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PALESTINE POLYTECHNIC UNIVERSITY

ELECTRICAL AND COMPUTER ENGINEERING DEPARTMENT

INTRODUCTION TO GRADUATION PROJECT

STAND ALONE HYBRID POWER SYSTEM

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Chapter One

Introduction

Foreword

Despite of having public support and advantages over other energy sources, renewable technologies have been repeatedly characterized as unable to meet our energy needs. People have been presented only a choice between conventional fossil fuels and nuclear power. This, however, is a false choice. Renewable energy can reliably generate as much energy as conventional fuels, and can do so without producing carbon emissions or radioactive waste.

Industrial Automation Engineering is the most improved sector in the field of the electrical engineering due to the wide spread applications in the world industry.

There are two fields covered in this project:

- Electrical.
- Computer.

The system will work by the solar and wind energies.

1.1 Project Aim:

The project aims to:

1. Use the hybrid solar and wind in an application.
2. Employment solar and wind energy to light a group of houses.
3. Use the new technology in our application.
4. Using environmental friendly sources of power.

1.2 literature View :

It is only a matter of time that the oil energy will be a thing of the past and facing the threat of depletion of that source, the world tries to develop new sources of energy. So all its researches are on finding sustainable energy that lasts forever. On our land for example many applications of lighting systems have been developed. But most of these applications are using unique power sources such as solar or wind, but in this project we will apply the hybrid system in our land with a new technique.

This technique depends on collecting natural resources from the wind and sun arrays and convert these resources through special generators where wind sources is changed to electrical power by a wind turbine which will be discussed in chapter 3, and sun arrays are changed to electrical power through Photovoltaic (PV) panels. Combining these resources to supply a sustainable energy to different applications depending on the demanded work.

That refers to the wind speed average here in Palestine and especially in the project land. The land is a small village of three houses in south of Yatta called (Beer El'ed).

This place has been located for many reasons , one of them is that the land mentioned has no electricity because it is too far from the city , and another reason is that those who live there are in a need of energy since they are shepherds and they need energy to store milks and whatever. Another reason which is the most important is that the Israeli occupation is trying to get out those who live there from their land, so a project like this can support them stay and still living in this plce.

A lot of studies has been explained could prove that the alternative power is the solution for our problem , and many projects that have been applied is the answer for those who claim that the alternative power is not available to be applied. So no need to improve the ability and necessity of this power. So this method of producing power is capable to supply a big quantity of people with power. So the importance of this type of producing power appears when you talk about nations who have no petrol enough to create energy and have no resources of power. So the source of power here in our project is a renewable energy that lasts forever.

1.3 Block Diagram :

The figure (1.1) shows the block diagram for the system.

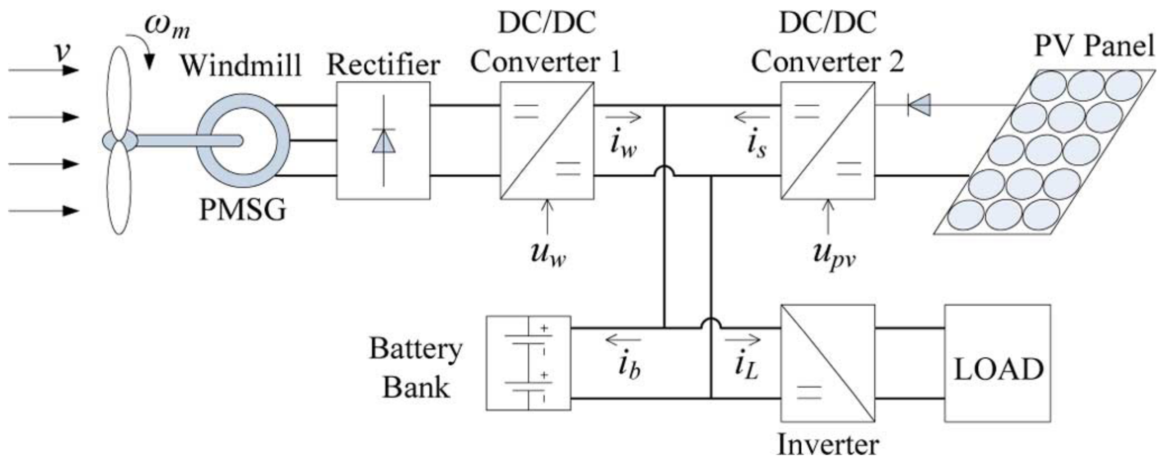


fig. 1.1 Block Diagram of the project.

- PV panel: this unit use to convert solar power to electrical power.
- Wind Turbine: this unit is used to convert wind power to electrical power.
- Rectifier: this element is an electrical circuit to convert AC power to DC power.
- Charge controller: this unit is used to the variable voltage to constant voltage and control the battery charge.
- Battery: used to store energy and provide the inverter with it.
- Inverter: device used to convert DC to AC voltage.
- Panel Box: contain (resistors, Diodes, switches ……) that contain supplying and controlling components of the system.
- Loads : it is home loads: lighting and power consuming devices.

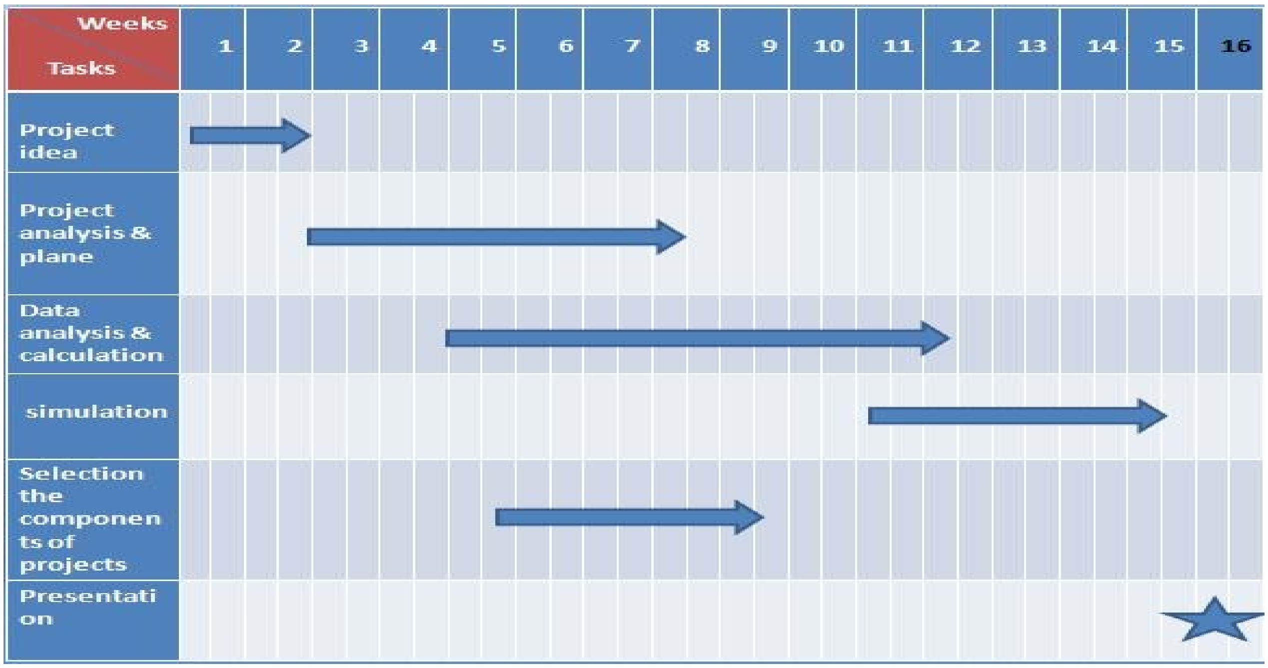
1.4 The project cost / (Visible study)

Table 1.1 Project cost table

The element type	Quantity	Cost/Qty	The price of units
Solar panel	5	500$	3000$
Wind turbine	1	2000$	2000$
Charge controller	1	100$	100$
Battery bank	4	120$	480$
Inverter	1	1000$	1000$
Panel box	1	50$	50$
Other elements	1	30$	30$
Total Price			6660$

1.5 Schedule Time:

Table 1.2 Schedule Time



1.6 Suggestions:

The suggestions are:

* Build a control system to control the direction of PV panels to maximum solar energy.

* using the project in a practical application .

* use a heater instead the temperature resistors to consume the overall power in windy days.

Chapter Two

Hybrid system

2.1 Definition Hybrid system:

A hybrid renewable energy system is a system in which two or more supplies from different renewable energy sources (solar-thermal, solar photovoltaic, wind, biomass, hydropower, etc.) are integrated to supply electricity or heat, or both, to the same demand. The most frequently used hybrid system is the hybrid which consists of Photovoltaic (PV) modules and wind turbines.

Hybrid power systems based on new and renewable energy sources, especially photovoltaic and wind energy, are an effective option to solve the power-supply problem for remote and isolated areas far from the grids.

Hybrid power systems, which combine conventional and renewable power conversion systems are the best solution for feeding the mini-grids and isolated loads in remote areas. Properly chosen renewable power sources will considerably reduce the need for fossil fuel leading to an increase in the sustainability of the power supply. At the same time, conventional power sources aid the renewable sources in hard environmental conditions, which improve the reliability of the electrical system.

Over the present years hybrid technology has been developed and upgraded its role in renewable energy sources while the benefits it produces for power production can't be ignored and have to be considered.

Nowadays many applications in rural and urban areas use hybrid systems. Many isolated loads try to adopt this kind of technology because of the benefits which can be received in comparison with a single renewable system.

2.2 Why hybrid power plants?

Currently very fast development of new electrical power sources called renewable sources can be observed. These sources are environmentally friendly and use primary energy carriers such as solar, wind and water flow, biogas, biomass etc. The sources mentioned above can be divided into two groups: controlled sources and uncontrolled sources. Controlled sources mean primary energy sources giving rise to the possibility of controlling electrical power production, for example coal. It is obvious that power production from uncontrolled sources is unpredictable and independent of human action. Solar and wind power plants are uncontrolled sources.

On the other hand, electricity should be produced exactly at the time it is needed. Sun and wind do not meet this requirement. So, special kind of power plants should be built to avoid shortages of power and to utilize all available sun or wind power. There are at least two ways to achieve this aim: electricity energy storage or power plants using two (or more) primary sources with additional control systems. One of the sources must be a controlled power source, such power plants are hybrid power plants.

Developers and manufacturers are looking for ways to combine technologies to improve performance and efficiency of distributed generation equipment. Several examples of hybrid systems include:

- A solid oxide fuel cell combined with a gas turbine or Micro turbine.
- A Sterling engine combined with a solar dish.
- Wind turbines with battery storage and diesel backup Generators.
- Engines (and other prime movers) combined with energy storage devices such as flywheels.

2.3 Why Hybrid?

Because the supply pattern of different renewable energy sources intermittent but with different patterns of intermittency, it is often possible to achieve a better overall supply pattern by integrating two or more sources. Sometimes also including a form of energy storage. In this way the energy supply can effectively be made less intermittent, or more firm.

Combining renewable hybrid system with batteries as a storage system, to increase duration of energy autonomy, will make optimal use of the available renewable energy resource and this in turn can guarantee high supply reliability.

To deal with different weather conditions and to make the system supplies load demand at the worst conditions, this strategy requires large storage capacity and therefore it is very expensive. It is cheaper to supply peaks or to supply demand during periods of cloudy weather or poor wind days with another back up supply (usually diesel generator), although this lowers the proportion of renewable energy used. Selecting appropriate size of the storage system is such that to minimize diesel running time and to maximize fuel savings.

Dump loads are recommended to be used in hybrid power systems as secondary loads to provide a sink for excess renewable generated power to keep power balance of the system at all times, also improve the economic return of the system by allowing excess renewable energy to meet an on-site energy needs that would otherwise have to be met with other energy source.

Optimum match design is very important for PV/wind hybrid system, which can guarantee battery bank working at the optimum conditions as possible as can be, therefore the battery bank's lifetime can be prolonged to the maximum and energy production cost decreased to the minimum.

In last few years, some commercial software packages for simulating wind power, PV and hybrid generating systems have been developed. By using computer simulation, the optimum system configuration can be found by comparing the performances and energy production costs of different system configurations. To simulate the practical operating situations of renewable energy systems, many factors need to be considered.

2.4 Advantages of the hybrid system:

The main advantages of hybrid system can be considered as:

- Its possibility of combining two or more renewable energy sources, based on the natural local potential of the users.
- Low cost – wind energy, and also solar energy can be competitive with nuclear, coal and gas especially considering possible future cost trends for fossil and nuclear energy.
- Environmental protection of harmful gases produced by energy production process such as coal and nuclear.
- Simplicity of the system, and availability of its sources anywhere without necessity of transporting them.
- Fuel is abundant, free and inexhaustible.
- Costs are predictable and not influenced by fuel price fluctuations although fluctuations in the price of batteries will be an influence where these are incorporated.
- The existing of the two sources all of the year, the wind and the sun.

2.5 The main disadvantages of the hybrid system:

- One is the complexity concept of controlling the system, by the meaning that when we connect a system like this we have to know that when the wind speed increase the power creative will be increased, so it is unacceptable for the system safety, so we have to build a control circuit to consider that one of the two systems should be disconnected.

- The other disadvantage is that the initial price for these systems is very high . but in future this problem will be solved since the word is heading to use sustainable energy , and companies are working to produce these devices.
- The dynamic interaction between the grid and/or the loads and the power electronic interface of renewable source can lead, to new system, critical problems stability and power quality that are not common in conventional power systems.

Radiation intensity For the Palestinian case, the daily average of solar on horizontal surface is about 5.4 kWh/m2 and day, while the total annual sunshine hours amounts to about 3000. These figures are relatively high and very encouraging to use PV generators for electrification of certain loads as it has been worldwide successfully used.

The annual average of wind velocity at different places in Palestine is about 3 m/s which makes the utilization of wind energy converters surely un feasible in such places. In other places it exceeds this number and reaches up to 5.5 m/s (Hebron is an example and it is the case under study in the project) which makes it feasible to be used to operate a wind turbine. At Nablus, the annual average of wind velocity reaches to about 4.5 m/s. Nablus site is also considered in this study as a comparison with Hebron site.

A hybrid system using wind, solar PV, as a backup system, and a battery as a storage system is expected to: satisfy the load demands, minimize the costs, maximize the utilization of renewable sources, optimize the operation of battery bank, which is used as back up unit, ensure efficient operation of the diesel generator, and reduce the environment pollution emissions from diesel generator if it is used as a standalone power supply.

The high capital cost of hybrid systems is affected by technical factors such as efficiency, technology, reliability, location, as well as some nontechnical factors, so the effect of each of these factors shall be considered in the performance study of the hybrid system.

Chapter 3

Electrical Elements

3.1 Introduction:

In this chapter we illustrate and explain the main electrical parts that should be used in the project, with justifications for choosing these elements**.**

The content parts are:

- Photovoltaic Panels.
- Wind Turbine.
- Charger Controller.
- Rectifier.
- Battery.
- Inverter.
- Control and protection elements.

3.2 Photovoltaics

3.2.1 Photovoltaic definition:

The photovoltaic panels are the main component to convert solar energy into electrical energy. The expression photovoltaic denotes the operation mode of photodiode in which current through the device is totally due to the transuded light energy. And we have to know that the solar cell produce direct current , which mean when they are used for a grid connected power generation they the must be connected by inverter in order to convert from DC to AC.

The cells are electrically connected together to form a photovoltaic module. And a group of modules can be connected together to produce array**.**

3.2.2 History of Photovoltaic:

In the middle of the last century the first conventional photovoltaic cells were produced, and throughout the 1960s were principally used to provide electrical power for earth-orbiting satellites. In the 1970s, improvements in manufacturing, performance and quality of PV modules helped on reduce costs and opened up a number of opportunities for powering remote terrestrial applications, including battery charging for navigational aids, signals, telecommunications equipment and other critical, low power needs.

After that and in the 1980s, photovoltaic become a popular source for consumer electronic devices, including calculators, watches, radios, lanterns and other small battery charging applications. Following the energy crises of the 1970s, significant efforts also began to develop PV power systems for residential and commercial uses both for stand-alone, remote power as well as for utility-connected applications. During the same period, international applications for PV systems to power rural health clinics, refrigeration, water pumping, telecommunications, and off-grid households increased dramatically, and remain a major portion of the present world market for PV products. Today, the industry's production of PV modules is growing at approximately 25 percent annually, and major programs in the U.S. Japan and Europe are rapidly accelerating the implementation of PV systems on buildings and interconnection to utility networks.

3.2.3 PV Technology:

The sun is classified as the largest energy source of life while at the same time it is the ultimate source of most of renewable energy sources. Solar energy can be used to generate electricity in a direct way with the use of photovoltaic modules. Photovoltaic is defined as the generation of electricity from light where the term photovoltaic is a compound word and comes from the Greek word for light, photo, with, volt, which is the unit of electromotive power. The technology of photovoltaic cells was developed rapidly over the past few decades. Nowadays the efficiency of the best crystalline silicon cells has reached 24% for photovoltaic cells under laboratory conditions and for that used in aerospace technology and about 14-17% overall efficiency for those available commercially while modules costs dropped to below 4$ per watt peak (4$/WP) .

A solar cell is considered the basic part in the photovoltaic system, it is a device that converts light energy into electrical energy by the photovoltaic effect. Solar cells are often electrically connected and encapsulated as a module. PV modules often have a sheet of glass on the front (sun up) side, allowing light to pass while protecting the semiconductor wafers from the elements (rain, hail, etc.). Solar cells are also usually connected in series in modules, creating an additive voltage. Connecting cells in parallel will yield a higher current. Modules are then interconnected, in series or parallel, or both, to create an array with the desired peak DC voltage and current.

PV cells consist basically of a junction between two thin layers of semi conducting materials, known as p (positive) type semiconductors and n (negative) type semiconductors. The p-type semiconductor is created when some of the atoms of the crystalline silicon are replaced by atoms with lower valence like boron which causes the material to have a deficit of free electrons. The n-type semiconductor is created when some of their atoms of the crystalline silicon are replaced by atoms of another material which has higher valence band like phosphorus in such a way that the material has a surplus of free electrons. The photovoltaic cell consists of 6 different layers of materials as shown in figure 3.1.

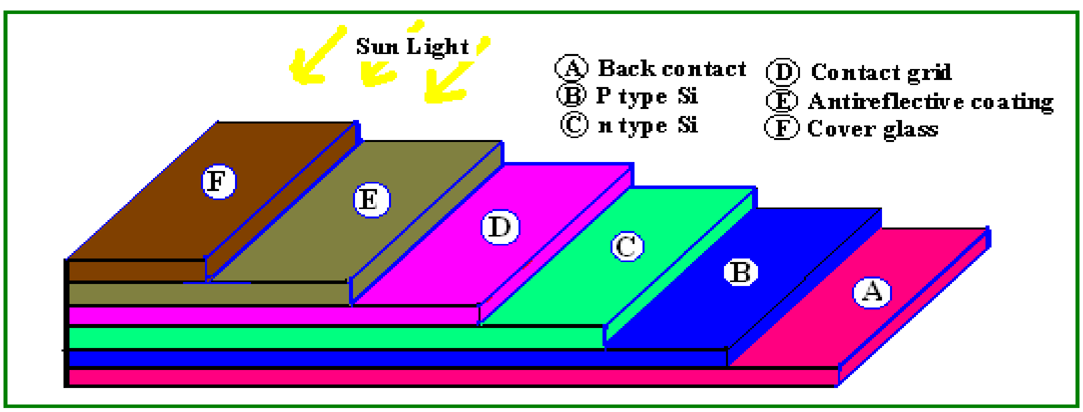


Fig. 3.1 Materials of photo cells

When we connect a variable load through the terminals of the PV cell, the current and the voltage will be found to vary. The relationship between the current and the voltage is known as the I-V characteristic curve of the PV cell. The I-V curve for a typical silicon PV cell under standard conditions is shown in figure 3.2.

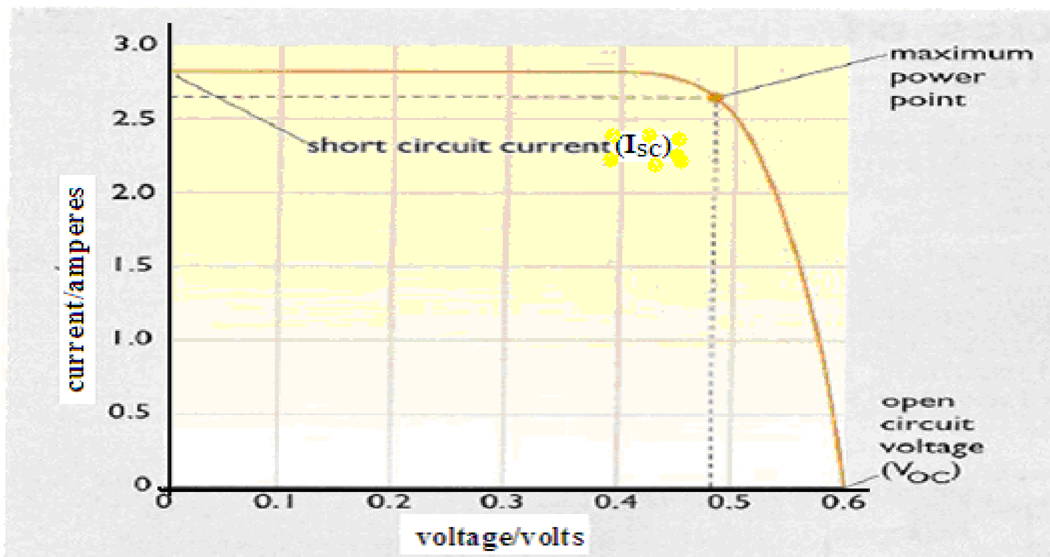


Fig. 3.2 IV curve

In order to measure the I-V characteristic of a PV cell and to find the maximum power point, an international standard conditions shall be fulfilled. These standard conditions are: irradiance level that shall be 1000 W/m², the reference air mass that shall be 1.5 solar spectral irradiance distribution, and cell or module junction temperature that shall be of 25°C. Open circuit voltage (VOC) is the voltage appears across the terminals of the PV cell when it is open circuited, while short circuit current (ISC) is the current passes through the short circuit when the terminals of the PV cell are short circuited. The term fill-factor is defined as the ratio between the maximum power delivered by the PV cell and the product of open circuit voltage and the short circuit current of the cell. The cell will deliver maximum power at maximum power point (MPP) on the I-V characteristic curve which represents the largest area of the rectangular under the I-V characteristic. A technique to utilize effectively the photovoltaic is known as a maximum-power- point tracking (MPPT) method, which makes it possible to acquire as much power as possible from the photovoltaic, this is accomplished by building a circuit in the charger controller or in the inverter circuit following the PV module. The efficiency of a solar cell is defined as the power P_{max} produced by the cell at MPPT divided by the power of radiation incident upon it.

3.2.4 Equivalent Circuit of a solar cell.

During darkness, the solar cell is not an active device; it works as a diode, i.e. a p-n junction. It produces neither a current nor a voltage. However, if it is connected to an external supply (large voltage) it generates a current ID, called diode current or dark current.

A solar cell is usually represented by an electrical equivalent one-diode model (Lorenzo, 1994), as shown in Figure 3.3.

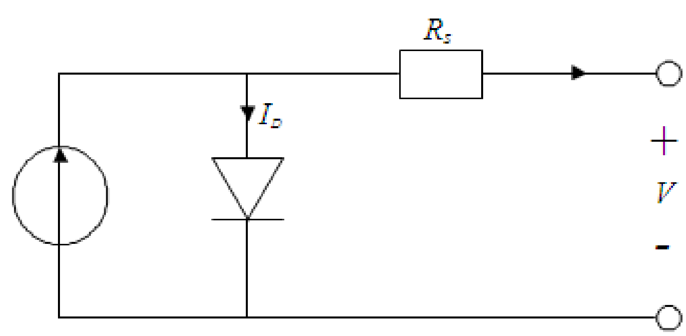


Fig 3.3: The Equivalent Circuit of a solar cell

3.2.5 The Electrical Characteristics of Solar Cells

3.2.5.1 Introduction

We have to consider that the supplied energy in our land for homes is 220v ac with frequency equal to 50Hz. And the power generated from the solar cells depends on many factors can be summarized as follows:

1. The intensity of the light: where the current generated of the cells will increase proportionally with the intensity of the sun light.
2. The size and the number of the used solar cells, so the increase in solar cells number will cause an increase in the generated energy.
3. The temperature of the solar cells when the temperature of the solar cell increases the operating point will be decrease and so the generated power will decrease too.
4. The electrical loads that are used where the electrical loads that used must be in relation with the magnitude of the generated electrical power.

3.2.5.2 Voltage /Current Characteristics :

This figure show the relationship between the current and voltage generated of the PV:

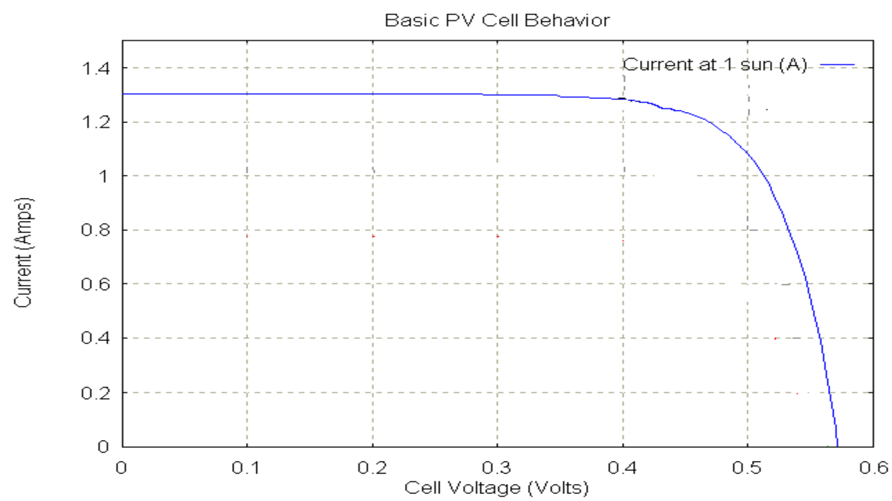


Fig. 3.4 Voltage-Current Relation Ship Curve of the Solar Cell.

The I-V curve shown above is for the type of a PV cell used in the Solar modules. So that comparisons can be made of the electrical characteristics of different PV cells these measurements are made at standard test conditions (STC) defined as alight intensity of 1000 W/m2 and a temperature of 25 °C. The graph also shows the maximum power point of the PV cell.

3.2.5.3 Voltage - Power and Current Characteristics:

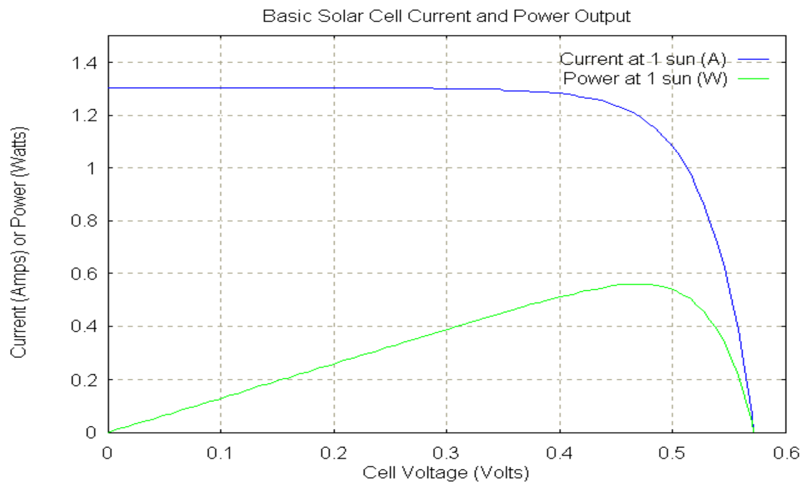


Fig. 3.5 Power – Voltage curve

The green line in the curve show the relationship between the cell voltage and the power generated from the photovoltaic cells. So we can note that the electrical power which be resulted from the solar cell increase when the output voltage of the cell increase where the electrical power can be reach to the maximum value at specific output voltage then the electrical power resulted from the solar cell will be decrease strongly until reaching zero.

3.2.6 Sizing PV System:

In order to calculate the number of the solar cells needed in this system we have to consider firstly the power needed, we decided to design the system with symmetry between the turbine and the PV since that the Sundays average and solar radiation in our land give us a suitable quantity of the power, and so the wind speed average here in our land give us a good quantity of power.

- $E = P_{in} \times T \longrightarrow$ (1) Where: E: Energy (Watt)

  P_{in}: input Power of the load and output power of the inverter (Watt)

  T: Time (Hour)

The following table shows the AC load rating:

1. AC load Watts X Hrs/Wk = Total WH/WK

AC load	Watts	X	Hrs/Wk	=	Total WH/WK
load	500	*	5*7	=	17500

2. Multiply line 1 by 1.25 to correct for inverter loss and battery efficiency.

   17500*1.25=21875

3. Inverter DC input voltage, usually 12, 24; or48 voltage .this is DC system voltage.

   12V

4. Divide line 2 by line 3.this is total amp hours per week used by AC load.

   21875/12=1822.9

5. Divide line 4 by 7 days .this is total average amp hours per day.

   1822.9/7=260.4 A

3.2.7 Solar array sizing work from [9]:

1. Total average amp hours per day from the system load work form, line 5.
   260.4
2. Multiply line 1 by 1.2 to compensate for loss from battery charge/discharge.
   260.4*1.2=312.5
3. Average sun hours per day in your area.
   9 hours
4. Divide line 2 by line 3.this is the total solar array amps required.
   312.5/9=34.7 A
5. Optimum or peak amps of solar module used. See module specification.
   2.48
6. Total number of solar modules in parallel required .divide line 4 by line 5.
   34.7/2.48=13.99
7. Round off to the next highest whole number.
   14
8. Number of modules in each series string to provide DC battery voltage:
   1

DC battery voltage	number of modules in each series string
12	1
24	2
48	4

9. Total number of solar modules required. Multiply line 7 by line 8.
   14*1=14

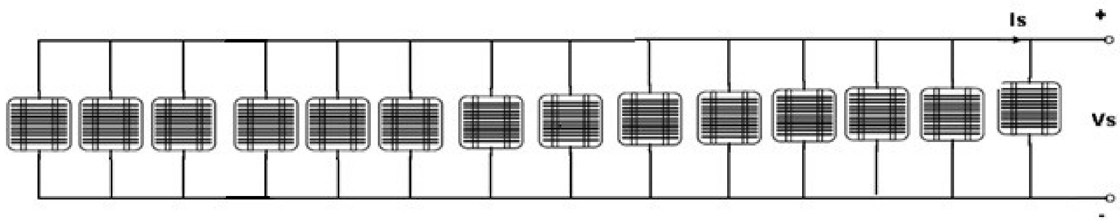


Fig3.6: Total number of solar modules

This is the calculations of the PV, so we have just to compensate the numbers in the previous equations in order to know the quantity of the PV needed in this project.

3.3 Wind Turbine:

3.3.1 Definition:

A wind turbine is a machine that converts the power in the wind into electricity to be an electrical generator. To understand the working of wind turbines we should know its working process, the actual conversion process uses the basic aerodynamic force of lift to produce a net positive torque on a rotating shaft, resulting first in production of mechanical power and then in its transformation to electricity in a generator. Wind Turbines have most of the same characteristics to every generator such as initial production so that it does not store an input power to future time nor transfer it. so that should be considered in any calculation to a system using generators.

The importance of using sustainable energy in common and especially wind turbines was referred to four points:

- A need of power in the light of diversion in the existence of the traditional resources such as fossil fuels.
- The stable existence of wind energy everywhere which could benefit that resource to generate power depending on its conditions in every area.
- The development of wind turbines that made the productivity of wind energy more efficient and easier.
- The political will to use that technological method.

3.3.2 Wind turbine components:

We will take the horizontal axis wind turbine in this project. And the principal subsystems of a typical horizontal axis wind turbine are shown in Figure 3.7. These include:

Wind Turbine components:

- The rotor, consisting of the blades and the supporting hub
- The drive train, which includes the rotating parts of the wind turbine (exclusive of the rotor); it usually consists of shafts, gearbox, coupling, a mechanical brake, and the generator
- The nacelle and main frame, including wind turbine housing, bedplate, and the yaw system
- The tower and the foundation
- The machine controls
- The balance of the electrical system, including cables, switchgear, transformers, and possibly electronic power converters
- Number of blades (commonly two or three)

- Rotor orientation: downwind or upwind of tower blade material, construction method, and profile Hub design: rigid, teetering or hinged Power control via aerodynamic control (stall control) or variable pitch blades (pitch control)
- Fixed or variable rotor speed
- Orientation by self aligning action (free yaw), or direct control (active yawl
- Synchronous or induction generator
- Gearbox or direct drive generator

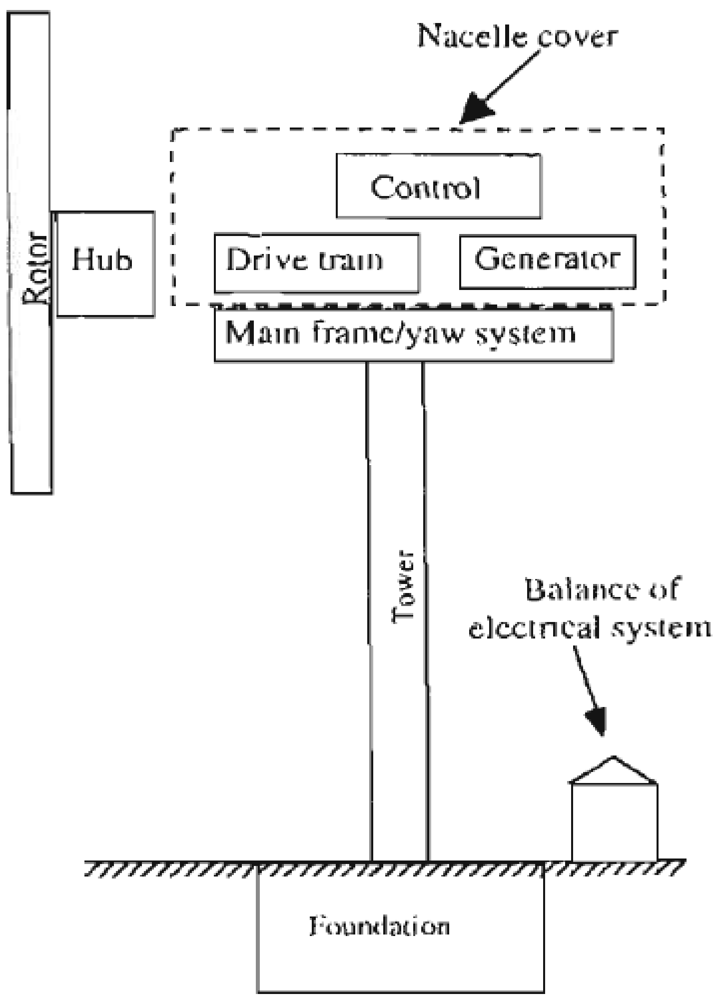


Fig. 3.7 turbine construction

3.3.3 Explanation the turbine components:

And we will take its components to describe it in details:

3.3.3.1 Rotor

The rotor consists of the hub and blades of the wind turbine. And it is considered to be the core of this elements cost. And this rotor holds two blades or three like most of the turbines today. There was single blade in the past but it was neglected due to the existence of the two and three blades today.

3.3.3.2 Drive train

It consists of the rotating parts of the wind turbine. These typically include a low speed shaft, a gearbox, and a high speed shaft. Other drive train components include the support bearings, one or more couplings, a brake, and the rotating parts of the generator. The purpose of the gearbox is to speed up the rate of rotation of the rotor from a low value to a rate suitable for driving a standard generator. Two types of gearboxes are used in wind turbines: parallel shaft and planetary for larger machines. The weight and size advantages of planetary gearboxes become more pronounced. Some wind turbine designs use specially designed, low-speed generators requiring no gearbox.

While the design of wind turbine drive train components usually follows conventional mechanical engineering machine design practice. The unique loading of wind turbine drive trains requires special considerations. Fluctuating winds and the dynamics of large rotating rotors impose significant varying loads on drive train components.

3.3.3.3 Generator

Nearly all wind turbines use either induction or synchronous generators. Both of these designs entail a constant or near-constant rotational speed of the generator when the generator is directly connected to a utility network.

The majority of wind turbines installed in grid connected applications use induction generators. An induction generator operates within a narrow range of speeds slightly higher than its synchronous speed (a four-pole generator operating in a 60 Hz grid has a synchronous speed of 1800 rpm). The main advantage of induction generators is that they are rugged, inexpensive, and easy to connect to an electrical network.

An option for electrical power generation involves the use of a variable speed wind turbine. There are a number of benefits that such a system offers, including the reduction of the wind turbine and potential operation of the wind turbine at maximum efficiency over a wind range of wind speeds, yielding increased energy capture.

Although Wind Energy Explained there are a large number of potential hardware options for variable speed operation of wind turbines, power electronic components are used in most variable speed machines currently being designed. When used with suitable power electronic converters, either synchronous or induction generators can run at variable speed.

3.3.3.4 Nacelle and yaw system

This category includes the wind turbine housing, the machine bedplate or main frame, and the yaw orientation system. The main frame provides for the mounting and proper alignment of the drive train components. The nacelle cover protects the contents from the weather. A yaw orientation system is required to keep the rotor shaft properly aligned with the wind. The primary component is a large bearing that connects the main frame to the tower.

An active yaw drive, generally used with an upwind wind turbine, contains one or more yaw motors, each of which drives a pinion gear against a bull gear attached to the yaw bearing. This mechanism is controlled by an automatic yaw control system with its wind direction sensor usually mounted on the nacelle of the wind turbine. Sometimes yaw brakes are used with this type of design to hold the nacelle in position, Free yaw systems (meaning that they can self-align with the wind) are commonly used on downwind wind machines.

Fig 3.8 Horizontal axis turbine

3.3.3.5 Tower and foundation:

This category includes the lower structure and the supporting foundation. The principal types of tower design currently in use are the free standing type using steel tubes, lattice (or truss) towers, and concrete towers. For smaller turbines, guyed towers are also used. Tower height is typically 1 to 1.5 times the rotor diameter, but in any case is normally at least 20 m. Tower selection is greatly influenced by the characteristics of the site. The stiffness of the tower is a major factor in wind turbine system dynamics because of the possibility of coupled vibrations between the rotor and tower.

For turbines with downwind rotors, the effect of tower shadow (the wake created by airflow around a tower) on turbine dynamics, power fluctuations, and noise generation must be considered. For example, because of the tower shadow, downwind turbines are typically noisier than their upwind counterparts.

3.3.4 Controls:

The control system for a wind turbine is important with respect to both machine operation and power production. A wind turbine control system includes the following components:

1- Sensors - speed, position, flow, temperature, current, voltage, etc.
2- Controllers - mechanical mechanisms, electrical circuits, and computers
3- Power amplifiers - switches, electrical amplifiers, hydraulic pumps and valves
4- Actuators - motors, pistons, magnets, and solenoids

The design of control systems for wind turbine application follows traditional control engineering practices. Many aspects, however, are quite specific to wind turbines, and are discussed in Chapter 7. Wind turbine control involves the following three major aspects and the judicious balancing of their requirements:

Setting upper bounds on and limiting the torque and power experienced by the drive train.

3.3.4.1 Introduction: Modem Wind Energy and its Origins

Maximizing the fatigue life of the rotor drive train and other structural components in the presence of changes the wind direction, speed and turbulence, as well as start-stop cycles of the wind turbine.

Maximizing the energy production, Balance of electric system In addition to the generator. the wind turbine system utilizes a number of other electrical components. Some examples are cables, switchgear, transformers, power electronic converters, power factor correction capacitors, yaw and pitch motors.

3.3.4.2 Equations and characteristics:

$$P_w = \begin{cases} 0 & V < V_{ci} \\ a * V^3 - b * P_r & V_{ci} < V < V_r \\ P_r & V_r < V < V_{co} \\ 0 & V > V_{co} \end{cases}$$

Where Pw (in W/m2): is the output power density generated by a wind turbine.

$$a = \frac{P_r}{{V_r}^3 - {V_{ci}}^3}$$

$$b = \frac{{V_{ci}}^3}{{V_r}^3 - {V_{ci}}^3}$$

P_r: rated power (w).

V: instantaneous wind speed (m/s).

V_{ci}: cut-in wind speed (m/s).

V_r: rated wind speed (m/s).

V_{co}: cut-out wind speed (m/s).

The real electrical power delivered is calculated as:

$P_{w\ out} = Pw * Aw * \eta_G$

Where:

Aw: total swept area of wind turbine in m^2.

η_G: the electrical efficiency of the wind generator.

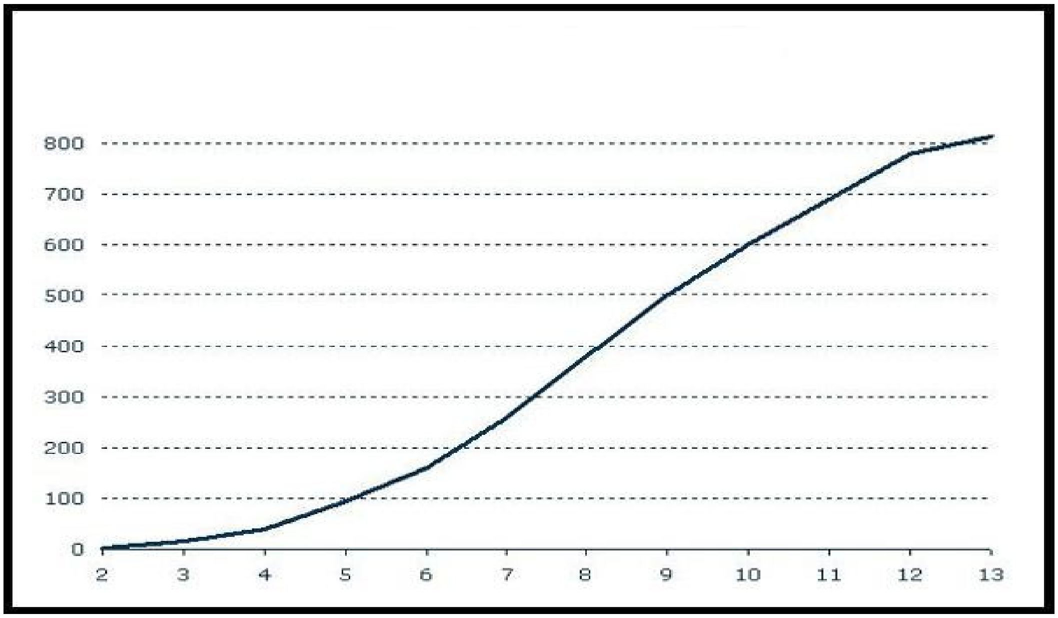


Fig.3.9 output power vs. wind speed curve.

3.4 solar charge controller:

The solar charge controller is and electrical circuit use to control and regulate the charging of the batteries.

In order to design the charge controller needed we have to consider these points:

1- Peak current produced by solar module .you can determine peak amperage if you divide the modules wattage by the peak power point voltage, usually (20-21.5). peak Amp=2.48
2- Total number of PV panels =14.
3- Your total Amp = #panels *peak Amp=14*2.48=34.7
4- Chose charge controller with an Amp rating no lower than 34.7A.

5- If the possibility of increasing the overall capacity of your solar system is anticipate, you may want to install a larger capacity charge controller.

3.4.1 Solar charge controller circuit:

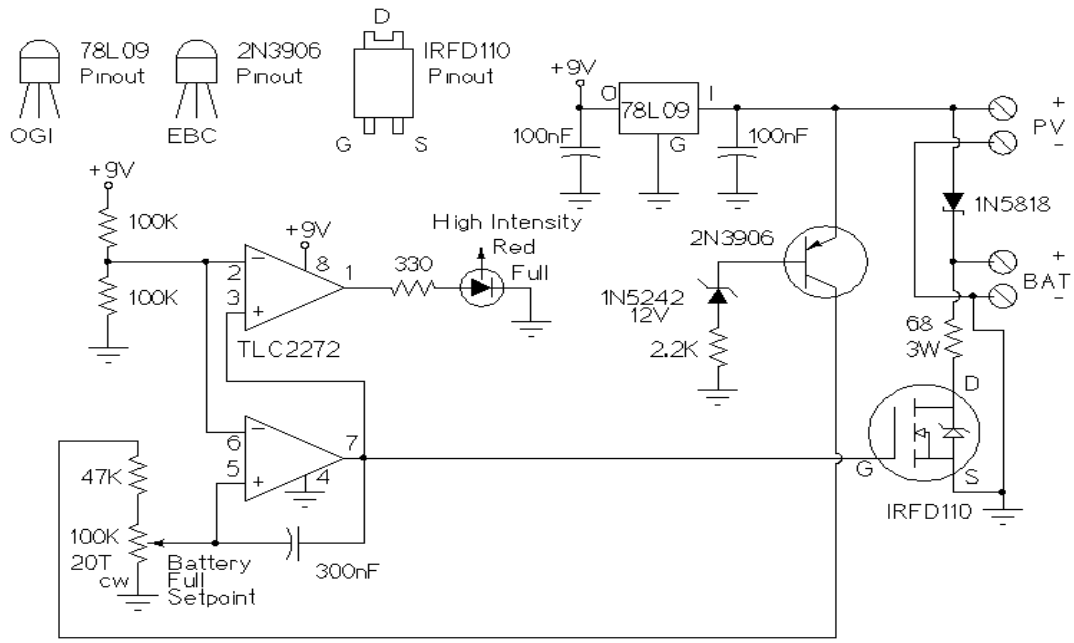


Fig3.10: Shunt-mode solar charge controller

When connecting a solar panel to the rechargeable battery, it is usually necessary to use a charge controller circuit to prevent the battery from overcharging. Charge control can be performed with a number of different circuit types. Lower power solar systems can use a series analog charge controller, an example is shown as the upper part of this circuit. Higher power systems can use a series switching charge controller or a maximum power-point (MPPT) charge controller. Series regulators control the charging current by interrupting the flow of current from the solar panel to the battery when the battery reaches a preset full voltage. MPPT controllers use an inductor for energy storage and a high frequency switching circuit to transfer the energy to the battery.

This circuit is for a shunt-mode charge controller. In a shunt-mode circuit, the solar panel is permanently connected to the battery via a series diode. When the solar panel charges the battery up to the desired full voltage, the shunt circuit connects a resistive load across the battery to absorb the excess power from the solar panel. The main advantage of shunt-mode solar regulation is the lack of a switching transistor in the power path between the solar panel and battery. Switching transistors are non-perfect devices; they waste a percentage of available solar power as heat. Inefficiency in the shunt-mode controller's switching transistor does not affect charging efficiency, it only turns on when excess power is purposely being wasted.

Another difference between series and shunt regulators is the load that the power source (solar panel) sees. In the series controllers, when the battery reaches the full point, the solar panel current path is opened up. In the shunt-mode controller, the solar panel is always presented with a load. This difference makes the shunt-mode regulator suitable for use as a regulator for a DC-output wind generator. Wind generators should always be connected to a load in order to keep the blades from spinning too fast in gusts of wind. If a wind generator is operated with no load, the rapid spinning will quickly wear out the bearings. In extreme winds, the blades can fly off of an unloaded wind generator.

Important notice:

- Solar Panel Open Circuit Voltage: 18V (36 cells)
- Solar Panel Short Circuit Current: 0-1 Amp max.

- Battery Voltage: 12V (nom.)
- Battery Capacity: 0.1 to 50 Amp Hours.

3.4.2 Theory of operation:

Solar power is routed from the PV panel through the 1N5818 Schottky diode to the battery. When the battery reaches the full set point, the output on the lower half of the TLC2272 dual op-amp turns on. This activates the IRFD110 MOSFET transistor and connects the 68 ohm 3W load resistor to the battery. The load across the battery causes the battery voltage to drop, and the comparator circuit turns back off. This oscillation continues while solar power is available. The 300nF capacitor across the op-amp slows the oscillation frequency down to a few hertz. The two 100K resistors in series provide a regulated 4.5V reference point for use as comparator reference points.

The 2N3906 transistor is wired with a zener diode in its base circuit, when the PV voltage is above 12V, the 2N3906 transistor turns on and enables the comparator circuit. The upper half of the TLC2272 op-amp inverts the dump load control signal, this is used to power the high intensity red LED. The LED turns on when the battery reaches the full set point. The LED does not waste any useful charging power since it only turns on when the battery is full.

The 78L09 IC provides 9V regulated power to the comparator circuitry. Operational power for this circuit is provided entirely from the PV panel, there is virtually no power taken from the battery at night.

This circuit can be modified for higher amperage by replacing the 1N5818 diode, 68 ohm load resistor and IRFD110 MOSFET with higher power components. If the load resistor is connected directly across the PV panel at noon on a sunny day, the PV output voltage should drop to 12V or less. Higher power PV panels will require a resistor with lower ohms and a higher wattage rating. In cold climates, it may be useful to use the load resistor's heat to keep the battery warm.

Operation of a high power version of this circuit with a wind generator should be possible, although the author has not tried this. For a 20 amp version of this circuit, the IRFD110 MOSFET should be replaced with an IRFZ44N and the 1N5818 schottky diode should be replaced with a 20L15T. Both of these parts should have large heat sinks. The 68 ohm/3W resistor should be changed to a much larger resistor, an 0.6 ohm/250W resistor would be able to handle 20 amps at 12V.

3.5 Battery sizing:

This type of work sheet helps determine what size batteries are required for your system. Battery size is measured in AMP-HOURS. This is a measure of battery capacity.

All lead-acid batteries have a nominal output of 2 volt per cell. Actual cell voltage varies from about 1.7 volts at full discharge to 2.4 volts at full charge12 volt lead-acid batteries are made of 6 separate cells in one case. 6 volt batteries are made of 3 cells in one case. Industrial 2 volt signal-cell batteries are also used in a series for larger application. Series connection is where the positive terminal of one battery is connected to the negative terminal of another, resulting in increased voltage. Putting battery cells in parallel (positive to positive and negative to negative) increase (amps) amp-hour capacity, but do not affect voltage So we needed ten batteries each one has the following specifications:

12 V DC, 104 Amp. Hour, 0.8 deep cycle, sun rise model.

Table3.1: Constant battery at average temperature

Temperature (C)	27.6	21.2	15.6	10.0	4.4	-1.1	-6.7
Multiplier	1.00	1.04	1.11	1.19	1.30	1.40	1.59

3.6 Inverters

3.6.1 Introduction

A photovoltaic (PV) array, regardless of its size or sophistication, generates only direct current (DC) electricity. Fortunately, there are many applications for which direct current is perfectly suitable. Even more fortunately, DC electricity can be converted to alternating current AC with relative ease and efficiency through the use of a piece the equipment called an inverter.

Inversion is the conversion of dc power to ac power at a desired output voltage or current and frequency. A static semiconductor inverter circuit performs this electrical energy inverting transformation. The terms voltage-fed and current-fed are used in connection with the output from inverter circuits. It is the inverter that makes PV technology compatible with the type of equipment and appliances encountered in the average home and pump applications

A voltage-source inverter (VSI) is one in which the dc input voltage is essentially constant and independent of the load current drawn. The inverter specifies the load voltage while the drawn current shape is dictated by the load.

Inverters are nothing new. They have been around as long as there has been a need for converting DC into AC electricity. The early rotary type of inverter had internal moving parts. The DC electrical source powered a DC motor connected to an AC alternator, which produced AC electricity for the load. Rotary inverters are still manufactured largely for use marine are aircraft electrical system were a clean AC signal desired and efficiency is not critical.

Virtually all the inverters used with alternative power system transistorized solid-state devices. Solid-state inverters are preferred for their higher efficiency, ease of maintenance, and infrequency of reaper. Broadly speaking, these inverters maybe divided into two categories: Stand alone (SA) and utility-interactive (UI), or lined-tied.

Types of inverters:

1. Single phase inverter.
   a) Half-wave inverter.
   b) Full-wave inverter.
2. Three phase inverter.

In this project used single phase inverter full wave convert battery voltage (12v Dc) to mains voltage (230v Ac). They are very convenient, as they allow the use of standard "mains" appliances on a DC (battery) system.

3.6.2 Basic design:

In one simple inverter circuit a switch is rapidly switched back and forth to allow current to flow back to the DC source following two alternate paths through one end of the primary winding and then the other. The alternation of the direction of current in the primary winding of the transformer produces alternating current (AC) in the secondary circuit. Figure 3.11 shows an H-bridge inverter (VSI) for producing an ac voltage and employing switches which may be transistors (MOSFET or IGBT), or at high powers, thyristors (GTO or GCT).

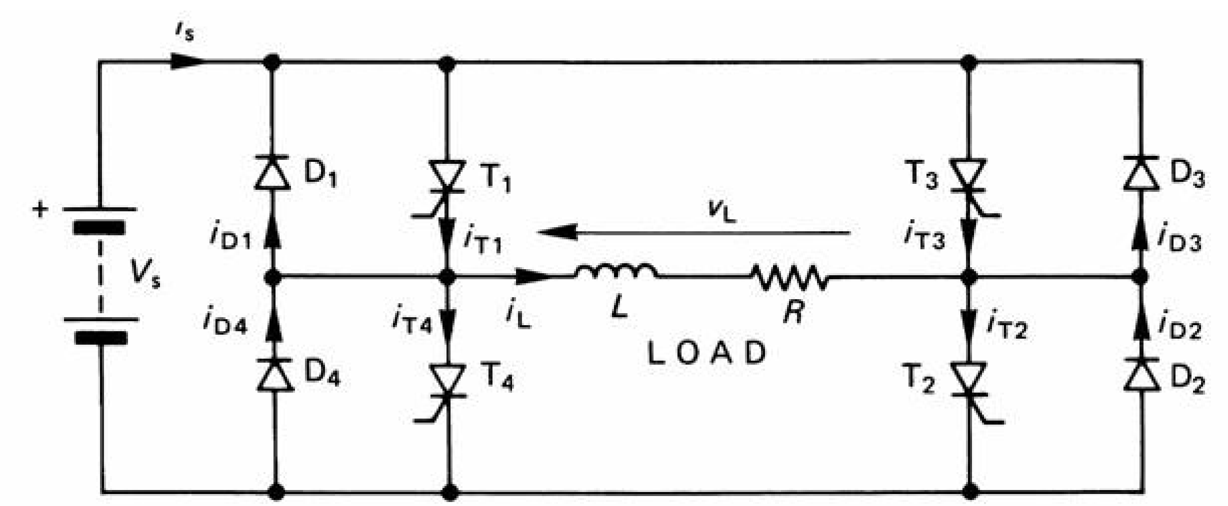


Fig 3.11: an H-bridge inverter (VSI).

The electromechanical version of the switching device includes two stationary contacts and a spring supported moving contact. The spring holds the movable contact against one of the stationary contacts and an electromagnet pulls the movable contact to the opposite stationary contact. The current in the electromagnet is interrupted by the action of the switch so that the switch continually switches rapidly back and forth. This type of electromechanical inverter switch, called a vibrator or buzzer, was once used in vacuum tube automobile radios. A similar mechanism has been used in door bells, buzzers and tattoo guns.

As they became available with adequate power ratings, transistors and various other types of semiconductor switches have been incorporated into inverter circuit designs.

3.6.3 circuit waveforms:

Using Fourier analysis, periodic waveforms are represented as the sum of an infinite series of sine waves. The sine wave that has the same frequency as the original waveform is called the fundamental component. The other sine waves, called harmonics that are included in the series have frequencies that are integral multiples of the fundamental frequency fig 3.12.a.

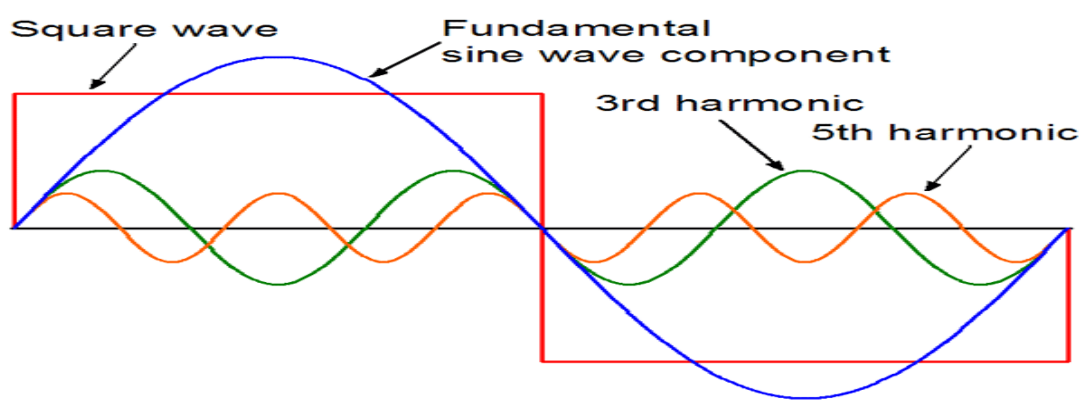


Fig 3.12.a: Square waveform with fundamental sine wave component, 3rd harmonic and 5th harmonic.

Device conduction patterns are also shown in figures 3.12b and c. With inductive loads (not purely resistive), stored energy at turn-off is fed through the bridge reactive feedback or freewheel diodes D1 to D4. These four diodes clamp the load voltage to within the dc supply voltage rails (0 to Vs).

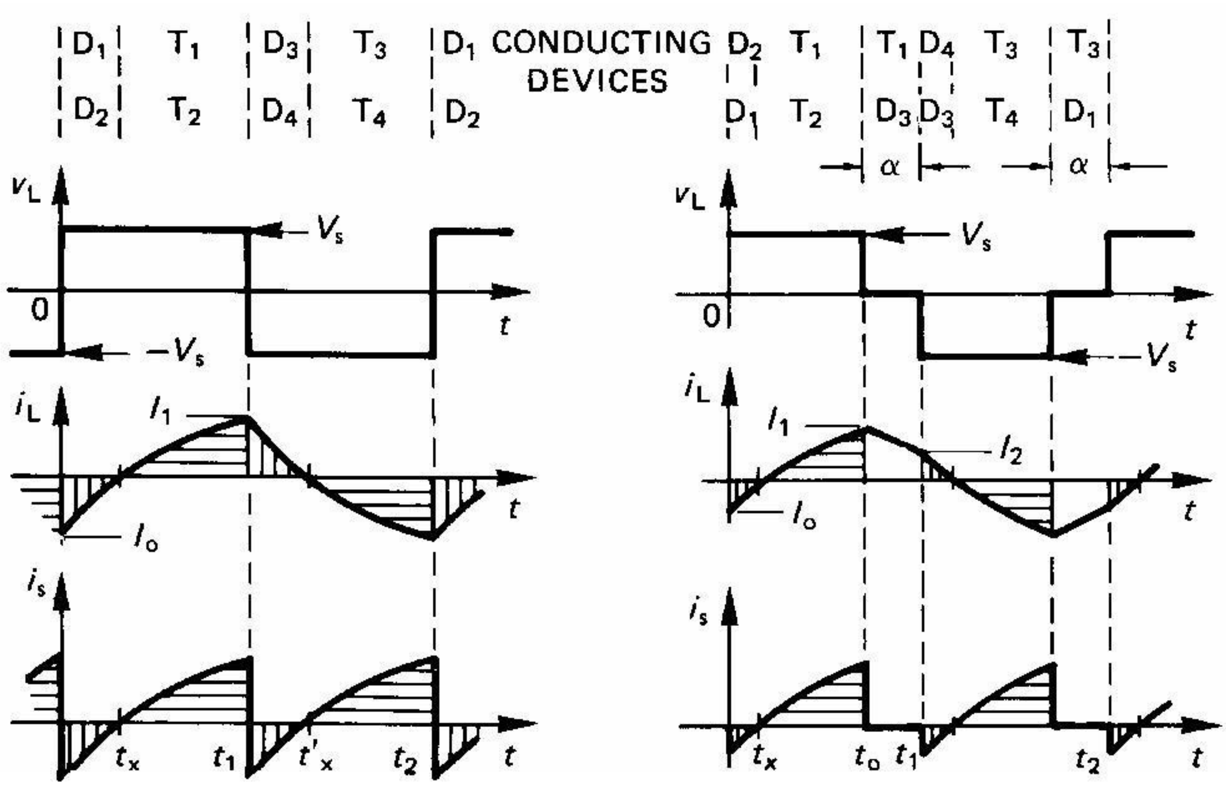


Fig 3.12.b and c

The quality of output waveform that is needed from an inverter depends on the characteristics of the connected load. Some loads need a nearly perfect sine wave voltage supply in order to work properly. Other loads may work quite well with a square wave voltage.

Chapter Four

Controlling the System

This technique deals with the control of the output power of a solar/wind stand-alone system. The control system regulates the generation of the wind subsystem in order to satisfy, jointly with the photovoltaic generation subsystem, the load and battery charge power demand. The controller is designed using a theoretical framework that unifies passivity and sliding mode techniques. The resultant control law does not need wind measurement and only relies on rotational speed and current measurements. An analysis of the acceleration estimate error is carried out and a countermeasure to compensate its effects is proposed. Finally, the performance of the controller is assessed through computer simulation, using a comprehensive nonlinear model of the plant.

4.1 Introduction

Estimates by the World Bank claim that as much as 40% of the world's population still lives in villages not tied to the utility grid. To supply these villages with electricity, it is often most feasible to give them an independent source of power than invest in transmission lines to connect them to the utility grid. For villages farther than 3 km from the nearest transmission line, it is usually economically more convenient to use a wind-based stand-alone system.

Renewable energy sources essentially have unpredictable random behaviors. However, some of them, like solar radiation and wind speed, have complementary profiles. Stand-alone hybrid systems usually take advantage of this particular characteristic combining photovoltaic (PV) panels and windmills, in conjunction with a diesel-powered backup generator. However, diesel generators demand fuel supply, then their use in isolated areas can be troublesome and, in comparison with renewable energy sources, uneconomical . In some applications, they can be avoided by including in the system adequate energy storage devices, like battery banks. Since storage cost still represents the major economic restraint, usually PV/wind systems are appropriately sized to minimize its requirements. Also, wind power is lower in cost than PV power approximately by a factor of five, so it often gets the main role in generation.

This technique presents a new strategy to regulate the output power of the hybrid system by controlling the power generated by the wind subsystem. Thus, the prime control objective is to regulate the wind power generation in order to satisfy the load and battery charge power requirements. It is important to remark that the proposed controller only relies on rotational speed and current measurements, and does not need wind measurement.

4.2 Wind turbine aerodynamics

The mechanical power captured by a wind turbine is proportional to the swept area (A), the air density(ρ) the cube of the wind speed (V), and the power coefficient. This coefficient (C_p) expresses the conversion efficiency of the turbine and is usually given as a function of the tip-speed ratio.

$$\lambda = \frac{r\omega_m}{V} \qquad (1)$$

Where r is the blade length and ω_m the angular shaft speed. Thus, the mechanical power generated by a turbine may be written as:

$$P_t = \frac{C_p(\lambda)\rho A v^3}{2} \qquad (2)$$

The power extracted from the wind can only be maximized provided that the power coefficient is maximized. It is important to $C_p(\lambda)$ remark that has a unique maximum at a constant value of λ , called the optimal tip-speed ratio From (2), it is straightforward to obtain the expression of λopt the driving torque:

$$T_t = \frac{P_t}{\omega_m} = \frac{C_t(\lambda)\rho A v^3}{2} \qquad (3)$$

Where $C_t(\lambda)$= $C_p(\lambda)/\lambda$ is the torque coefficient of the turbine.

4.3 Hybrid System Modeling

The wind turbine of the stand-alone hybrid system already presented in the main figure, drives a multi-polar PMSG whose terminal voltage equations can be described by the following matrix expression:

$$v_{abc} = R_{s\ abc}\, i_{abc} + s\emptyset_{m\ \ abc} \qquad (4)$$

Where R_s is the stator phase winding resistance matrix . $\emptyset_m$ is the matrix of flux linked by the stator windings, and is the Laplace operator. Expressing this model in a rotor reference frame, (4) can be written as:

$$v_q = -R_s i_q - L_q s i_q - \omega_e L_q i_d + \omega_e \emptyset_m \qquad (5a)$$

$$v_d = -R_s i_d - L_d s i_d - \omega_e L_d i_q \qquad (5b)$$

and the electromagnetic torque is given by:

$$T_e = \frac{3P(\emptyset_m i_q + \left(L_d - L_q\right) i_q i_d)}{4} \qquad (5c)$$

Where L_q and L_d are the stator inductances in the d-q axes, $\omega_e = P\omega_m/2$ is the electrical angular speed, and P is the number of poles.

As it showed in the block diagram in chapter one, the generator is linked to the dc bus through a diode bridge rectifier and a dc/dc converter. This configuration presents to the PMSG terminals a pure active power load whose value can be modified through the duty cycle (δ) of the converter.

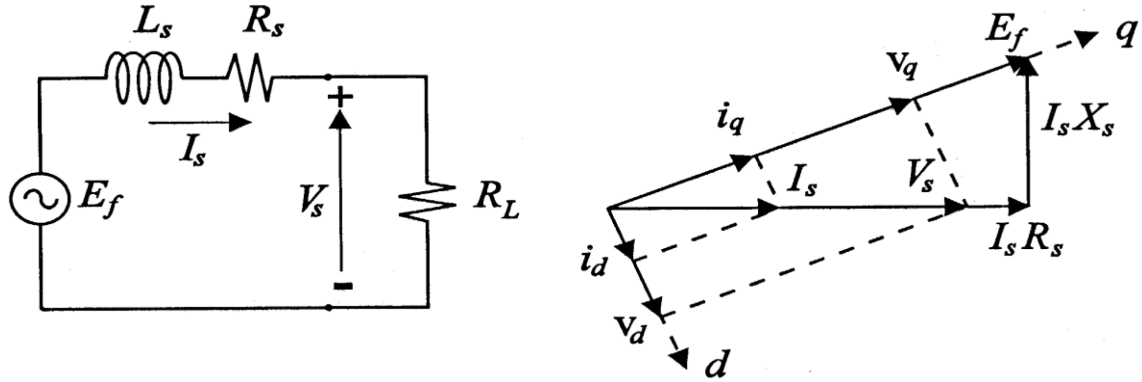


Fig. 4.1 Per-phase circuit and phasor diagram of the generator.

Fig. 4.1 shows a simple per phase equivalent circuit of the PMSG working under this condition and its corresponding phasor diagram V_s and I_s are the line voltage and current in the PMSG terminals, respectivelyE_f, corresponds to the *emf* in the stator windings and Xs is the synchronous reactance. From this last figure, using simple mathematical relationships, (5.a) and (5.b) can be expressed in terms of the terminal PMSG voltage, as:

$$\frac{V_s i_q}{\sqrt{i_q^2 + i_d^2}} = -R_s i_q - L_q s i_q - \omega_e L_q i_d + \omega_e \emptyset_m \qquad (6a)$$

$$\frac{V_s i_d}{\sqrt{i_q^2 + i_d^2}} = -R_s i_d - L_d s i_d - \omega_e L_d i_q \qquad (6b)$$

Then, assuming a full bridge topology for the dc/dc converter, the relationship between the voltage on the dc bus terminals v_b and V_s can be described by the following expression:

$$V_s = \frac{\pi v_b u_x}{3\sqrt{3}} \qquad (7)$$

Where u_x is a simple function of the dc/dc converter duty cycle, given for this configuration u_x =κtr/ δ by, with the winding ratio of the transformer included in the dc/dc converter. Thus, replacing (7) in (6) and operating, the latter can be rewritten as:

$$\dot{i}_q = -\frac{R_s}{L} i_q - \omega_e i_d + \frac{\omega_e \emptyset_m}{L} - \frac{\pi v_b i_q u_x}{3L\sqrt{3\left(i_q^2 + i_d^2\right)}} \qquad (8a)$$

$$\dot{i}_d = -\frac{R_s}{L} i_d - \omega_e i_q - \frac{\pi v_b i_d u_x}{3L\sqrt{3\left(i_q^2 + i_d^2\right)}} \qquad (8b)$$

Assuming an ideal static conversion, the current injected by the wind subsystem in the dc bus can be readily determined equating the input and output power of the dc/dc converter. This yields:

$$i_0 = \frac{\pi\sqrt{i_q^2 + i_d^2}\, u_x}{2\sqrt{3}} \qquad (9)$$

As it was previously said, this paper deals with the regulation of the output power of the system by focusing in the control of the wind subsystem. The control design of the photovoltaic subsystem is not under consideration here, so its operation is represented by a variable but measurable current i_f injected in the dc bus. Similarly, assuming an ideal voltage inverter, the load demand can be referred to the dc side as a measurable output current i_l . Therefore, the current across the battery bank can be written as:

$$i_b = \frac{\pi\sqrt{i_q^2 + i_d^2 u_x}}{2\sqrt{3}} + i_f - i_L \qquad (10)$$

Where i_f and i_L are measurable currents, and thus, assumed to be known currents. To complete the dynamic model of the system, it is necessary to outline the mechanical dynamic equation of the wind subsystem.

Neglecting the friction term, this equation is given by:

$$\omega_e = \frac{P(T_t - \dot{T}_c)}{2J} \qquad (11)$$

Where J is the inertia of the rotating system and is the turbine torque, Thus, replacing (5c) in (11) and considering that in radial flux PMSGs it holds Ld ≈Lq ≈Ls≈L. (11) can be rewritten as:

$$\omega_e = \frac{P\left(\frac{\dot{T_t} - 3P\emptyset_m i_q}{4}\right)}{2J} \qquad (12)$$

Therefore, considering (8), (10), and (12), and modeling the battery bank as a voltage source E_b connected in series with a resistance R_b and a capacitance C_b , a complete nonlinear dynamical model of the hybrid system may be written as:

$$\ddot{i_q} = -\frac{R_s}{L} i_q - \omega_e i_d + \frac{\omega_e \emptyset_m}{L} - \frac{\pi v_b i_q u_x}{3L\sqrt{3\left(i_q^2 + i_d^2\right)}} \qquad (13a)$$

$$\dot{i_d} = -\frac{R_s}{L} i_d - \omega_e i_q + \frac{\omega_e \emptyset_m}{L} - \frac{\pi v_b i_q u_x}{3L\sqrt{3\left(i_q^2 + i_d^2\right)}} \qquad (13b)$$

$$\dot{\omega_e} = \frac{P}{2J}\left(T_t - \frac{3}{2}\frac{P}{2}\emptyset_m i_q\right) \qquad (13c)$$

$$\dot{v_c} = \frac{1}{c_b}\left(\frac{\pi}{2\sqrt{3}}\sqrt{i_q^2 + i_d^2} u_x + i_f - i_L\right) \qquad (13d)$$

Where v_c is the voltage in the capacitor C_b , and the voltage on the dc bus terminals is given by :

$$v_b = E_b + v_c + \left(\frac{\pi}{2\sqrt{3}}\sqrt{i_q^2 + i_d^2} u_x + i_f - i_L\right) R_b \qquad (14)$$

Fig. 4.2 shows in the torque shaft speed plane, the turbine torque T_t developed by a horizontal shaft turbine parameterized in terms of the wind speed (dashed line) and the generator torque Te curves parameterized in function of Vs in solid line. It is interesting to note that for a given constant voltage in the PMSG terminals, there exists a minimum shaft speed below which the wind subsystem cannot generate. This lower limit arises naturally from the analysis of the phasor diagram depicted in Fig. 4.1, since it cannot be built for speeds that induce E_f smaller than Vs. Its expression is obtained in through the steady state analysis of a similar topology, and can be written for the electrical angular speed as:

$$\omega_{e\ lim} = \frac{V_s}{\emptyset_m} = \frac{\pi v_b u_x}{3\sqrt{3}\emptyset_m} \qquad (15)$$

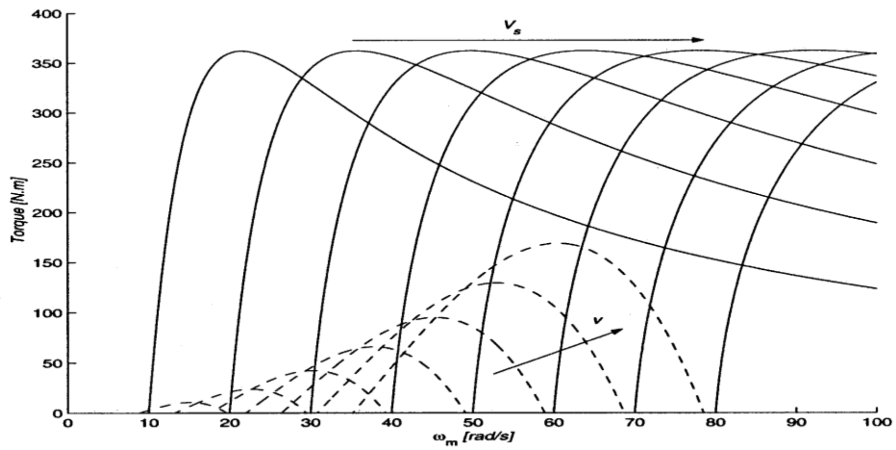


Fig. 4.2 Turbine and PMSG torque-shaft speed.

4.4 Design of Passivity/Sliding mode Controller

4.4.1 Control Law Without Wind Measurement

The primary objective is to control the power generated by the wind subsystem in order to satisfy the total power demand (i.e., it must adequately complement the PV generated power to satisfy the external load and battery charge power requirements). Thus, during wind regimes of sufficient generation, the system can meet the load demand and, in addition, store energy to be used in periods of insufficient generation. However, during insufficient wind regimes (i.e., when the power available in the wind is not enough to satisfy the total power demand), the control objective must be changed to maximize the wind power generation. Both control objectives can be condensed in a unique sliding manifold, given by:

$$h(x) = P_{ref} - T_e\omega_m = 0 \qquad (27)$$

where P_{ref} is the power reference, which is modified depending on the generation conditions and the total power demand (load plus battery). Fig. 4.2 depicts, in the shaft speed-torque plane, the reference power P_{ref} parameterized in terms of the power demanded from the wind. The hyperbolas describe P_{ref} during sufficient wind regimes, while the parabolic limit corresponds to operation under insufficient wind regimes (i.e., maximum wind power generation locus). Then, the power reference for sufficient wind regimes can be expressed as:

$$P_{ref} = v_b\left(i_L + I_{bref} - i_f\right) \qquad (28)$$

Where I_{bref} is the reference for the charge current of the battery bank, which varies according with its state of charge, and i_L and i_f are measurable currents.

On the other hand, the expression of the P_{ref} for insufficient wind regimes is obtained from (3), by maximizing the conversion efficiency (i.e., for $\lambda=\lambda_{opt}$). It yields:

$$P_{ref} = K\omega_m^3 \qquad (29)$$

Where $\mathrm{K} = \mathrm{Ct}\ (\lambda opt)\rho \mathrm{A}\, r^3/2\lambda^2 opt$.

Now, it is important to establish a way to decide when to use (28) or (29) to compute P_{ref} For this purpose, it is possible to find an expression for the shaft speed which determines the boundary between sufficient an insufficient generation. It can be readily obtained by equating (28) and (29). The boundary shaft speed results :

$$\omega_{m\ SW} = \sqrt[3]{\frac{v_b\left(i_L + I_{bref} - i_f\right)}{K}} \qquad (30)$$

Then, it is important to note that the decision on the power reference expression does not relay on wind measurement but only on shaft speed measurement.

Up to this point, the input of system (13) is u_x . However, the injection of a switched control signal through that input would produce undesirable wide variations in T_e. This would result in an important ripple in the generated power of the wind subsystem. To avoid this problem, a dynamic extension is proposed, including an integrator previous to the input u_x . Then u_x , becomes a new state variable and the integrating signal ω is the new control input of the extended system. In this way, the switched control signal is filtered, reducing the ripple [14]. Thus, the dynamic model of the extended system is expressed by (13a)–(d) plus the next expression:

$$u_x = w \qquad (31)$$

For the design of the control law, according with the passivity sliding mode theory $h(x)$, must be expressed in function of the state variables. That is :

$$h(x) = \frac{P_{ref} - 3\emptyset_m i_q w_e}{2} = 0 \qquad (32)$$

However, some inconveniences may arise. It can be seen that this surface does not have unitary relative degree, consequently, it does not fulfill the transversality condition. One possible solution could be to redefine the sliding surface incorporating the temporal derivative of $h(x)$ on it and, thus, creating a dynamic sliding regime. Regretfully, this would result in expressions for the discontinuous control extremely long and complex. In addition, they would involve detailed information of the turbine, which normally is not available. These problems can be avoided by maintaining the sliding manifold given by (32) and using a linear approximation for the generator torque, like:

$$T_c = \frac{3P\emptyset_m^2(\omega_e - \omega_{elim})}{4R_s} \qquad (33)$$

In this way, the relative degree one is attained and the discontinuous control expressions are much more simple and easy to handle, without a significant loss of accuracy. It is important to remark that the proposed approximation is suitable for a wide range of the PMSGs in wind applications. Now, substituting (33) in (27), the resultant control law is:

$$w = \frac{sgn(h)\sqrt{\sum_{i=1}^{4} f_i^2}}{4} \times \left[f_3 \frac{\frac{18\emptyset_m}{\sqrt{3}\pi v_b} - \frac{18KR_s\omega_e}{\sqrt{3}\pi v_b \emptyset_m}\frac{SW}{2} - \frac{u_x}{\omega_e}}{\sqrt{\sum_{i=1}^{4} f_i^2}} + sgn(h) \right]^2 \qquad (34)$$

Where $Sw = [1 - sgn(\omega_m - \omega_m sw)]$ and f_i^2 corresponds to each element of the drift field of the model. Note that the presence of the factor Sw in the control law is taking into account the change of P_{ref} , due to operation under sufficient or insufficient wind regimes.

There is still a problem to be overcome before being able to compute the control action (34). This problem is the calculation of factor f_3 . From the right hand side of (13c), it can be seen that its computation would require accurate information of the turbine and a wind speed measurement. However, given that f_3 is directly related with the shaft acceleration ω_m , a practical approximation can be readily obtained by employing a digital encoder, to measure the shaft speed, and then using a practical differentiator, to estimate the electrical acceleration. A suitable practical differentiator can be implemented through the following linear filter:

$$G_d(s) = \frac{sP}{2(sT_d + 1)^2} \qquad (35)$$

Where T_d has to be chosen regarding the mechanical dynamics of the rotating parts, given by (13c), and $P/2$ corresponds to the conversion factor between mechanical and electrical speed.

4.4.2 Acceleration Estimate Error Compensation

It may happen that, under certain extreme circumstances, the acceleration estimation error can weaken the discontinuous control values, rendering them insufficient to cancel the internal forces that drive the system away of the sliding manifold. This can be counteracted by using in (34), not only the electrical acceleration estimate f_3 obtained from the differentiator, but also an extra factor to cover the effects of estimation errors. Then, the proposed practical value of f_3 for implementation becomes:

$$\hat{f}_3 + sgn(\hat{f}_3)\mu \qquad (36)$$

Where μ is a positive function that can be designed through the following stochastic analysis of the acceleration estimate error. Considering a digital encoder of N_T slots, the most accurate method to measure low speeds presents an absolute error distributed uniformly in the interval given by:

$$\left|E_{\omega_m}\right| \leq \frac{\omega_m^2 N_T}{2\pi} \qquad (37)$$

Where T is the period of an auxiliary pulse train used to take the measurement. The period between measurements is shaftspeed dependent and it is determined by the interval between consecutive slots:

$$T_s = \frac{2\pi}{N\omega_m} \qquad (38)$$

Thus, the power spectrum density of the electrical speed measurement error can be obtained as:

$$S_{e_w}(\omega) = \frac{T_s}{3}\left(\frac{\omega_e^2 PN\tau}{4\pi}\right)^2 \left(\frac{\sin\left(\frac{\omega T_s}{2}\right)}{\frac{\omega T_s}{2}}\right)^2 \qquad (39)$$

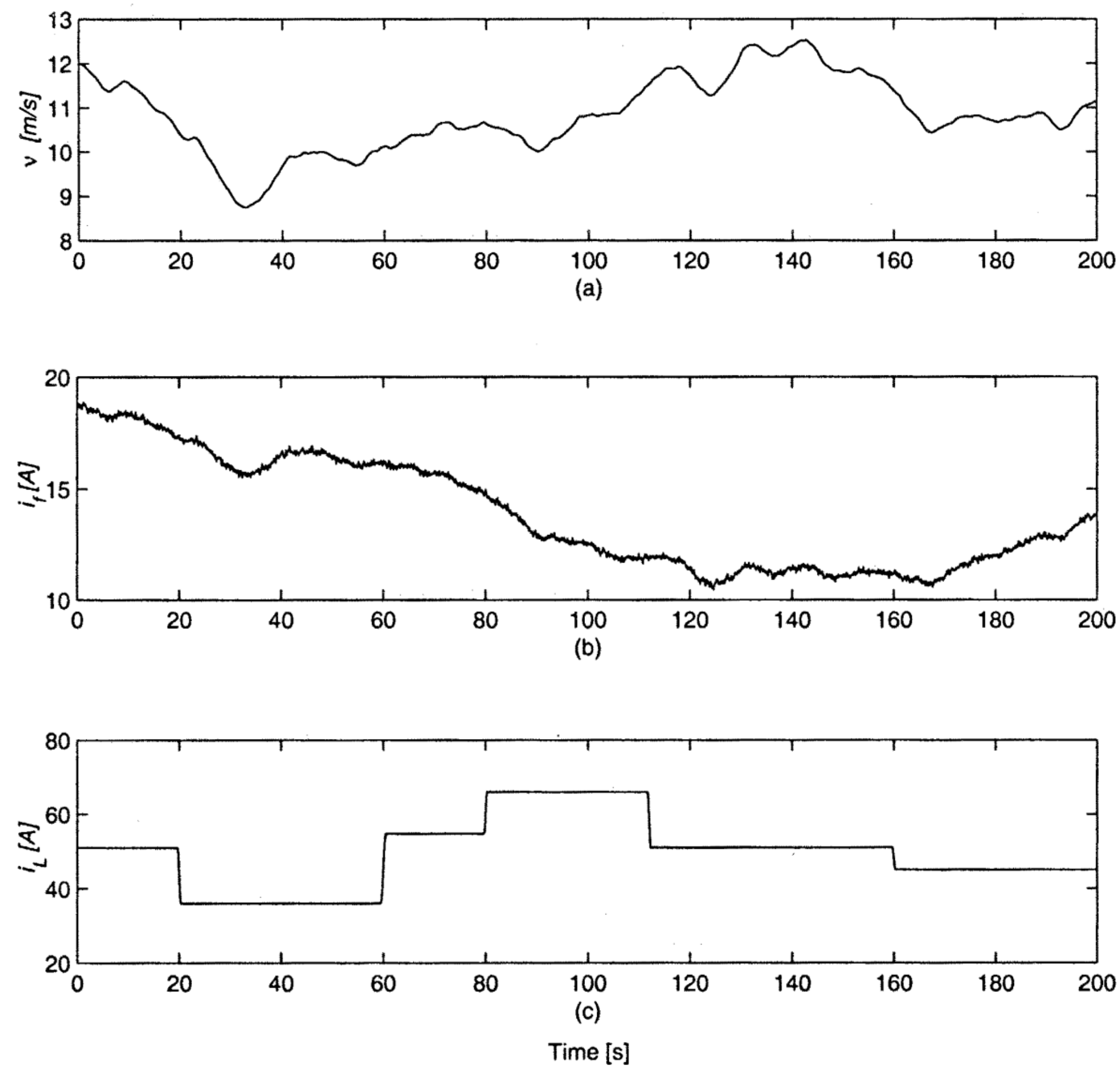


Fig. 4.3. (a) Wind speed _. (b) Current injected in the dc bus by the PV subsystem $\ddot{i}_f$.

(c) Load current referred to the dc bus side $\ddot{i}_L$.

Then, the power spectrum density of the acceleration error is:

$$S_{e_a}(\omega) = \frac{T_s}{3}\left(\frac{\omega_e^2 P N_T}{4\pi}\right)^2 \left(\frac{\sin\left(\frac{\omega T_s}{2}\right)}{\frac{\omega T_s}{2}}\right)^2 \frac{\omega^2}{((\omega T_d)^2 + 1)^2} \qquad (40)$$

4.5 Conclusion

A control strategy based on passivity and sliding mode techniques was developed in order to regulate the power output of a stand-alone hybrid system, which comprises wind and photovoltaic generation, a battery bank, and is intended for ac supply. The proposed strategy does not rely on wind measurement, yet it is capable of controlling the system during sufficient and insufficient wind regimes. This is a significant feature because controllers designed for complex control objectives, usually, require information of the wind. The design based on passivity sliding mode theory yields to a variable-structure minimum-effort control law. It possesses the characteristic robustness of the sliding mode while its minimum-effort nature grants a significant reduction of the output power chattering.

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