CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Literature review is the source of knowledge and information that we have get. We have to investigate the history of some equipment or components or materials which are involved in Instrumentation and Control course. So that, we have searched some journals for the equipment or components or materials. Then we have read and analysis how to use them, how their operation and what benefits we can get from them if we use them

A literature review is a body of text that aims to review the critical point of current knowledge includes substantive finding as well as theoretical and methodological contributions to a particular topic. Literature review are secondary sources, and as such, do not report any new or original experiment work. A well-structured literature review is characterized by a logical flow a of ideas, current and relevant references with consistent, appropriate referencing style, proper use of terminology and an unbiased and comprehensive view of the previous research on the topic.

2.2 Solar Energy

Solar energy is the light and radiant heat from the Sun that influences Earth's climate and weather and sustains life. Solar power is sometimes used as a synonym for solar energy or more specifically to refer to electricity generated from solar radiation. Solar radiation is secondary resources like as wind and wave power, hydroelectricity and biomass account for most of the available flow of renewable energy on Earth. Solar energy technologies can provide electrical generation by heat engine or photovoltaic means, space heating and cooling in active and passive solar buildings, potable water via distillation and disinfection, day lighting, hot water, thermal energy for cooking, and high temperature process heat for industrial purposes.

Solar energy refers primarily to the use of solar radiation for practical ends. All other renewable energies other than geothermal derive their energy from energy received from the sun. Solar technologies are broadly characterized as cither passive or active depending on the way they capture, convert and distribute sunlight. Active solar techniques use photovoltaic panels, pumps, and fans to convert sunlight into useful outputs.

Passive solar techniques include selecting materials with favorable thermal properties, designing spaces that naturally circulate air, and referencing the position of a building to the Sun. Active solar technologies increase the supply of energy and are considered supply side technologies, while passive solar technologies reduce the need for alternate resources and are generally considered demand side technologies.

2.2.1 Review of Photovoltaic Energy

A definition of a photovoltaic (PV) system is a system that converts directly solar radiation into electricity. Since it was first found, in 1839 by Edmond Becquerel, and after improvements made in the almost 100 following years, the photovoltaic energy has raised a constantly growing interest all over the world, The possibility to generate electrical energy in practically any place in the world was extremely appealing. With the major drawback of the high cost of solar cells, the almost exclusive use of PV energy was made by space industry to fuel satellites, where no budget constraints were applied. The efficiency of solar cells more than double from 6% in 1954 to 13.5%, but still too expensive. Today the top efficiency of silicon cells is around 27.6%.

Ironically, it was in offshore oilrigs and isolated on-shore gas and oil fields, among others, where PV systems were used, replacing the toxic and short-lived batteries. Nowadays, total PV installed capacity is estimated to reach 50.9 GWp, representing a growth of 62.1% comparing to 2010. The continuously increasing price of oil, the global warming. the Kyoto Protocol, and the recent nuclear disaster that occurred in Fukushima Japan, turns the attention of the world to renewable energies.

2.2.2 Functional of Solar Energy

Photovoltaic energy is the conversion of sunlight into electricity. A photovoltaic cell, commonly called a solar cell or PV, is the technology used to convert solar energy directly into electrical power.

Sunlight is composed of photons, or particles of solar energy. These photons contain various amounts of energy corresponding to the different wavelengths of the solar spectrum. When photons strike a photovoltaic cell, they may be reflected, pass right through, or be absorbed. Only the absorbed photons provide energy to generate electricity.

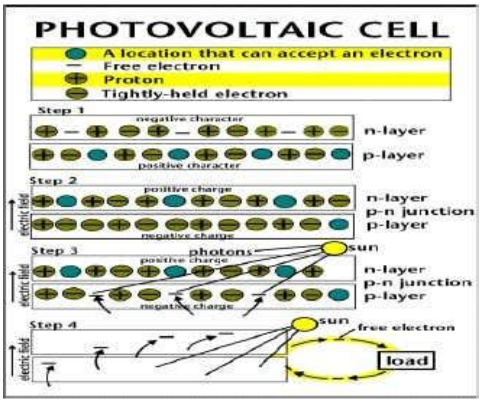

Figure 2.1 Photovoltaic cell

When enough sunlight energy is absorbed by the material that is a semiconductor, electrons are come out from the material's atoms. Special treatment of the material surface during manufacturing makes the front surface of the cell more receptive to free electrons, so the electrons naturally migrate to the surface. When the electrons leave their position, holes are formed.

When many electrons, each carrying a negative charge, travel toward the front surface of the cell, the resulting imbalance of charge between the cell's front and back surfaces creates a voltage potential like the negative and positive terminals of a battery. When the two surfaces are connected through an external load, electricity flows. Photovoltaic cells, like butteries, generate direct current (DC) which is generally used for small loads like electronic equipment.

When DC from photovoltaic cells is used for commercial applications or sold to electric utilities using the electric grid, it must be converted to alternating current (AC) using inverters. Advantages of photovoltaic systems are:

1. Conversion from sunlight to electricity is direct, so that bulky mechanical generator systems are unnecessary.
2. PV arrays can be installed quickly and, in any size, required or allowed
3. The environmental impact is minimal, requiring no water for system cooling and generating no by-products.

2.3 Solar Irradiance

Total solar irradiance is defined as the amount of radiant energy emitted by the Sun over all wavelengths that fall each second on 11 sq ft (1 sq m) outside the earth's atmosphere.

By way of further definition, irradiance is defined as the amount of electromagnetic energy incident on a surface per unit time per unit area. Solar refers to electromagnetic radiation in the spectral range of approximately 1-9 ft (0.30-3 m), where the shortest wavelengths are in the ultraviolet region of the spectrum, the intermediate wavelengths in the visible region, and the longer wavelengths are in the near infrared. Total means that the solar flux has been integrated over all wavelengths to include the contributions from ultraviolet, visible, and infrared radiation.

By convention, the surface features of the Sun are classified into three regions: the photosphere, the chromospheres, and the corona. The photosphere corresponds to the bright region normally visible to the naked eye. About 3,100 mi (5,000 km) above the photosphere lies the chromospheres, from which short-lived, needle-like projections may extend upward for several thousands of kilometers. The corona is the outermost layer of the Sun; this region extends into the region of the planets. Most of the surface features of the Sun lie within the photosphere, though a few extend into the chromospheres or even the corona.

The average amount of energy from the Sun per unit area that reaches the upper regions of the earth's atmosphere is known as the solar constant; its value is approximately 1,367 watts per square meter. As earth-based measurements of this quantity are of doubtful accuracy due to variations in the earth's atmosphere, scientists have come to rely on satellites to make these measurements.

Although referred to as the solar constant, this quantity actually has been found to vary since careful measurements started being made in 1978. In 1980, a satellite-based measurement yielded the value of 1,368.2 watts per square meter Over the next few years, the value was found to decrease by about 0.04% per year Such variations have now been linked to several physical processes known to occur in the Sun's interior, as will be described below.

From the each, it is only possible to observe the radiant energy emitted by the Sun in the direction of our planet, this quantity is referred to as the solar irradiance This radiant solar energy is known to influence the earth's weather and climate although the exact relationships between solar irradiance and long-term climatologically changes such a global warming, are not well understood.

The total radiant energy emitted from the Sun in all directions is a quantity known as solar luminosity. The luminosity of the Sun has been estimated to be 3.8478 x 10 watts. Some scientists believe that long-term variations in the solar luminosity may be a better correlate to environmental conditions on Earth than solar irradiance, including global warming. Variations in solar luminosity are also of interest to scientists who wish to gain a better understanding of stellar rotation, convection, and magnetism.

Because short-term variations of certain regions of the solar spectrum may not accurately reflect. Changes in the true luminosity of the Sun, measurements of total solar irradiance, which by definition take into account the solar flux. Contributions over all wavelengths, provide a better representation of the total luminosity of the Sun.

Short-term variations in solar irradiation vary significantly with the position of the observer, so such variations may not provide a very accurate picture of changes in the solar luminosity but the total solar irradiance at any given position gives a better representation because it includes contributions over the spectrum of wavelengths represented in the solar radiation.

Variations in the solar irradiance are at a level that can be detected by ground-based astronomical measurements of light. Such variations have been found to be about 0.1% of the average solar irradiance. Starting in 1978, space-based instruments aboard the Nimbus 7, Solar Maximum Mission, and other satellites began making the sort of measurements (reproducible to within a few parts per million cache year) that allowed scientists to acquire a better understanding of variations in the total solar irradiance.

2.3.1 Solar Irradiance Data Sets

The most accurate measurements of solar radiation are obtained by a pyrometer placed at a location for a number of years, usually on the order of a decade or more, measuring the direct radiation every few minutes. However, the volume of data generated by this technique makes it impractical (and unnecessary) to provide the full data set for each location for PV system design. Instead, the data can be presented in several other formats.

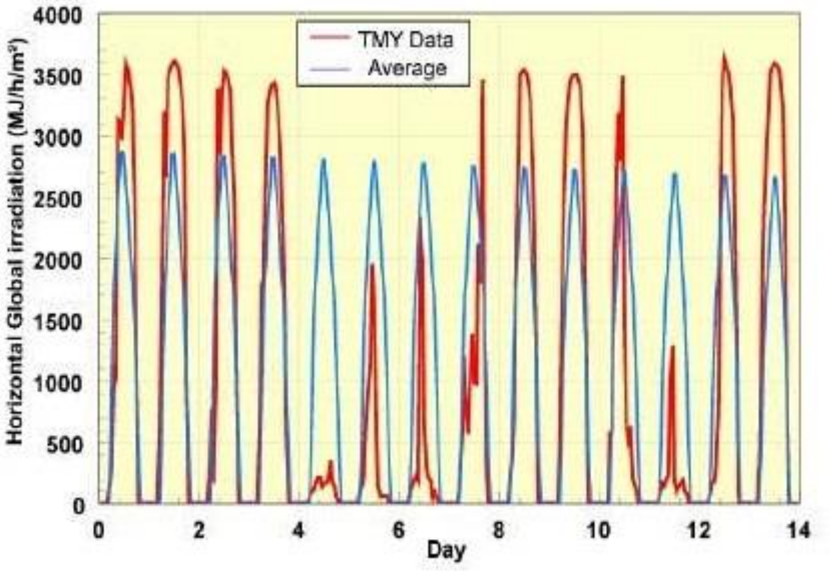

Figure 2.2 Comparison of TMY and average solar radiation data

The most conceptually straight forward method of reducing the data set is to average the data. Over the measuring period. This form of data is called average daily, monthly or yearly radiation data. Although this data is useful for basic system design, the day-to-day variation in the solar radiations lost. The loss of the day-to-day variation is critical since the design and performance of a system with, for example, 5 kWh/day nearly every day is quite different than one with 8 kWh/day on some days followed by several cloudy days with 2 kWh/day.

The most common format for solar radiation data is TMY data (or TMY2 data used by the National Renewable Energy Laboratories in the USA) which includes daily variability in the data. TMY data sets are described in the following page. However, average solar radiation data, particularly for cache month of the year is also extensively used in rough estimates on the amount of PV panels required.

An additional useful, although less common data which can be determined from the full radiation data sets, is the probability of having a certain number of cloudy days which occur in a row. whereby the definition of a cloudy day is usually a day where less than 50 of the theoretically expected radiation is received.

For example, at a certain location, 4 cloudy days in a row may occur once a year and 5 cloudy days in a row may occur once every 5 years. This information is particularly useful in estimating storage sufficient requirements. However, this information is less commonly tabulated and, if used, must be determined from the original data sets.

2.4 PV Module Temperature

An unwanted side-effect of the encapsulation of solar cells into a PV module is that the encapsulation alters the heat flow into and out of the PV module, thereby increasing the operating temperature of the PV module. These increases in temperature have a major impact on the PV module by reducing its voltage, thereby lowering the output power. In addition, increases in temperature are implicated in several failure or degradation modes of PV modules, as elevated temperatures increase stresses associated with thermal expansion and also increase degradation rates by a factor of about two for each 10°C increase in temperature.

The operating temperature of a module is determined by the equilibrium between the heat produced by the PV module, the heat lost to the environment and the ambient operating temperature. The heat produced by the module depends on the operating point of the module, the optical properties of the module and solar cells, and the packing density of the solar cells in the PV module.

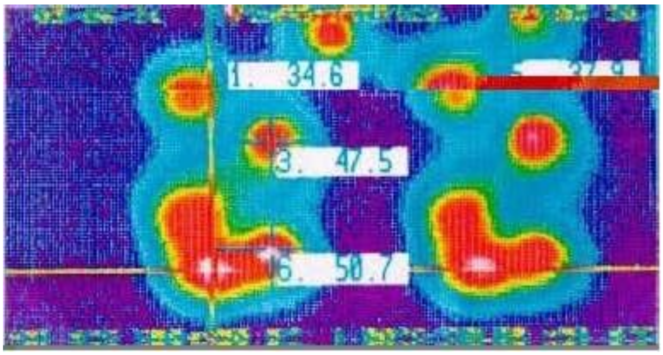

Figure 2.3 Thermo graphic image of sixteen cell modules with integral bypass diode cells under reverse bias conditions. Each colour change corresponds to a 40℃ change in temperature

The heat lost to the environment can proceed via one of three mechanisms; conduction, convection and radiation. These loss mechanisms depend on the thermal resistance of the module materials, the emissive properties of the PV module, and the ambient conditions (particularly wind speed) in which the module is mounted. These factors are discussed in the following pages.

2.5 Air Mass

The Air Mass is the path length which light takes through the atmosphere normalized to the shortest possible path length (that is, when the sun is directly overhead). The Air Mass quantifies the reduction in the power of light as it passes through the atmosphere and is absorbed by air and dust. The Air Mass is defined as:

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$$AM = Icos0$$

where 0 is the angle from the vertical (zenith angle) When the sun is directly overhead. the Air Mass is 1.

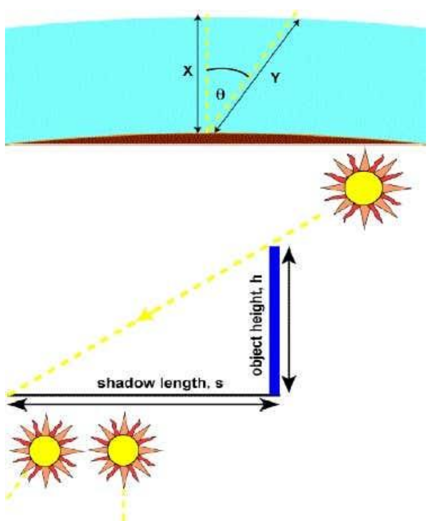

Figure 2.4 Hypotenuse Air Mass

Air mass is the length of the hypotenuse divided by the object height h, and from Pythagoras's theorem we get:

$$Air\ Mass -\ 1 + sh2$$

The above calculation for air mas assumes that the atmosphere is a flat horizontal layer, but because of the curvature of the atmosphere, the air mass is not quite equal to the atmospheric path length when the sun is close to the horizon Al sunrise, the angle of the sun from the vertical position is 90 and the air mass is infinite, whereas the path length clearly is not. An equation which incorporates the curvature of the earth is:

$$\mathrm{Air\ Mass} = 1 \sin \theta + 0.5057296.07995 - 0 - 1.6364$$

2.5.1 Standardized Solar Spectrum and Solar Irradiation

The efficiency of a solar cell is sensitive to variations in both the power and the spectrum of the incident light. To facilitate an accurate comparison between solar cells measured at different times and locations, a standard spectrum and power density has been defined for both radiation outside the Earth's atmosphere and at the Earth's surface.

The standard spectrum at the Earth's surface is called AMI.5G, (the G stands for global and includes both direct and diffuse radiation) or AMISD (which includes direct radiation only). The intensity of AMI SD radiation can be approximated by reducing the AMO spectrum by 28% (18% due to absorption and 10% to scattering). The global spectrum is 10% highest than the direct spectrum. These calculations give approximately 970 W/m for AMI SG. However, the standard AMI SG spectrum has been normalized to give IkW/m' due to the convenience of the round number and the fact that there are inherently variations in incident solar radiation.

The standard spectrum outside the Earth's atmosphere is called AMO, because at no stage does the light pass through the atmosphere This spectrum is typically ed so predict the expected performance of cells in space

2.5.2 Intensity Calculations Based on the Air Mass

The intensity of the direct component of sunlight throughout each day can be determined as a function of air mass from the ex perimentally determined equation:

$$I_D = 1.353 \cdot 0.7^{AM^{0.678}}$$

I_D is the intensity on a plane perpendicular to the sun's rays in units of kW/m^2

AM is the air mass

1.353 $kW/m^2$is the solar constant

0.7 arises from the fact that about 70% of the radiation incident on the atmosphere is transmitted to the Earth.

0.678 is an empirical fit to the observed data and takes into account the non-uniformities in the atmospheric layers

Where Io is the intensity on a plane perpendicular to the San's rays in units of kW/m and AM is the air mass. The value of 1.353 kW/mi's the solar constant and the number 0.7 arises from the fact that about 70% of the radiation incident on the atmosphere is transmitted to the Earth. The extra power term of 0.678 is an empirical fit to the observed data and takes into account the non-uniformities in the atmospheric layers.

Sunlight intensity increases with the height above sea level The spectral content of sunlight also changes making the sky bluer' on high mountains. Much of the southwest of the United States is two kilometers above sea level, adding significantly to solar isolation. A simple empirical fit to observed data and accurate to a few kilometers above sea level is given by:

$$I_D = 1.353 \cdot \left[(1 - ah)0.7^{AM^{0.678}} + ah\right]$$

I_D is the intensity on a plane perpendicular to the sun's rays in units of kW/m^2
AM is the air mass
1.353 kW/m^{2}is the solar constant
0.7 arises from the fact that about 70% of the radiation incident on the atmosphere is transmitted to the Earth.
0.678 is an empirical fit to the observed data and takes into account the non-uniformities in the atmospheric layers

a = 0.14

h is the location height above sea level in kilometres

Even on a clear day, the diffuse radiation is still about 10% of the direct component. Thus, on a clear day the global irradiance on a module perpendicular to the sun's rays is:

$$I_G = 1.1 \cdot I_D$$

I_G = Global Irradiance

I_D = Intensity

2.6 Fill Factor

The short-circuit current and the open-circuit voltage are the maximum current and voltage respectively from a solar cell. However, at both of these operating points, the power from the solar cell is zero. The "fill factor", more commonly known by its abbreviation "FF", is a parameter which, in conjunction with V and L determines the maximum power from a solar cell. The FF is defined as the ratio of the maximum power from the solar cell to the product of V and L Graphically, the FF is a measure of the "squareness" of the solar cell and is also. He area of the largest rectangle which will fit in the IV curve The FF is illustrated below As FF is a measure of the squareness of the IV curve, a solar cell with a highest voltage has a larger possible FF since the "rounded" portion of the IV curve takes up less area.

The maximum theoretical FF from a solar cell can be determined by differentiating the power from a solar cell with respect to voltage and finding where this is equal to zero. Hence:

$$\frac{d(IV)}{dV} = 0$$

Giving:

$$V_{mp} = V_{oc} - \frac{nkT}{q} In\left(\frac{V_{mp}}{nkT/q} + 1\right)$$

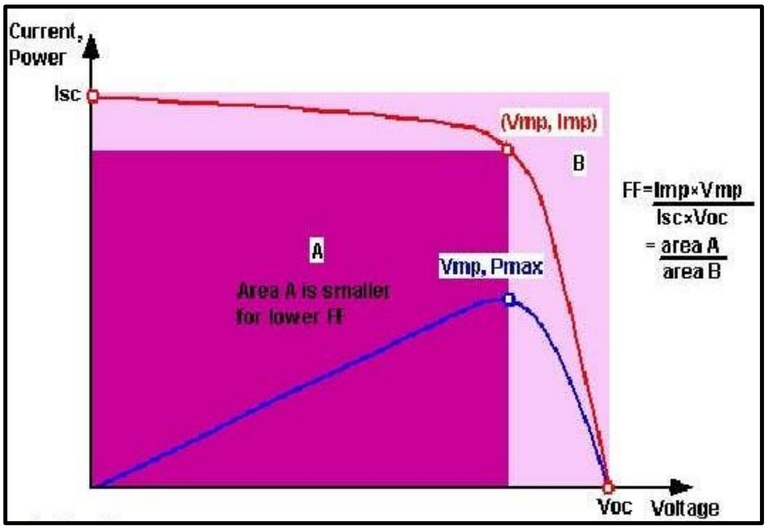

Figure 2.5 Graph of cell output current (red line) and power (blue line) as function of voltage

Also shown are the cell short-circuit current (I_{sc}) and open-circuit voltage (V_{oc}) points, as well as the maximum power point (V_{mp}, I_{mp}). However, the above technique does not yield a simple or closed form equation. The equation above only relates V_{oc} to V_{mp} and extra equations are needed to find L and FF. A more commonly used expression for the FF can be determined empirically as:

$$FF = \frac{V_{oc} - In(V_{oc} + 0.72)}{V_{oc} + 1}$$

The above equations show that a highest voltage will have a highest possible FF. However, large variations in open-circuit voltage within a given material system are relatively uncommon. For example, at one sun, the difference between the maximum open-circuit voltage measured for a silicon laboratory device and a typical commercial solar cell is about 120 mV, giving maximum FF's respectively of 0.85 and 0.83. However, the variation in maximum FF can be significant for solar cells made from different materials. For example, a GaAs solar cell may have an FF approaching 0.89.

The above equation also demonstrates the importance of the ideality factor, also known as the "n-factor" of a solar cell. The ideality factor is a measure of the junction quality and the type of recombination in a solar cell. For the simple recombination mechanisms discussed in Types of Recombination, the n-factor has a value of 1. However, some recombination mechanisms, particularly if they are large, may introduce recombination mechanisms of 2. A high n-value not only degrades the FF, but since it will also usually signal high recombination, it gives low open-circuit voltages.

2.7 Efficiency

The efficiency is the most commonly used parameter to compare the performance of one solar cell to another. Efficiency is defined as the ratio of energy output from the solar cell to input energy from the sun. In addition to reflecting the performance of the solar cell itself, the efficiency depends on the spectrum and intensity of the incident sunlight and the temperature of the solar cell. Therefore, conditions under which efficiency is measured must be carefully controlled in order to compare the performance of one device to another, Terrestrial solar cells are measured under AMI.5 conditions and at a temperature of 25°C Solar cells intended for space use are measured under AMO conditions. Recent top efficiency solar cell results are given in the page Solar Cell Efficiency Results.

The efficiency of a solar cell is determined as the fraction of incident power which is converted to electricity and is defined as:

$$P_{max} = V_{oc} I_{sc} FF$$

$$n = \frac{V_{oc} I_{sc} FF}{P_{in}}$$

Where:

V_{oc} is the open − circuit voltage

I_{sc} is the short − circuit current

FF is the fill factor

n is the efficiency

The input power-for efficiency calculations are 1 kW/m^2 or 100 mW/cm^2 Thus the input power for a 100 x 100 mm cell is 10 W and for a 156 x 156 mm cell is 24.3 W.

2.8 Photovoltaic Charge Controller

A charge controller is needed in photovoltaic system to safely charge sealed lead acid battery. The most basic function of a charge controller is to prevent battery overcharging. If battery is allowed to routinely overcharge, their life expectancy will be dramatically reduced. A charge controller will sense the battery voltage, and reduce or stop the charging current when the voltage gets high enough. This is especially important with sealed lead acid battery where we cannot replace the water that is lost during overcharging. Unlike Wind or Hydro System charge controller, PV charge controller can open the circuit when the battery is full without any harm to the modules.

Most PV charge controller simply opens or restricts the circuit between the bleary and PV array when the voltage rises to a set point. Then, as the battery absorbs the excess electrons and voltage begins dropping, the controller will turn back on. Some charge controllers have these voltage points factory-preset and non-adjustable, other controllers can be adjustable.

2.8.1 DC – DC Converters

There is various dc to dc converters topologies like buck converter, boost converter, buck-boost converter and others converter topology are used in PV charge controller. Since solar panels are only capable of producing a DC voltage, the DC-DC converter becomes quite useful by providing the flexibility to adjust the DC voltage or current at any point in the circuit. DC-DC converters are often preferred in modem electronics since they are smaller, light weight, provide a high-quality output, and more efficient.

2.8.2 Buck (Step-Down) Converter

One of the research projects made is about buck converter topology which is one of many topologies that were used in PV charge controller development. A buck converter is called a step-down DC to DC converter because the output voltage is less than the input. Its design is similar to the step-up boost converter, and like the boost converter it is a switched-mode power supply that uses two switches (a transistor and a diode) and an inductor and a capacitor.

A buck converter can be remarkably efficient (easily up to 95% for integrated circuits) and self-regulating. Most buck converters are designed for continuous-current mode operation compared to the discontinuous-current mode operation. The continuous- current mode operation is characterized by inductor current remains positive throughout the switching period. Conversely, the discontinuous-current mode operation is characterized by inductor current returning to zero during each period.

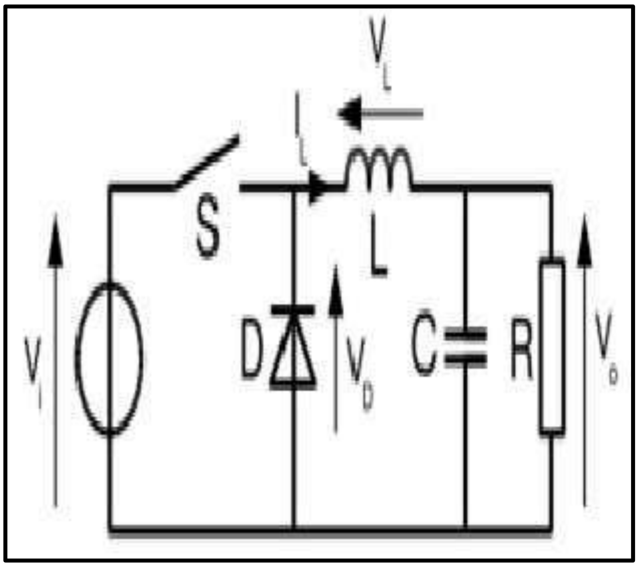

Figure 2.6 A basic buck converter topology circuit

2.9 The battery: When is it needed, and how does it function?

The module in a PV system generates electricity when the sun shines on it, but in the evening, when the user needs the electricity for example for lighting, there is almost no current coming out of the module (Markvart 2003). Therefore, in most PV systems there is a need for some kind of energy storage. There are different ways of storing energy, for example using the electricity to pump up water, in which case the energy is stored as potential energy in the water. The method that is most usual in PV systems is using an electrochemical battery. The battery is charged during the day, and it can be discharged during the evening. This section describes some of the main battery characteristics. The section is based on theory from GEP's (1992) "Rechargeable Batteries, Application Handbook", on Markvart's (2003) "Solar Electricity" and Patel's (1999) "Wind and Solar Power".

2.9.1 The battery

The battery is the most expensive life cycle component of the SHS system. It accounts for approximately 13% of the initial cost, but around 30% of the life cycle cost (Diaz and Lorenzo 2001). The batteries used in SHS should allow for deep discharge without seriously reducing the lifetime of the battery. It is recommended in UNBS (2000a) that the batteries used in the PV systems should be designed for PV applications. The batteries that are most usual in solar home systems in developing countries are the ones locally produced (Vervaart and Nieuwenhout 2001). Common battery types in Uganda are three types of lead acid batteries, solar batteries, car batteries, modified car batteries and truck batteries20 (Sandgren 2001). Lead acid batteries are generally the most commonly used battery in SHS (Diaz and Lorenzo 2001). To reduce the cost of the SHS it is important that the battery is used in an optimal way, to ensure that the life time will be as long as possible. The battery lifetime depends on various factors, including battery type, correct sizing of the system, local environment, charge regulation and maintenance.

The performance characteristics of a battery mentioned in Patel (1999) and Louineau (1998) are typically:

- Charge/discharge voltages
- Charge/discharge ratio21
- Efficiency
- Internal impedance Re
- Temperature rise
- Lifetime in number of cycles

- Self-discharge
- Consumption of distilled water

2.9.2 Different types of batteries

Batteries can be primary or secondary type, which means they are none rechargeable or rechargeable, respectively. Secondary batteries are those used in PV systems. In the market there are various types of secondary batteries, for example nickel cadmium (NiCd), lead-acid (Pb), nickel metal hydride (NiMH) and lithium-ion batteries. Here only the lead acid battery will be discussed further.

2.9.3 The lead acid battery

The lead acid battery is as mentioned the most common battery used in PV systems, mostly because it has high performance compared to its cost, but it has the least energy density by weight and by volume. The lead acid battery is available in various terminal voltages, e.g., 6V, 12V and 24V, and in various capacity rates, e.g., 75 Ah, 100 Ah and 115 Ah. The lead acid battery is made up of cells, one cell has two electrodes + and −, one electrode has lead and the other lead dioxide, and the electrolyte consists of sulphuric acid diluted with water. The chemical reactions that take place in the battery are:

$$PbO2 + Pb + 2H2SO4 \Leftrightarrow 2PbSO4 + 2H2O$$

2.9.4 The cell connections in the battery

For example, a typical 12V lead acid battery consist of six 2V cells, where each cell has both a positive and a negative terminal. When connecting the cells together, there are two options; connecting them in series or in parallel. If the series connection is chosen, the positive terminal of one cell is connected to the negative terminal of another cell, and if the parallel connection is chosen, then the negative terminals are connected together and the positive terminals are connected together. In a series connection the voltages are added, but in the parallel connection the voltage remains constant but the current can be added.

2.9.5 Characteristics of the battery

The efficiency of a battery is defined as the ratio of the delivered energy to the energy that the battery is charged with:

$$E = \frac{Ah_{out}}{Ah_{in}}$$

Where the energy can be calculated in ampere hours. The battery efficiency is usually around 85-90%. The internal resistance in the battery is the total resistance of all resistance contributors in the battery, for example the resistivity at the terminals and the ionic resistance in the electrolyte. The internal resistance increases with deeper state of charge, because when the battery is discharged the sulphate ions concentration decreases, which corresponds with an increased Re, as shown in Figure 2.7.

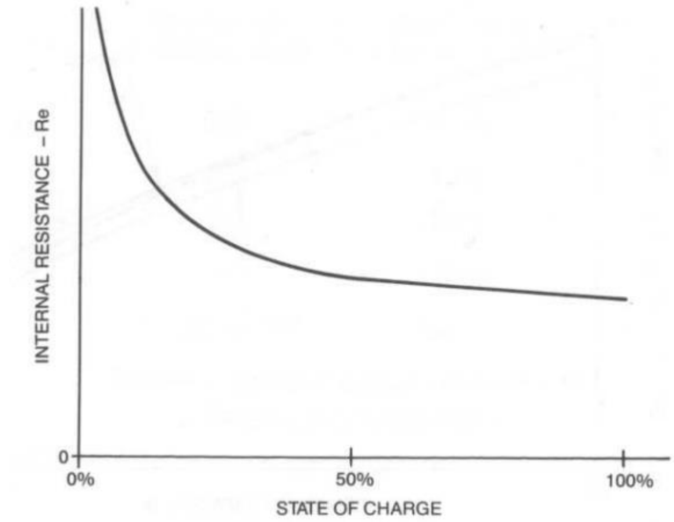

Figure 2.7 Effective Re as a function of SOC. Figure from Gates Energy Products (1992): "Rechargeable Batteries", p. 168.

As the battery gets older Re increases; the contact resistance between the active material in the plates and the plate grid increases. As observed in Figure 2.8, this increase is quite slow in the beginning of the battery lifetime but increases as the battery lifetime gets closer to the end.

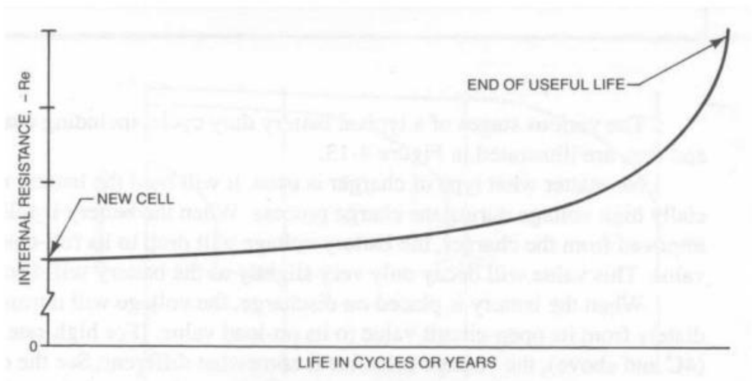

Figure 2.8 Effective Re as a function of cell life. Figure from Gates Energy Products (1992):

"Rechargeable Batteries", p. 168.

2.9.6 Discharging

If a 100 Ah battery is discharged at C/10 rate the discharge current is 10A, and if the discharge rate is C/20 the discharge current is 5A. Sealed lead acid batteries are usually rated at 10 or 20 Ah.

The state of charge (SOC) is defined as

$$SOC = \frac{\text{Ah capacity remaining in the battery}}{\text{Rated Ah capacity}}$$

The battery capacity decreases with increasing discharge current and vice versa, as shown in Figure 2.10. The voltage drop is greatest in the first period of discharge, then it goes into a more stabilized phase until it starts to drop significantly at the knee of the discharge curve, as shown in Figure 2.9.

The duration of the discharge is depended on the discharge rate. As shown in Figure 2.11, it is a linear relationship. The cycling procedures have impact on the battery lifetime, which has to be considered in the system design. To obtain a long life for the battery the daily depth of discharge should be less than 20%.

2.9.7 Charging

A lead acid battery can be charged at a rate that does not cause excessive gassing, overcharging or high temperatures in the battery. In Vervaart and Nieuwenhout (2001), the following steps are mentioned for charging a lead acid battery:

1. Main charge, used for charging the battery up to a level when gassing starts and the voltage rises

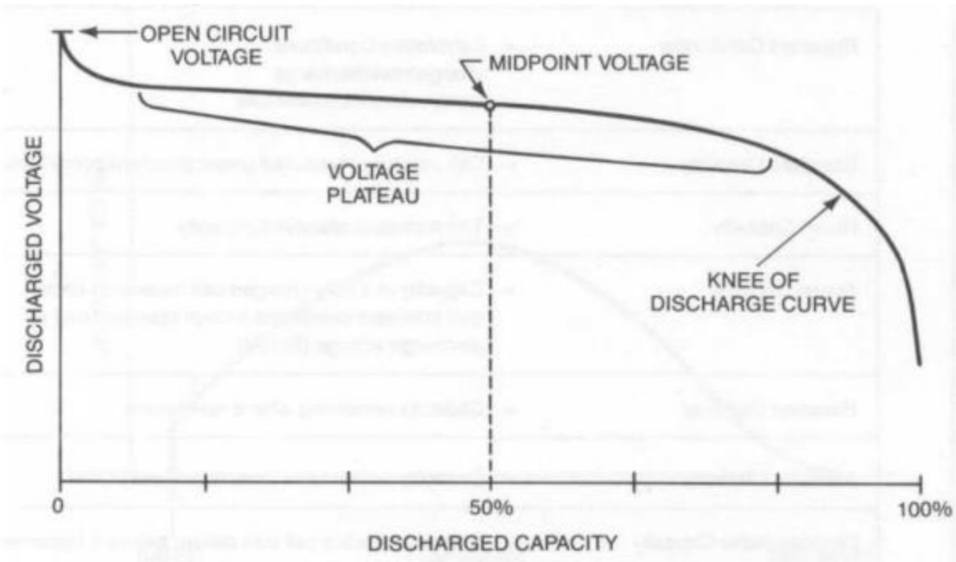

Figure 2.9 Voltage discharge performance of a sealed lead acid battery. Figure from Gates Energy Products (1992): "Rechargeable Batteries", p. 159.

2. Top-up charge, to reach the 100% state of charge from a level of 90-95%
3. Maintenance charge, used for maintaining the full capacity in a battery that is already fully charged, but not frequently used for some period
4. Equalizing charge

The parameters operating when the battery is being charged are the current, voltage and temperature. The battery should not be charged with too high voltages, because the corrosion in the battery can increase which leads to a shorter lifetime for the battery. The battery can be damaged by overcharging or by undercharging. It has been observed that undercharging of the battery is a greater problem than overcharging. When charging the battery, it is possible that some generation of gas takes place. This can reduce the battery efficiency, but is generally not a big problem.

The voltage control, when the battery is being charged, assumes that the battery charge is the same for each cell in the battery, but this may not always be the case. It is therefore recommended that, if possible, the voltage of each unit in the battery should be measured regularly. If one unit is not fully charged, this can cause sulphation's in the battery (Vervaart and Nieuwenhout 2001).

2.9.8 Battery capacity

The nominal capacity for the battery is specified for a reference discharge period in hours, with a cell temperature of 20◦C and a minimum voltage of 1.80V per cell (IEC 1999).

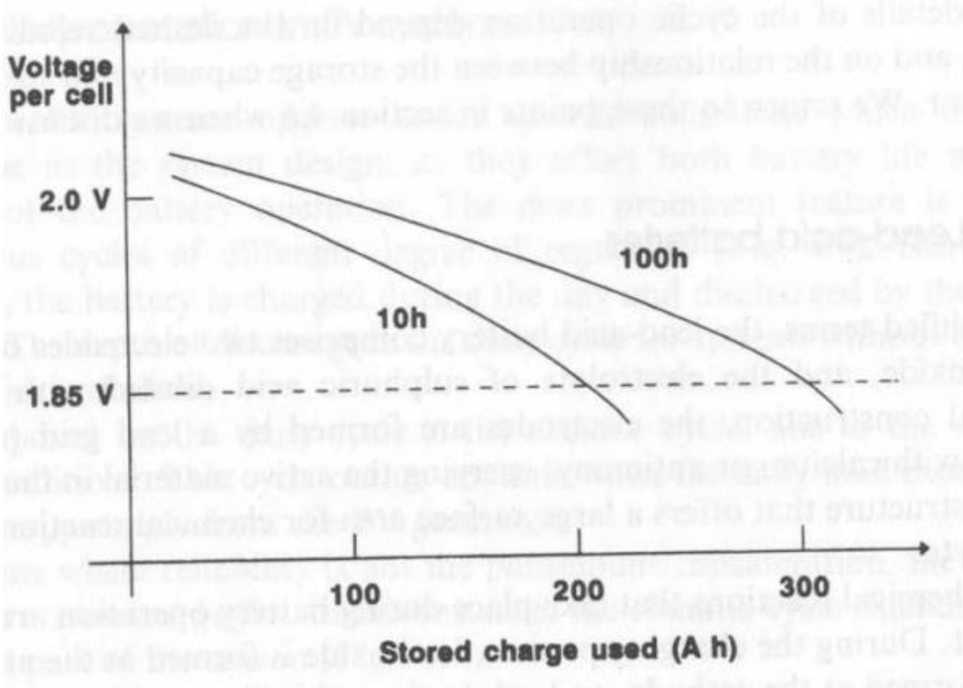

Figure 2.10 The battery discharge characteristics. Figure from Markvart(2000), p. 96.

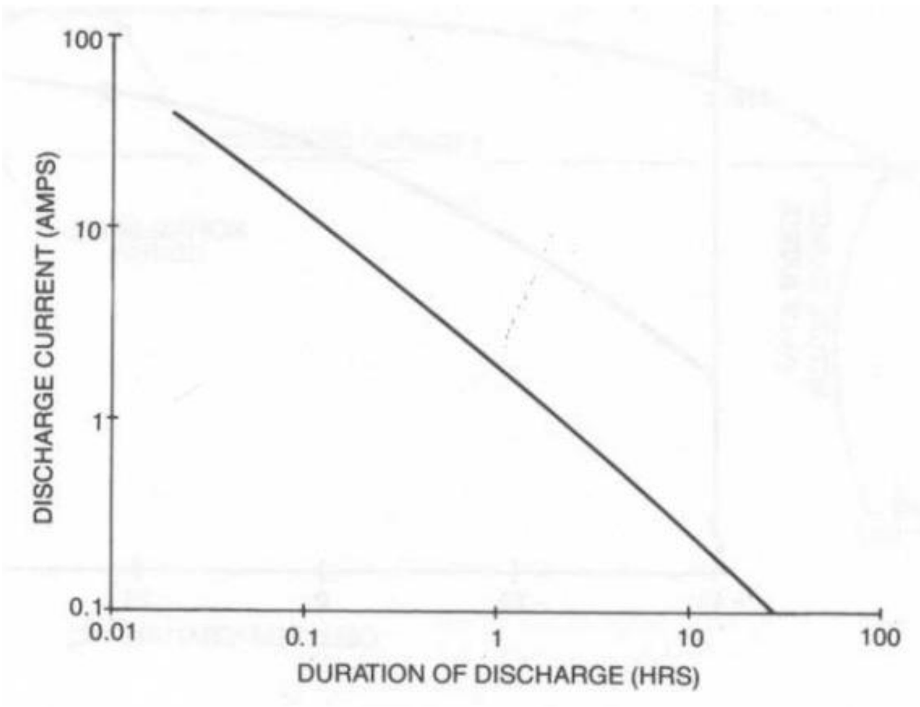

Figure 2.11 Typical discharge time for a sealed lead acid cell. Figure from Gates Energy Products (1992): "Rechargeable Batteries", p. 163.

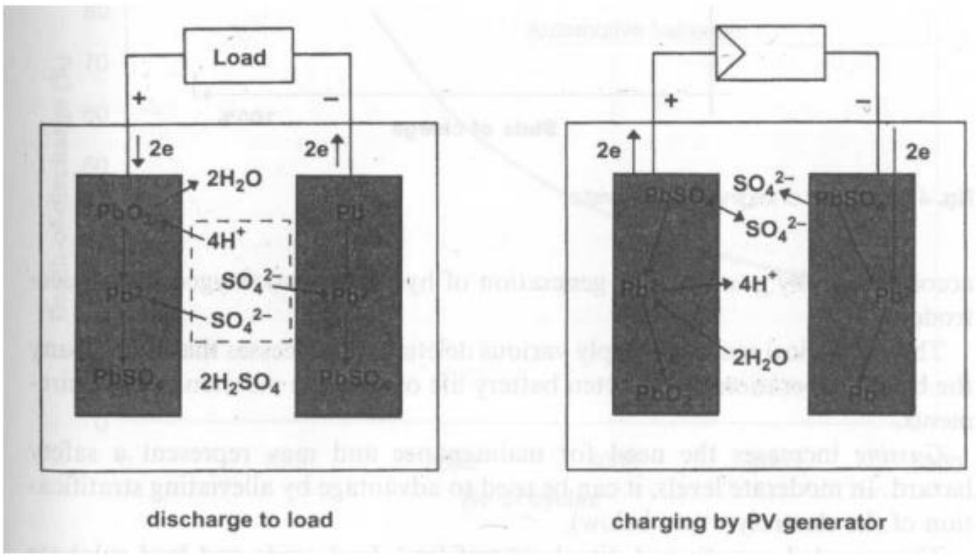

Figure 2.12 Charge and discharge of the battery. Figure from Markvart (2000), p. 95.

The capacity of a cell is essentially the number of electrons that can be obtained from it. The current is defined as the number of electrons per unit of time, thus the cell capacity (relative to a time interval [0, t]) is the current i supplied by the cell integrated over time:

$$Capacity = \int_0^t i \, d_T$$

This equation applies both to the charge and discharge capacity of the battery. A new battery will not operate under full capacity before it has been charged/discharged up to 50 times. This effect can be in the range of 10–20 % of the nominal capacity (Vervaart and Nieuwenhout 2001).

In Figure 2.13 the typical cell capacity during its lifetime is illustrated. The battery is assumed dead when its actual capacity falls to 80% but is often used much longer (Diaz and Lorenzo 2001).

If the charge/discharge rates are not controlled well the battery performance can suffer, some of the problems can be

- Low charge efficiency, low SOC
- Loss of capacity to maintain Ah charge
- Excessive gassing and heating

Battery capacity is sensitive to temperature if the temperature gets much higher than 20◦C the corrosion in the battery can increase. If the temperature in the battery is 30◦C the corrosion effect is twice as high as at 20◦C (Vervaart and Nieuwenhout 2001).

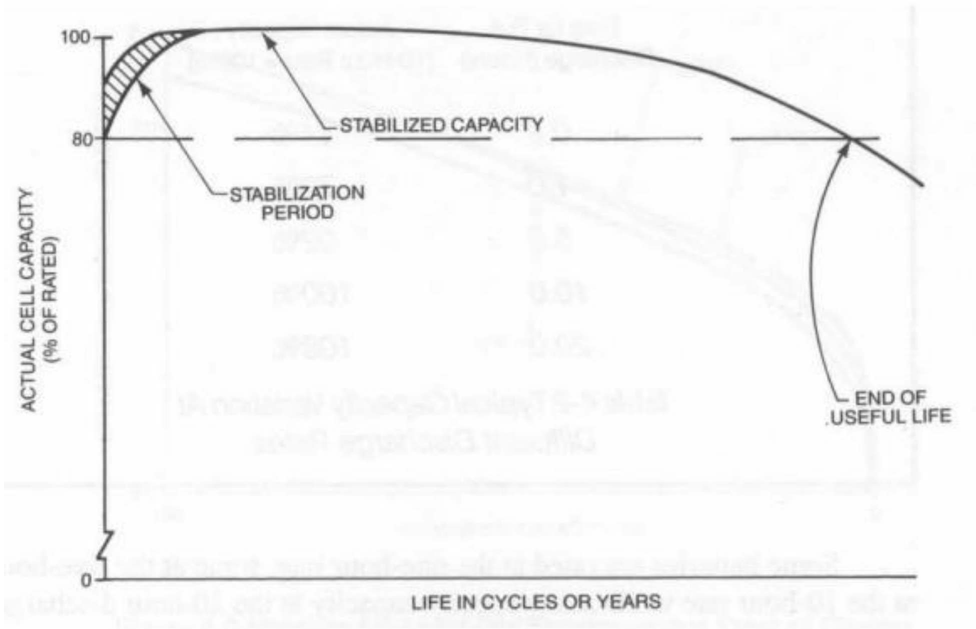

Figure 2.13 Cell capacity during its lifetime. Figure from Gates Energy Products (1992): "Rechargeable Batteries", p. 165.