CHAPTER – 3

Photovoltaic (PV) System

3.1 Photovoltaic (PV) Cell

A photovoltaic cell (also called solar cell) is an electrical device that converts the energy of light directly into electricity by the photovoltaic effect. It is a form of photoelectric cell (in that its electrical characteristics-- e.g. current, voltage, or resistance-- vary when light is incident upon it) which, when exposed to light, can generate and support an electric current without being attached to any external voltage source.

Figure 3.1 : PV Cell

3.2 Theory of PV Cell

When a photon hits a piece of silicon, one of the three things can happen:

- The photon can pass straight through the silicon — this (generally) happens for lower energy photons,
- The photon can reflect off the surface,

- The photon can be absorbed by the silicon, if the photon energy is higher than the silicon band gap value. This generates an electron-hole pair and sometimes heat, depending on the band structure.

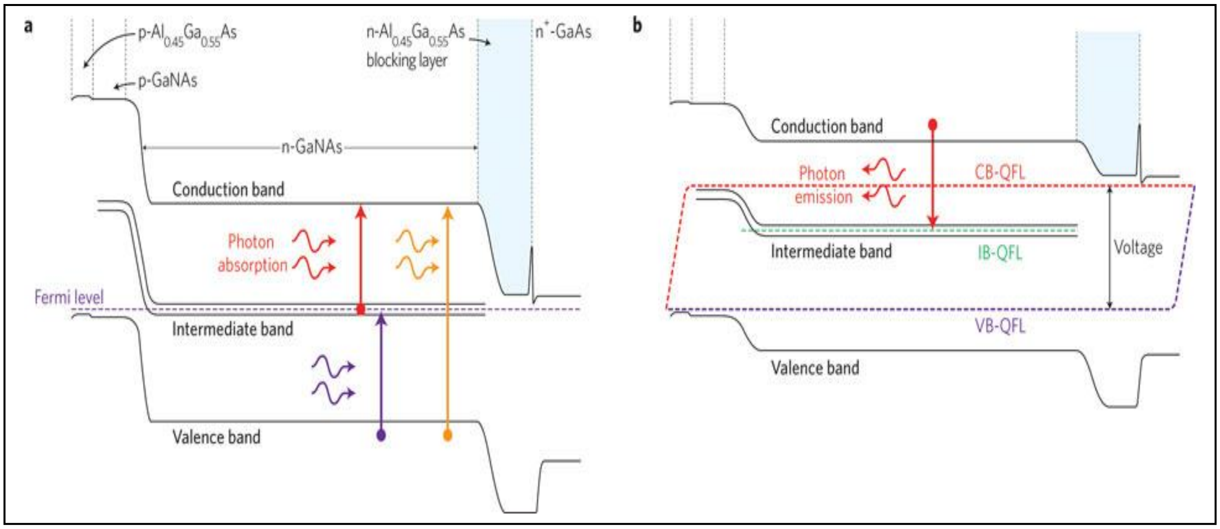

Figure 3.2 : (a) Band diagram of the cell in equilibrium, showing the AlGaAs blocking layer. (b) The cell out of equilibrium, showing the Fermi level split into three QFLs and illustrating photon emission due to transitions from the CB to the IB sustained by the split between CB-QFL and IB-QFL.

When a photon is absorbed, its energy is given to an electron in the crystal lattice. Usually this electron is in the valence band, and is tightly bound in covalent bonds between neighboring atoms, and hence unable to move far. The energy given to it by the photon "excites" it into the conduction band, where it is free to move around within the semiconductor. The covalent bond that the electron was previously a part of now has one fewer electron — this is known as a hole. The presence of a missing covalent bond allows the bonded electrons of neighboring atoms to move into the "hole," leaving another hole behind, and in this way a hole can move through the lattice. Thus, it can be said that photons absorbed in the semiconductor create mobile electron-hole pairs.

A photon need only have greater energy than that of the band gap in order to excite an electron from the valence band into the conduction band. However, the solar frequency spectrum approximates a black body spectrum at about 5,800 K, and as such, much of the solar radiation reaching the Earth is composed of photons with energies greater than the band gap of silicon. These higher energy photons will be absorbed by the solar cell, but the difference in energy between these photons and the silicon band gap is converted into heat (via lattice vibrations — called phonons) rather than into usable electrical energy.

3.3 Working Principle of PV Cell

The way, in which solar cells work is shown below, taking crystalline silicon cells as an example. Highly pure silicon with a high crystal quality is needed to make solar cells. The silicon atoms form a stable crystal lattice. Each silicon atom has four bonding electrons (valence electrons) in its outer shell. To form a stable electron configuration, in each case in the crystal lattice two electrons of neighboring atoms form an electron pair bond. By forming electron pair bonds with four neighbors, silicon achieves its stable noble gas configuration with eight outer electrons. An electron bond can be broken by the action of light or heat. The electron is then free to move and leaves a hole in the crystal lattice. This is known as intrinsic conductivity

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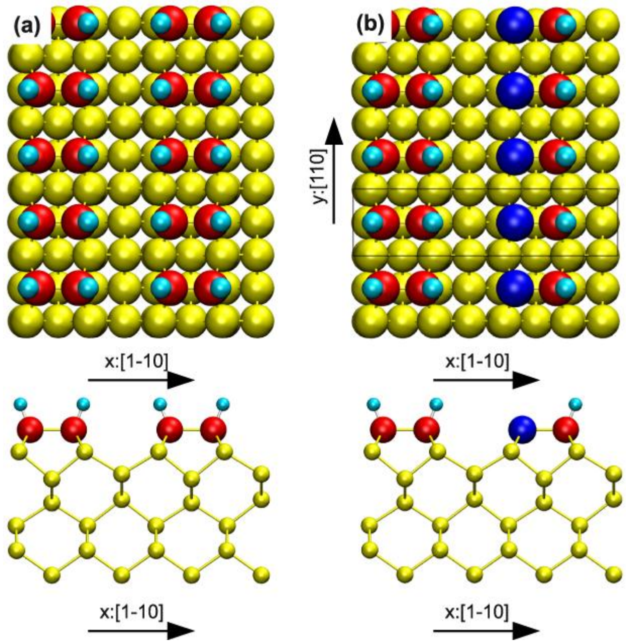

Figure 3.3.1 : The atomic structure of (a) the Si(100)-(2 × 1)-H surface, (b) the infinite ideal wire drawn along the *y* direction. H atoms are depicted in cyan, while Si atoms are depicted in red (surface dimers), yellow (others) and blue when holding a dangling-bond.

Intrinsic conductivity cannot be used to generate electricity. So that the silicon material can be used to generate energy, impurities are deliberately introduced into the crystal lattice. These are known as doping atoms. These atoms shave one electron more (phosphorus) or one electron less (boron) than silicon in their outermost electron shell. Hence, the doping atoms result in ‘impurity atoms’ in the crystal lattice.

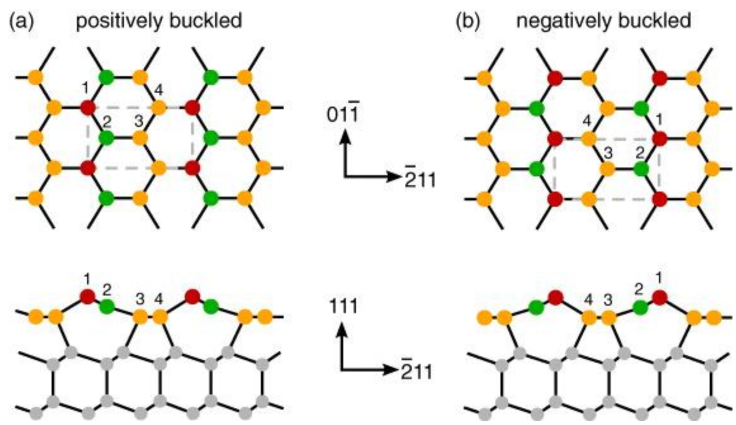

Figure 3.3.2 : Top view and ($01\bar{1}$) cut of the Si(111)-2 × 1 surface with (a) positively and (b) negatively buckled π-bonded chains extending along atom positions 1 and 2. Dashed lines indicate the 2 × 1 surface unit cell with lattice constants a_s = 0.384 nm and b_s = 0.665 nm. The Si lattice constant is a = 0.543 nm.

In the case of phosphorus doping (n-doped), there is a surplus electron for every phosphorus atom in the lattice. This electron can move freely in the crystal and hence transport an electron charge. With boron doping (p-doped), there is a hole (missing bond electron) for every boron atom in the lattice. Electrons from neighboring silicon atoms can fill the hole, creating a new hole somewhere else. The conduction method based on doping method atoms is known as impurity conduction or extrinsic conduction. Considering the n-doped or p-doped on its own, however, the free charges have no pre-determined direction to their movement. If n-doped and p-doped semiconductor layers are bought together, a p-n (positive - negative) junction is formed.

At this junction, surplus electrons from then semiconductor diffuse into the p-semiconductor layer. This creates a region known as space charge region. Positively charged doping atoms remain in the p-region of the transition. An electrical field is created that is opposed to the movement of the charge carriers, with the result that diffusion does not continue indefinitely.

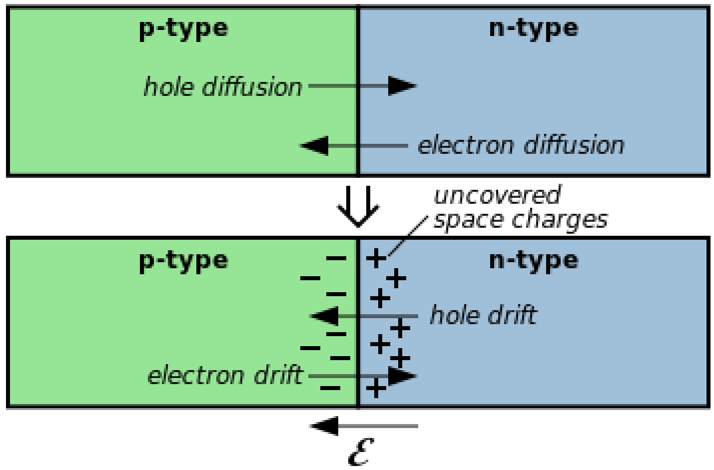

Figure 3.3.3 : Diffusion between free Electron and Holes

If the p-n semiconductor (solar cell) is now exposed to light, photons are absorbed by the electrons. This input of energy breaks electron bonds. The released electrons are pulled through the electric al field into the n-region. The holes that are formed migrate in the opposite direction, into the p-region. This process, as a whole, is called the photovoltaic effect. The diffusion of carriers to the electrical contacts causes a voltage to be present at the solar cell.

In an unloaded state, the open circuit voltage OCV arises at the solar cell. If the electrical circuit is closed, a current flows. Some electrons do not reach the contacts and recombine instead. Recombination refers to the bonding of a free electron to an atom lacking an outer electron (hole). Diffusion length here is the average distance that an electron covers in the crystal lattice during its lifetime until it meets an atom with a missing electron and bonds with it.

Here, free charge carries are lost and can no longer contribute to generating electricity. The diffusion region depends upon the material. With one crystal impurity atom (doping) to 10 billion silicon atoms, this distance is 0.5mm. This corresponds to roughly twice the cell thickness. In the space region, there is a high probability of successful charge separation (electrons and holes) without recombination. Outside of the space charge region, the probability of recombination increases with the distance from the space charge region.

3.4 Types of PV Cell

One can distinguish three cell types according to the type of crystal: mono-crystalline, polycrystalline and amorphous. To produce a mono-crystalline silicon cell, absolutely pure semiconducting material is necessary. Mono-crystalline rods are extracted from melted silicon and then sawed into thin plates. This production process guarantees a relatively high level of efficiency.

The production of polycrystalline cells is more cost-efficient. In this process, liquid silicon is poured into blocks that are subsequently sawed into plates. During solidification of the material, crystal structures of varying sizes are formed, at whose borders defects emerge. As a result of this crystal defect, the solar cell is less efficient.

If a silicon film is deposited on glass or another substrate material, this is a so-called amorphous or thin layer cell. The layer thickness amounts to less than 1µm (thickness of a human hair: 50-100 µm), so the production costs are lower due to the low material costs. However, the efficiency of amorphous cells is much lower than that of the other two cell types. Because of this, they are primarily used in low power equipment (watches, pocket calculators) or as facade elements.

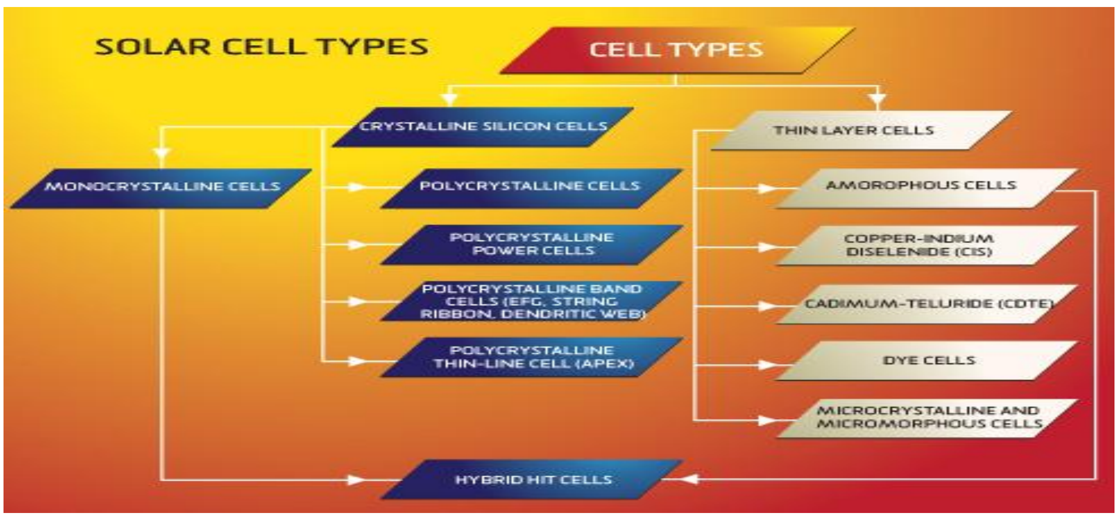

Figure 3.4 : Types of PV Cell

3.5 Equivalent Circuit of PV Cell

To understand the electronic behavior of a solar cell, it is useful to create a model which is electrically equivalent, and is based on discrete electrical components whose behavior is well known. An ideal solar cell may be modeled by a current source in parallel with a diode; in practice no solar cell is ideal, so a shunt resistance and a series resistance component are added to the model. The resulting equivalent circuit of a solar cell is shown on the left. Also shown, on the right, is the schematic representation of a solar cell for use in circuit diagrams.

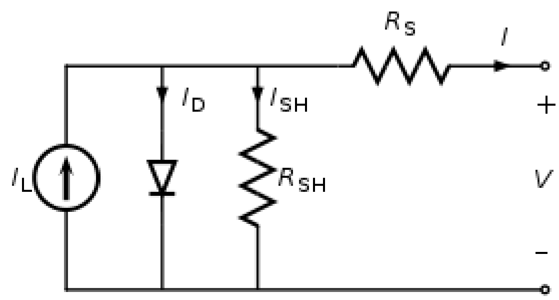

Figure 3.5 : The Equivalent Circuit of a PV Cell

3.6 Characteristics of PV Cell

3.6.1 I-V Characteristics of PV Cell

Photovoltaic cells are electronic devices that use P-N junctions to directly convert sunlight into electrical power. Like the electronics covered in the section above, the P-N junction in the solar cell has a complex relationship between voltage and current. As both the voltage and current is a function of the light falling on the cell, the relationship between insulation (sunlight) and output power is complex.

In particular, solar cells have a number of mechanisms that will capture slow-moving electrons of low energy (voltage). Under normal conditions in bright sunlight, these effects are saturated and represent a fixed loss in energy terms. However, at lower insulation levels, say on an overcast day, these mechanisms represent an increasing percentage of the total power being generated. It is also common for cells to be saturated if there is too much insulation, and the number of free electrons or their mobility is too small. For instance, in silicon the holes left by the photoelectrons take some time to be neutralized, and during this time they can absorb a photoelectron from another atom within the cell. This leads to maximum production rates as well as minimum.

If a cell was free of these effects, the graph between voltage, current and output power would form a rectangle on a graph of current vs. voltage. In practice, the actual output is non-linear. The fill factor, more commonly known by its abbreviation FF, is a parameter which characterizes the non-linear electrical behavior of the solar cell. Fill factor is defined as the ratio of the maximum power from the solar cell to the product of Voc and Isc, and in tabulated data it is often used to estimate the power that a cell can provide with an optimal load under given conditions, P=FF × Voc × Isc. For most purposes, FF, Voc, and Isc are enough information to give a useful approximate model of the electrical behavior of a photovoltaic cell under typical conditions.

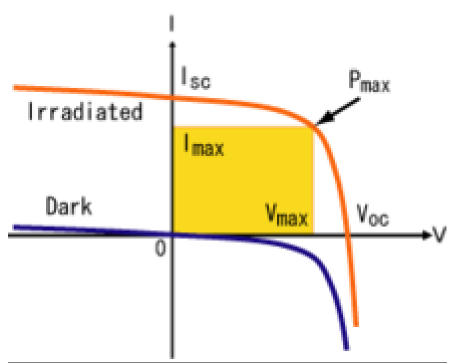

Figure 3.6.1 : I-V Curve of a Solar Cell

The IV-curve of a solar cell at a particular light level, and in darkness. The yellow area is the maximum power able to be drawn from this cell.

3.6.2 P-V characteristic of the PV Cell

The power output of the panel is the product of the voltage and current outputs. In Figure 2.7, the power is plotted against the voltage which is P-V curve of the PV cell. Note that the cell produces no power at zero voltage or zero current, and produces the maximum power at the voltage corresponding to the knee point of the I-V curve. This is why the PV power circuit is always designed to operate close to the knee point with a slight slant on the left-hand side. The PV circuit is modeled approximately as a constant current source in the electrical analysis of the system.

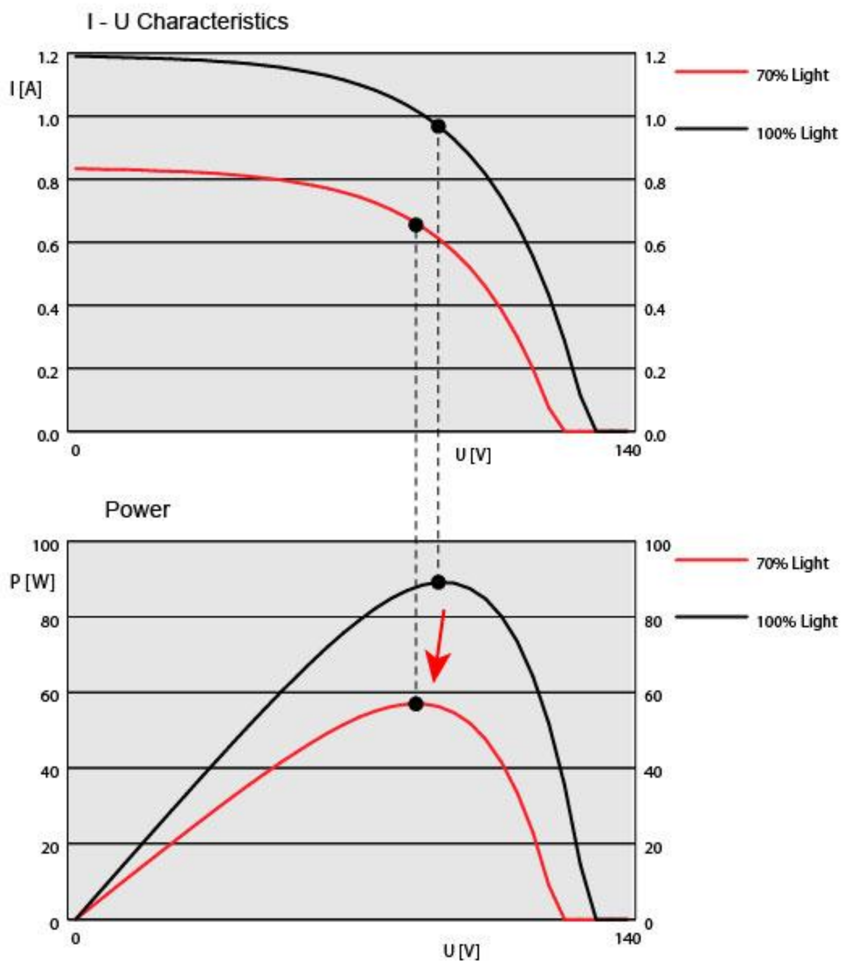

Figure 3.6.2 : P-V Characteristic of the PV Cell

Finally in order to measure the photovoltaic cells output power the following standard test conditions are established internationally. The irradiance level is 1000 W/m², with the reference air mass 1.5 solar spectral irradiance distributions and cell or module junction temperature of 25°C.

3.6.3 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 Voc and Isc, 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 Voc and Isc. Graphically, the FF is a measure of the "squareness" of the solar cell and is also the area of the largest rectangle which will fit in the IV curve. The FF is illustrated below.

$$FF = \frac{P_{max}}{P_t} = \frac{I_{mp}}{I_{sc}} \frac{V_{mp}}{V_{oc}} \quad \text{...(3.1)}$$

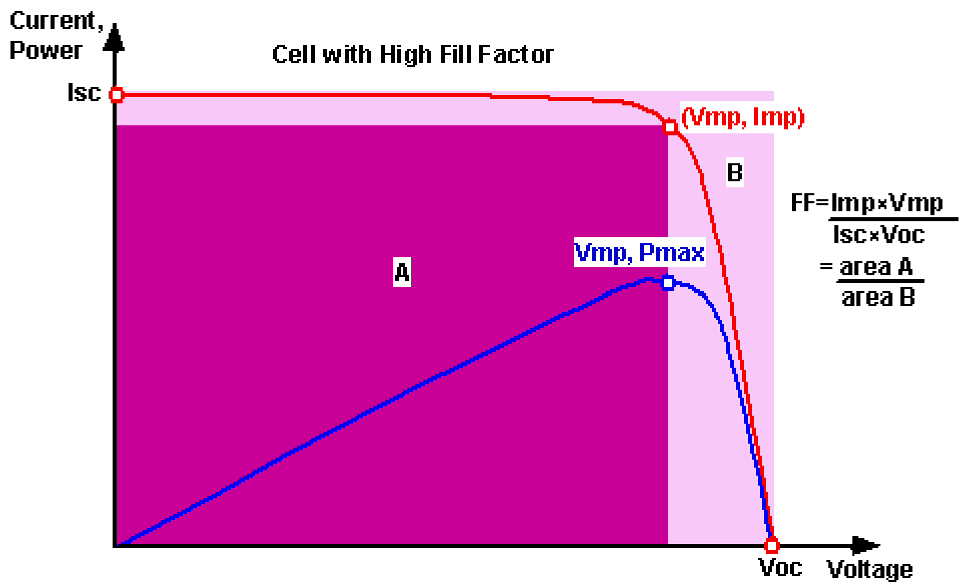

Figure 3.6.3 : Graph of Cell Output Current (red line) and Power (blue line) as function of Voltage

3.6.4 Characteristic Equation

From the equivalent circuit it is evident that the current produced by the solar cell is equal to that produced by the current source, minus that which flows through the diode, minus that which flows through the shunt resistor:

$$I = I_L - I_D - I_{SH} \quad \text{...(3.2)}$$

Where

I = output current (amperes)

I_L = photo generated current (amperes)

I_D = diode current (amperes)

I_{SH} = shunt current (amperes).

The current through these elements is governed by the voltage across them:

$$V_j = V + IR_S \quad \text{.. (3.3)}$$

where

V_j = voltage across both diode and resistor RSH (volts)

V = voltage across the output terminals (volts)

I = output current (amperes)

R_S = series resistance (Ω).

By the Shockley diode equation, the current diverted through the diode is:

$$I_D = I_0 \left\{ exp\left[\frac{qV_j}{nkT}\right] - 1 \right\} \quad \text{...(3.4)}$$

where

I_0 = reverse saturation current (amperes)

n = diode ideality factor (1 for an ideal diode)

q = elementary charge

k = Boltzmann's constant

T = absolute temperature At 25°C, kT/q ≈ 0.0259volts.

By Ohm's law, the current diverted through the shunt resistor is:

$$I_{SH} = \frac{V_j}{R_{SH}} \qquad \text{..........(3.5)}$$

where

R_{SH} = shunt resistance (Ω).

Substituting these into the first equation produces the characteristic equation of a solar cell, which relates solar cell parameters to the output current and voltage:

$$J = J_L - I_O \left\{\exp\left[\frac{q(V + JRs)}{nkT}\right] - 1\right\} - \frac{V + JR_S}{R_{SH}} \qquad \text{..........(3.6)}$$

An alternative derivation produces an equation similar in appearance, but with V on the left-hand side. The two alternatives are identities; that is, they yield precisely the same results.

In principle, given a particular operating voltage V the equation may be solved to determine the operating current I at that voltage. However, because the equation involves I on both sides in a transcendental function the equation has no general analytical solution. However, even without a solution it is physically instructive. Furthermore, it is easily solved using numerical methods. (A general analytical solution to the equation is possible using Lambert's W function, but since Lambert's W generally itself must be solved numerically this is a technicality.)

Since the parameters I_0, n, R_S, and R_{SH} cannot be measured directly, the most common application of the characteristic equation is nonlinear regression to extract the values of these parameters on the basis of their combined effect on solar cell behavior.

3.7 Solar Power Storage system

A power storage system is one of the more important things for the project because we cannot get sufficient power to run a vehicle for the whole day. Again in cloudy condition and in rainy days we will not get sunlight. Though there is sunlight in these conditions it must not have the sufficient light intensity to produce required power. So battery is significant part of our design. In our design there is a battery connected with controller to solar panel. These devices store the DC energy from PV panel in chemical form, and when needed converts the stored chemical energy to electrical energy.

3.7.1 Charge Storage System

Several methods exist for storing the large amounts of charge needed to power a Vehicle. Of these, the most feasible are batteries and capacitors. These two are described below

3.7.1.1 Capacitors

Ultra capacitors differ from batteries as they store charge between solid state materials, instead of through electrochemical reactions. This allows ultra-capacitors to discharge quickly and without damage to the capacitor. Though ultra-capacitors have many ideal operating characteristics, their cost and must be lowered, and reliability improved before their wide-spread usage in alternative energy systems.

3.7.1.2 Batteries

Batteries utilize electro chemical reactions to store energy. Lead-acid batteries are the most common batteries used for storage in small-scale alternative energy systems. Lead dioxide (PbO2) is used for the cathode, metallic sponge lead (Pb) is used for the anode, and the electrolyte is a mixture of sulfuric acid (H2SO4) and water. A single cell exhibits a nominal voltage of 2.1 V. These cells are then combined in series to sum voltages to the desired battery.

3.7.2 Types of Batteries

The most commonly used batteries are: Lead-Acid, Nickel-Metal Hybrid (NiMH), Nickel-Cadmium (NiCad), Lithium Ion, Lithium Polymer and recent invention Lithium Iron Phosphate ($LiFePO_4$).

In solar system batteries are charged and discharged randomly. Life time of battery is depends on charging and discharging of battery. The charging capacity of the battery measured with Amp-hour. Battery ratings are depended according to cycle. In vehicle there is used shallow cycle battery which means battery have cycles between 10% - 15% of batteries total capacity. But in solar system there is used deep cycle batteries which have up to 50% - 80% of total battery's capacity. This type of battery is best for solar project.

There are many variety of batteries found in the market but only four types of batteries are usually used in solar system.

3.7.2.1 Deep Cycle battery

Marine type deep cycle battery is basically used in boats and camps where small load is used to get powered. These types of batteries do not have capacity for continuous service with charger or discharger. These batteries are designed to deliver maximum durability, reliability, and performance.

3.7.2.2 Lead Acid Battery

Lead acid batteries can be used in solar energy storage. These types of batteries are deep cycled and have long life time for charging and discharging. A deep-cycle battery is designed to discharge between 50% and 80% depending on the manufacturer and construction of the battery. Typical life time of lead- acid batteries is 3- 5 years. Life time of Battery actually depends on the charging and discharging cycle. Lead acid batteries releases some gas while charging. That's why these batteries are needed to be kept outside or cross ventilated place, where air circulation is good enough.

3.7.2.3 AGM Battery

The full meaning of AGM battery is absorbed glass material battery. It allows the electrolyte to be suspended in close proximity with the plate's active material. The AGM batteries are expensive batteries and typically cost twice as much as a premium wet cell battery. However they store very well and do not tend to sulfate or degrade as easily as wet cell. There is little chance of a hydrogen gas explosion or corrosion when using these batteries. The larger AGM batteries are typically good deep cycle batteries and they deliver their best life performance if recharged before allowed to drop below the 50% discharge rate. When Deep Cycle AGM batteries are discharged to a rate of no less than 60% the cycle life will be 300. AGM batteries are used in airplanes and hospitals where large charging time is needed.

3.7.2.4 Gel Battery

A gel battery (also known as a "gel cell") is a VRLA battery with a jelli filed electrolyte; the sulfuric acid is mixed with silica fume, which makes the resulting mass gel-like and immobile. Unlike a flooded wet-cell lead-acid battery, these batteries do not need to be kept upright. Gel batteries reduce the electrolyte evaporation, spillage (and subsequent corrosion issues) common to the wet-cell battery, and boast greater resistance to extreme temperatures, shock, and vibration. Chemically they are almost the same as wet (non-sealed) batteries except that the antimony in the lead plates is replaced by calcium, and gas recombination could take place.

3.7.3 DC Battery Selection

Figure 3.6.3 : Ni-cd Battery

Among the four types of battery all are not suitable for solar system and some are much expensive. So, for selecting a type of battery for a solar driven vehicle like ours, we always have to concern about less expensive, comparatively light in weight and high energy supply and consumed battery. Considering the economic factor and availability in our country we will be using Lead acid batteries, which are being widely used as a solar system storage device. These batteries are comparatively cheap, efficient in power storing and have a life time of 3 – 5 years. Though these types of batteries release some hydrogen gas while charging and needs some maintenance. In our project we have used Ni-cd battery because it does not need any maintenance and light in weight.

3.8 Charge Controller

Solar panels are almost always charging some type of battery. Overcharging or discharging under certain level some can damage some types of battery. Also, the battery voltage determines the voltage level at which the solar panel will operate. However, operating at this voltage level probably will not be the most efficient for the solar panel. Due to these two reasons, charge controllers are commonly put in between the solar panel's output leads and the storage batteries.

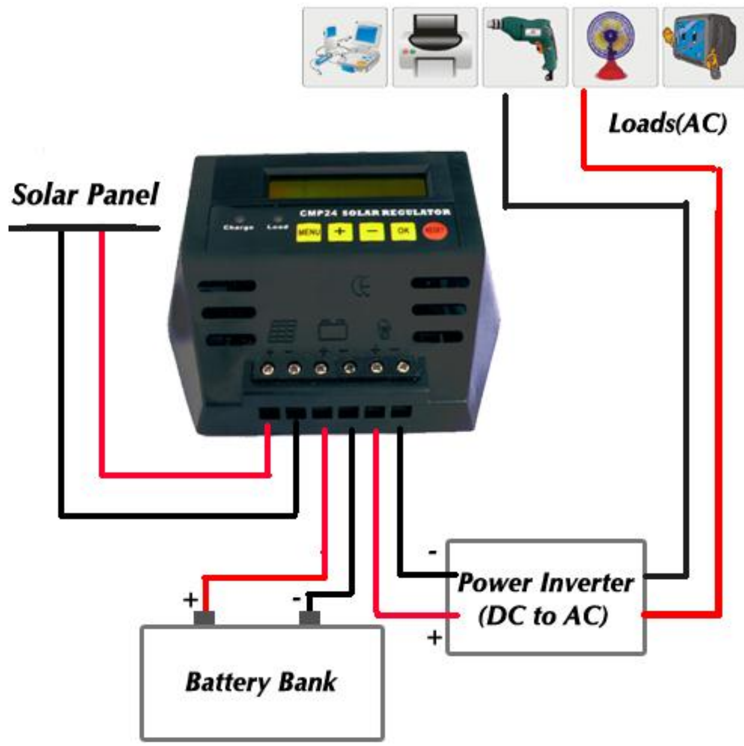

Figure 3.8 : CMP24 solar charge controller regulator circuit diagram

3.8.1 Working Principle

Constantly solar power systems will need a charge controller. The purpose of this is to ensure that the battery is never overcharged, by diverting power away from it once it is fully charged. Only if a very small solar panel such as a battery saver is used to charge a large battery is it possible to do without a controller. Most charge controllers also incorporate a low-voltage disconnect function, which prevents the battery from being damaged by being completely discharged. It does this by switching off any DC appliances when the battery voltage falls dangerously low.

The principle behind a solar charge controller is simple. There is a circuit to measure the battery voltage, which operates a switch to divert power away from the battery when it is fully charged. Because solar cells are not damaged by being short or open-circuits, either of these methods can be used to stop power reaching the battery.

A controller which short-circuits the panel is known as a shunt regulator, and that which opens the circuit as a series regulator. Optionally there may also be a switch which automatically disconnects the power from the appliances or loads when the battery voltage falls dangerously low. This is known as a low-voltage disconnect function.

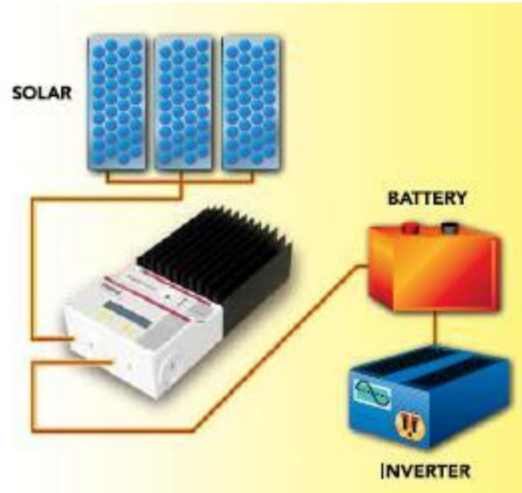

Figure 3.8.1 : Basic Function of Charge Controller

3.8.2. Types of Charge Controllers

3.8.2.1. Basic Charge Controllers

The basic charge controller is designed to protect the battery from any form of damage due to overcharge or undercharge and prevents any reverse current that may be drawn from the battery during the time period in which the solar panels are not generating any power. Overcharging some types of batteries can damage the battery as well as cause possible explosions or leaking. If energy is continually applied to the battery after it has reach full capacity, then the battery voltage will raise causing chemical reactions, which will eventually overheat the battery and damage it. To prevent overcharge, the charge controller simply monitors the charge going into the battery and regulates the voltage level sent to the battery to prevent any further charging once a certain maximum capacity level is reached. The batteries life cycle will be dramatically shortened if the batteries are undercharged for too long a period of time. In this situation, the charge controller will disconnect the battery, known as Low Voltage Disconnect (LVD), from any loads (lamps, appliances, etc.) once a certain capacity is reached in order to prevent the battery from losing any more charge. The basic charge controllers are essential to proper charging of batteries in order to protect the batteries from damage.

3.8.2.2. PWM Charge Controllers

PWM charge controllers are similar to the basic charge controller. While basic charge controllers can only disconnect or connect the battery to stop overcharging, PWM charge controllers can actually control the amount of current charging the batteries in order to optimize the charging time. When the battery nears full capacity, the PWM charge controller switches the charging on and off using PWM (pulse width modulation) causing a “trickle” charge, which allows the battery to maintain a full charge. This feature optimizes the speed and efficiency of charging the battery.PWM and basic charge controllers both control the current going into the battery but do not attempt to optimize the efficiency of the solar panel.

3.8.2.3. Maximum Peak Power Trackers (MPPT) Charge Controllers

Maximum Peak Power Trackers (MPPT) charge controllers can optimize the power output from the solar panel, as well as charge the battery up to its optimal charge capacity. The problem with the PWM charge controller and basic charge controllers is that they operate the solar panels at the voltage level designated by the voltage level of the battery. As demonstrated earlier, the V-I characteristic of the solar panel is not linear. By operating at a fixed voltage level, nothing guarantees that this voltage level is where the maximum amount of power can be drawn. Further, the maximum power point will change due to irradiance and temperature guaranteeing that the PWM and basic charge controllers will rarely draw the maximum amount of power from the solar panel. The MPPT tracks this maximum power point and changes the operating point of the solar panels in order to constantly draw the maximum amount of power available. The MPPT allows for the maximum efficiency of the solar panel to be reached as well as control the batteries charging requirements.