]	16.7 [7.6]

1) Wp (Watt peak) = Peak power (Minimum Wp = 70 Watts)
   Air Mass AM = 1.5
   Irradiance E = 1000 W/m²
   Cell temperature T_c = 25 °C
2) Normal Operating Cell Temperature at:
   Irradiance E = 800 W/m²
   Ambient temperature T_U = 20 °C
   Wind Speed v_W = 1 m/s
3) Diagonal lifting of module plane
4) Per IEC 61215 test requirements
5) 12 volt configuration

Voltage-current characteristic



Module dimensions

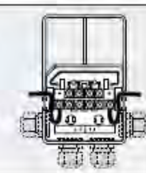


Hole Diameter 0.26 inch (6.6mm)
Mounting hole dimensions are center to center

ProCharger™-CR Junction-box

Maximum cable diameter: 4mm²

Type of protection: IP44



Your address for photovoltaics from Siemens Solar

 Status 11/98 - Subject to modification.

Siemens Solar GmbH
A joint venture of Siemens AG and Bayernwerk AG
Postfach 46 07 05
D-80915 München
Germany

Siemens Solar Industries
P.O.Box 6032
Camarillo, CA 93011, U.S.A.
Web site: www.siemenssolarpv.com
E-mail: sunpower@solarpv.com
Tel: 805-482-6800
Fax: 805-388-6395

Siemens Showa Solar Pte. Ltd.
166 Kallang Way
Singapore 349249
Tel: 65-842-3886
Fax 65-842-3887

Order No: 019897, Rev. D

APPENDIX- B

Datasheet of ATMEGA 32, IC 7805

B.1 Datasheet of ATMEGA 32 AVR Microcontroller

Features

- High-performance, Low-power AVR® 8-bit Microcontroller
- Advanced RISC Architecture
  - 131 Powerful Instructions – Most Single-clock Cycle Execution
  - 32 × 8 General Purpose Working Registers
  - Fully Static Operation
  - Up to 16 MIPS Throughput at 16 MHz
  - On-chip 2-cycle Multiplier
- High Endurance Non-volatile Memory segments
  - 32 Kbytes of In-System Self-programmable Flash program memory
  - 1024 Bytes EEPROM
  - 2 Kbytes Internal SRAM
  - Write/Erase Cycles: 10,000 Flash/100,000 EEPROM
  - Data retention: 20 years at 85°C/100 years at 25°C[1]
  - Optional Boot Code Section with Independent Lock Bits
    In-System Programming by On-chip Boot Program
    True Read-While-Write Operation
  - Programming Lock for Software Security
- JTAG (IEEE std. 1149.1 Compliant) Interface
  - Boundary-scan Capabilities According to the JTAG Standard
  - Extensive On-chip Debug Support
  - Programming of Flash, EEPROM, Fuses, and Lock Bits through the JTAG Interface
- Peripheral Features
  - Two 8-bit Timer/Counters with Separate Prescalers and Compare Modes
  - One 16-bit Timer/Counter with Separate Prescaler, Compare Mode, and Capture Mode
  - Real Time Counter with Separate Oscillator
  - Four PWM Channels
  - 8-channel, 10-bit ADC
    8 Single-ended Channels
    7 Differential Channels in TQFP Package Only
    2 Differential Channels with Programmable Gain at 1x, 10x, or 200x
  - Byte-oriented Two-wire Serial Interface
  - Programmable Serial USART
  - Master/Slave SPI Serial Interface
  - Programmable Watchdog Timer with Separate On-chip Oscillator
  - On-chip Analog Comparator
- Special Microcontroller Features
  - Power-on Reset and Programmable Brown-out Detection
  - Internal Calibrated RC Oscillator
  - External and Internal Interrupt Sources
  - Six Sleep Modes: Idle, ADC Noise Reduction, Power-save, Power-down, Standby and Extended Standby
- I/O and Packages
  - 32 Programmable I/O Lines
  - 40-pin PDIP, 44-lead TQFP, and 44-pad QFN/MLF
- Operating Voltages
  - 2.7V - 5.5V for ATmega32L
  - 4.5V - 5.5V for ATmega32
- Speed Grades
  - 0 - 8 MHz for ATmega32L
  - 0 - 16 MHz for ATmega32
- Power Consumption at 1 MHz, 3V, 25°C for ATmega32L
  - Active: 1.1 mA
  - Idle Mode: 0.35 mA
  - Power-down Mode: < 1 µA

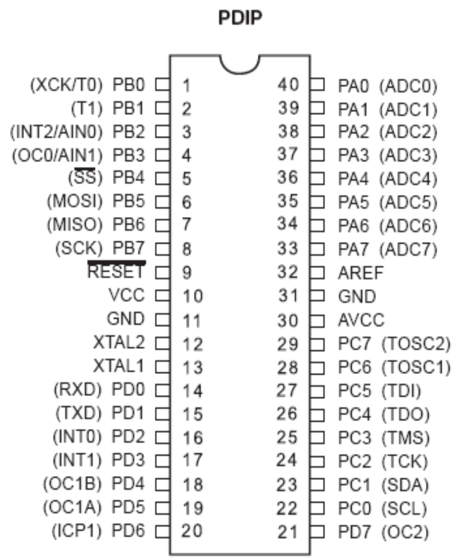
8-bit AVR® Microcontroller with 32K Bytes In-System Programmable Flash

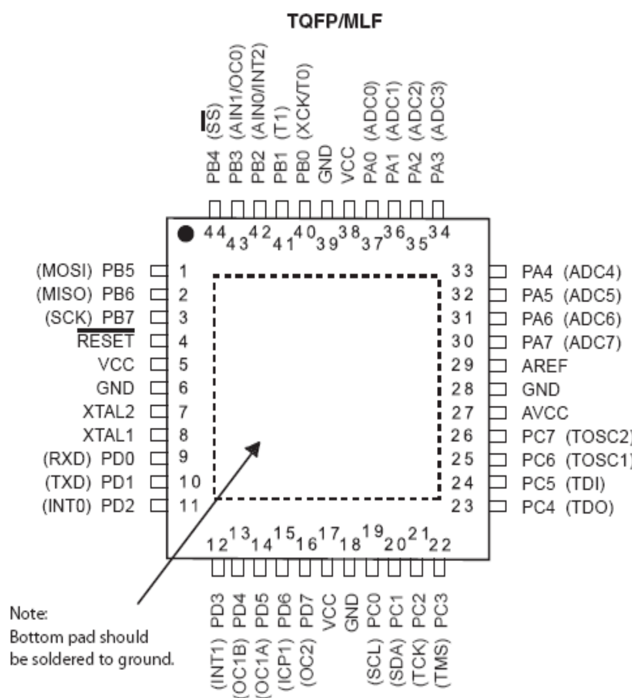
ATmega32
ATmega32L

2503P–AVR–07/10

Pin Configurations

Figure 1. Pinout ATmega32





B. 2 Datasheet of Regulator IC- 7805

Advanced Analog Circuits

Preliminary Datasheet

3-TERMINAL POSITIVE LINEAR REGULATOR **AZ7805**

General Description

The AZ7805 is a monolithic integrated circuit designed as fixed-voltage regulator for a wide variety of applications including local, on-card regulation.

This regulator is complete with internal current limiting, thermal shutdown protection, and safe-area compensation which makes it virtually immune from output overload. If adequate heat sinking is provided, this regulator can deliver output current up to 1.0A.

The AZ7805 is available in two plastic packages: TO-220 and TO-252.

Features

- Output Current up to 1.0A
- Fixed Output Voltage of 5V
- Output Voltage Tolerances of ± 5% over the Full Temperature Range
- Internal Short Circuit Current-Limiting
- Internal Thermal Overload Protection

Applications

- Consumer Electronics
- Microprocessor Power Supply
- Mother Board I/O Power Supply

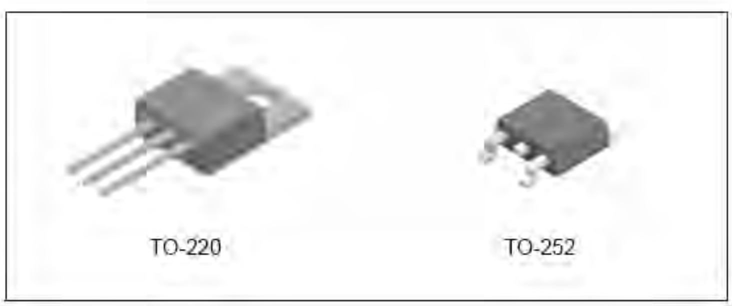
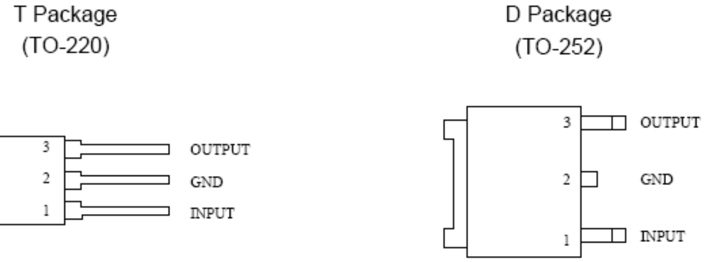


Figure 1. Package Types of AZ7805

Pin Configuration



Top View

Figure 2. Pin Configuration of AZ7805

Pin Description

Pin Number	Pin Name	Function
1	INPUT	Voltage Input
2	GND	Ground
3	OUTPUT	Voltage Output

APPENDIX- C

Datasheet of SMPS SG-3524

C.1 Datasheet of SMPS SG-3524

Philips Semiconductors | Product specification

SMPS control circuit SG3524

DESCRIPTION

This monolithic integrated circuit contains all the control circuitry for a regulating power supply inverter or switching regulator. Included in a 16-pin dual-in-line package is the voltage reference, error amplifier, oscillator, pulse-width modulator, pulse steering flip-flop, dual alternating output switches and current-limiting and shut-down circuitry. This device can be used for switching regulators of either polarity, transformer-coupled DC-to-DC converters, transformerless voltage doublers and polarity converters, as well as other power control applications. The SG3524 is designed for commercial applications of 0°C to +70°C.

FEATURES

- Complete PWM power control circuitry
- Single ended or push-pull outputs
- Line and load regulation of 0.2%
- 1% maximum temperature variation
- Total supply current is less than 10mA
- Operation beyond 100kHz

PIN CONFIGURATION

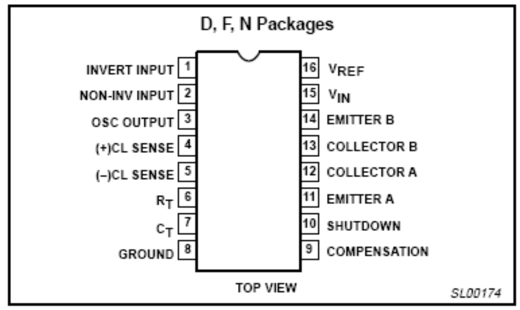


Figure 1. Pin Configuration

ORDERING INFORMATION

DESCRIPTION	TEMPERATURE RANGE	ORDER CODE	DWG #
16-Pin Plastic Dual In-Line Package (DIP)	0 to +70°C	SG3524N	SOT38-4
16-Pin Ceramic Dual In-Line Package (CERDIP)	0 to +70°C	SG3524F	0582B
16-Pin Small Outline (SO) Package	0 to +70°C	SG3524D	SOT109-1

BLOCK DIAGRAM

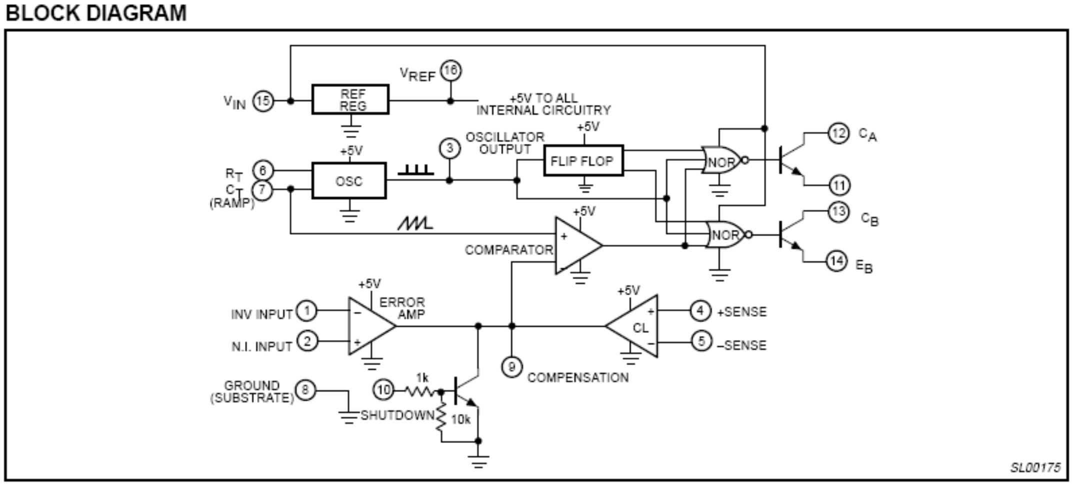


Figure 2. Block Diagram

ABSOLUTE MAXIMUM RATINGS

SYMBOL	PARAMETER	RATING	UNIT
V_{IN}	Input voltage	40	V
I_{OUT}	Output current (each output)	100	mA
I_{REF}	Reference output current	50	mA
	Oscillator charging current	5	mA
P_D	Power dissipation		
	Package limitation	1000	mW
	Derate above 25°C	8	mW/°C
T_A	Operating temperature range	0 to +70	°C
T_{STG}	Storage temperature range	-65 to +150	°C

DC ELECTRICAL CHARACTERISTICS

T_A=0°C to +70°C, V_{IN}=20V, and f=20kHz, unless otherwise specified.

SYMBOL	PARAMETER	TEST CONDITIONS	LIMITS			UNIT
			Min	Typ	Max	
Reference section						
V_{OUT}	Output voltage		4.6	5.0	5.4	V
	Line regulation	V_{IN}=8 to 40V		10	30	mV
	Load regulation	I_L=0 to 20mA		20	50	mV
	Ripple rejection	f=120Hz, T_A=25°C		66		dB
I_{SC}	Short circuit current limit	V_{REF}=0, T_A=25°C		100		mA
	Temperature stability	Over operating temperature range		0.3	1	%
	Long-term stability	T_A=25°C		20		mV/kHz
Oscillator section						
f_{MAX}	Maximum frequency	C_T=0.001 μF, R_T=2kΩ		300		kHz
	Initial accuracy	R_T and C_T constant		5		%
	Voltage stability	V_{IN}=8 to 40V, T_A=25°C			1	%
	Temperature stability	Over operating temperature range			2	%
	Output amplitude	Pin 3, T_A=25°C		3.5		V_P
	Output pulse width	C_T=0.01 μF, T_A=25°C		0.5		μs
Error amplifier section						
V_{OS}	Input offset voltage	V_{CM}=2.5V		2	10	mV
I_{BIAS}	Input bias current	V_{CM}=2.5V		2	10	μA
	Open-loop voltage gain		68	80		dB
V_{CM}	Common-mode voltage	T_A=25°C	1.8		3.4	V
CMRR	Common-mode rejection ratio	T_A=25°C		70		dB
BW	Small-signal bandwidth	A_V=0dB, T_A=25°C		3		MHz
V_{OUT}	Output voltage	T_A=25°C	0.5		3.8	V
Comparator section						
	Duty cycle	% each output "ON"	0		45	%
	Input threshold	Zero duty cycle		1		V
	Input threshold	Maximum duty cycle		3.5		V
I_{BIAS}	Input bias current			1		μA
Current limiting section						
	Sense voltage	Pin 9=2V with error amplifier set for maximum out, T_A=25°C	180	200	220	mV
	Sense voltage T.C.			0.2		mV/°C
V_{CM}	Common-mode voltage		-1		+1	V

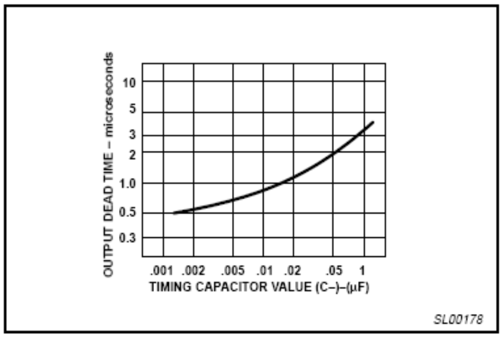


Figure 5. Output Stage Dead Time as a Function of the Timing Capacitor Value

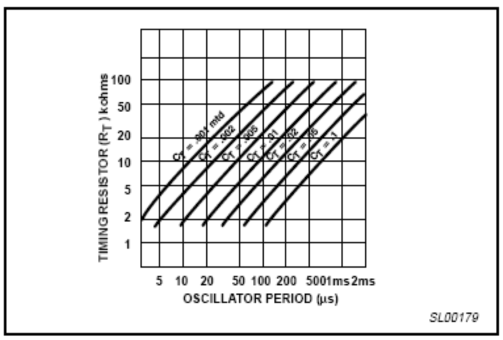


Figure 6. Oscillator Period as a Function of R_T and C_T

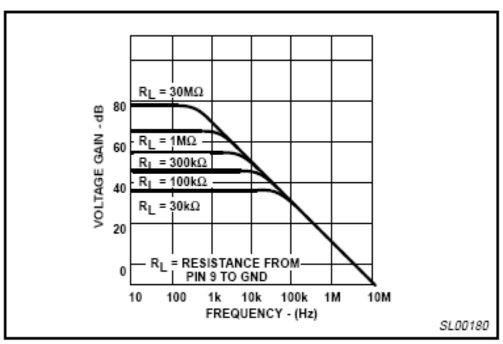


Figure 7. Amplifiers Open-Loop Gain as a Function of Frequency and Loading on Pin 9

Oscillator

The oscillator in the SG3524 uses an external resistor (R_T) to establish a constant charging current into an external capacitor (C_T). While this uses more current than a series-connected RC, it provides a linear ramp voltage on the capacitor which is also used as a reference for the comparator. The charging current is equal to 3.6 V ÷ R_T and should be kept within the approximate range of 30µA to 2mA; i.e., 1.8k<R_T<100k.

The range of values for C_T also has limits as the discharge time of C_T determines the pulse-width of the oscillator output pulse. This pulse is used (among other things) as a blanking pulse to both outputs to insure that there is no possibility of having both outputs on simultaneously during transitions. This output dead time relationship is shown in Figure 5. A pulse width below approximately 0.5µs may allow false triggering of one output by removing the blanking pulse prior to the flip-flop's reaching a stable state. If small values of C_T must be used, the pulse-width may still be expanded by adding a shunt capacitance (≅100pF) to ground at the oscillator output. [(Note: Although the oscillator output is a convenient oscilloscope sync input, the cable and input capacitance may increase the blanking pulse-width slightly.)] Obviously, the upper limit to the pulse width is determined by the maximum duty cycle acceptable. Practical values of C_T fall between 0.001 and 0.1 µF.

The oscillator period is approximately $t=R_TC_T$ where t is in microseconds when R_T=Ω and C_T=µF. The use of Figure 6 will allow selection of R_T and C_T for a wide range of operating frequencies. Note that for series regulator applications, the two outputs can be connected in parallel for an effective 0-90% duty cycle and the frequency of the oscillator is the frequency of the output. For push-pull applications, the outputs are separated and the flip-flop divides the frequency such that each output's duty cycle is 0-45% and the overall frequency is one-half that of the oscillator.

External Synchronization

If it is desired to synchronize the SG3524 to an external clock, a pulse of ≅+3V may be applied to the oscillator output terminal with R_TC_T set slightly greater than the clock period. The same considerations of pulse-width apply. The impedance to ground at this point is approximately 2kΩ.

If two or more SG3524s must be synchronized together, one must be designated as master with its R_TC_T set for the correct period. The slaves should each have an R_TC_T set for approximately 10% longer period than the master with the added requirement that C_T(slave)=one-half C_T (master). Then connecting Pin 3 on all units together will insure that the master output pulse—which occurs first and has a wider pulse width—will reset the slave units.

Error Amplifier

This circuit is a simple differential input transconductance amplifier. The output is the compensation terminal, Pin 9, which is a high-impedance node (R_L≅ 5MΩ). The gain is

$$A_V = g_M R_L = \frac{8\ I_C\ R_L}{2kT} \approx 0.002R_L$$

and can easily be reduced from a nominal of 10,000 by an external shunt resistance from Pin 9 to ground, as shown in Figure 7.

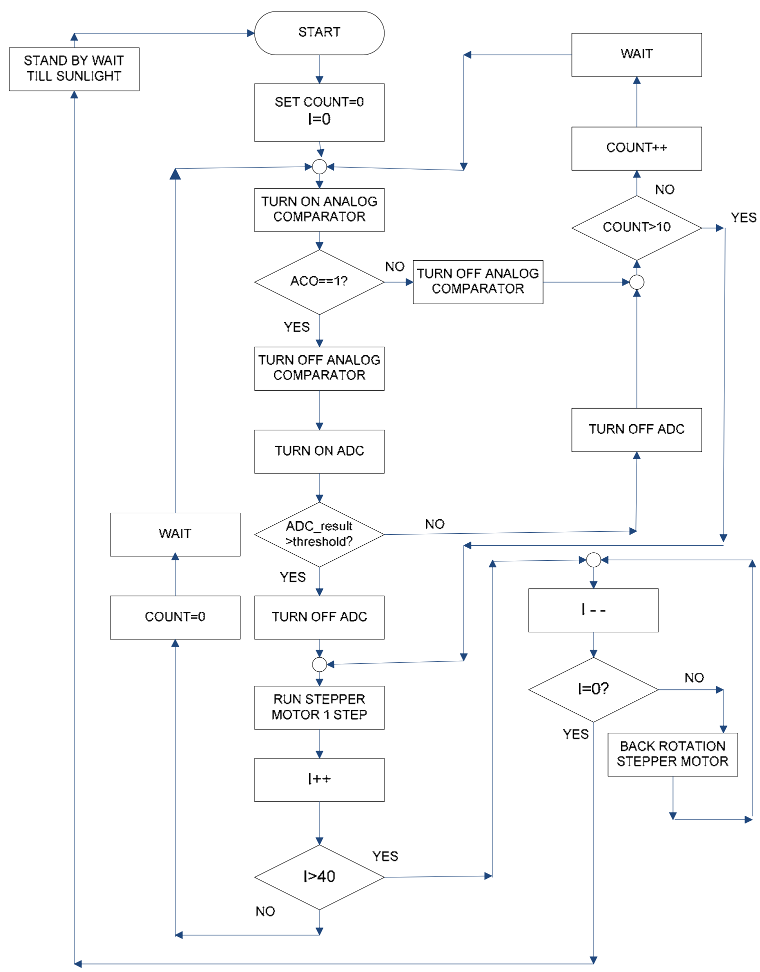
In addition to DC gain control, the compensation terminal is also the place for AC phase compensation. The frequency response curves of Figure 7 show the uncompensated amplifier with a single pole at approximately 200Hz and a unity gain crossover at 5MHz.

Typically, most output filter designs will introduce one or more additional poles at a significantly lower frequency. Therefore, the best stabilizing network is a series RC combination between Pin 9 and ground which introduces a zero to cancel one of the output filter poles. A good starting point is 50kΩ plus 0.001µF.

APPENDIX- D

Programming Code and Flow Chart for Solar Tracker

D. 1 Flowchart of Solar Tracker



D.2 Microcontroller code

```
#include<avr/io.h>
void adc_init(void);
void adc_disable(void);
void anacom_init(void);
void anacom_disable(void);
void adc_operation(void);
void run_stepper(void);
void delay(unsigned int delayms);
```

```
void port_init(void);

void anacom_wait(void);

void adc_check(void);

unsigned char count_stepper = 0; // needed for the function run_stepper() to control motor rotation.

unsigned char count_analog = 0;  // needed for the function anacom_wait()

int main(void)

{

	port_init();

	while(1)

	{

		//delay(10);

		anacom_init();

		if ( ACSR & (1<<ACO) ) // checking if the output of the analog comparator is set to 1

		{

			anacom_disable();

			adc_operation();

		}

		else  // if analog comparator output is not set to 1

		{

			anacom_wait();

			anacom_disable();

		}

	}

	return 0;

}

void port_init(void) // Port initialization function

{

	DDRC = 0xFF; // Initializing PORTC as output. the motor will be connected at pins PC0, PC1, PC2 and PC3 to present a pulse sequence
```

```
}

void anacom_init(void) // Initializes Analog Comparator and enables it to generate ACO.

{

        ACSR &= ~( (1<<ACD) | (1<<ACIE) ) ;

}

void adc_init(void) // initializes adc, enables it and starts conversion

{

        ADMUX = (  (1<<REFS0) |  (1<<ADLAR) | (9<<MUX0) );

        ADCSRA |= ( (1<<ADEN) | (1<<ADSC) );

}

void anacom_disable(void) // turn off the power of analog comparator

{

        ACSR |=  (1<<ACD) ;

        ACSR &= ~(1<<ACIE);

}

void adc_disable(void) // disabling adc to activate the operation of analog comparator

{

        ADCSRA &= ~( (1<<ADEN) | (1<<ADSC) );

}

void adc_operation(void) // controls total operation of the ADC from initialization to disabling

{

        adc_init();

        adc_check();

        adc_disable();

}

void run_stepper(void) // Defines how the stepper motor will rotate

{

        unsigned char step[] = {1,3,2,6,4,12,8,9}; // Stepper motor pulse sequence for half stepping counter clockwise
```

```
}

        PORTC = step[count_stepper % 8]; // rotates the motor only one step

        count_stepper++;

        if (count_stepper>=120)

                count_stepper = 0;

}

void delay(unsigned int delayms) // creates delay, if argument is 2000, a delay of
about 3.5 seconds is produced.

{

        unsigned char i;

        i = 30;

        while(i)

        {

                while(delayms)

                {

                        delayms--;

                }

                i--;

        }

}

void anacom_wait(void) // keeps analog comparator waiting during ACO=0 for a
duration of time and rotates the motor one step

{

        //delay(2000);

        if (count_analog > 10)

        {

                run_stepper();

                count_analog = 0;

        }

        count_analog++;

}
```

```
void adc_check(void) // checks only the result with threshold
{
	unsigned char threshold = 0b00000100;
	unsigned char result;

	ADCSRA &= ~(1<<ADIE);

	result = ADCH;

	if(result > threshold)
		run_stepper();

	//delay(2000);
}
```

<u>END</u>