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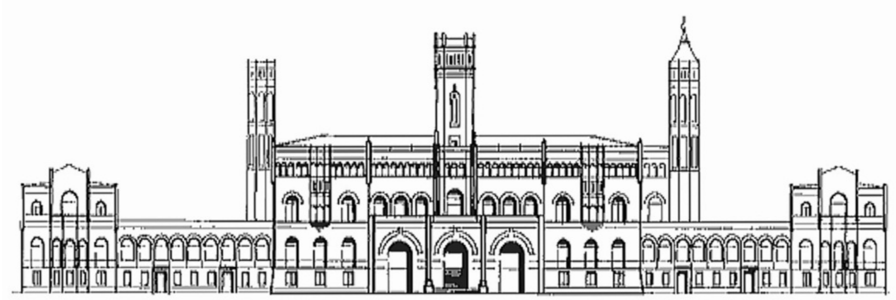

INSTITUTE FOR DRIVE SYSTEMS

AND POWER ELECTRONICS

Title

DCDC converter for photovoltaic powered battery charger

Master Thesis

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Matriculation Number: 2839510

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Autonomy

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I hereby declare that I have done this work myself and used no more sources and tools than the specified sources and tools.

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Contents

1 List of Abbreviation

PV	Photovoltaic
MPPT	Maximum Power Point Tracker
SC	Short Circuit
OC	Open Circuit
FF	Fill Factor
NOCT	Nominal Operating Cell Temperature
STC	Standard Test Condition
P&O	Perturb and Observation
INC	Incremental Conductance
CV	Constant Voltage
R_s	Series Resistance
R_{SH}	Shunt Resistance
ADC	Analog to Digital Converter
PCB	Printed Circuit Board

2 Introduction

Many mobile and off-grid devices include electronics and other electrical consumers like servo drives, which need a quite low supply power. Since the price for photovoltaic modules drops continuously, photovoltaic power supply is interesting in more and more applications. In solar powered systems, a battery is needed to store energy for the night and cloudy periods. The power electronics of such a system needs to convert the voltage of the solar panel to the voltage of the battery. Furthermore, it has to control the current in order to operate the solar panel in the Maximum Power Point or it has to shut down battery charging in case that the maximum battery voltage is reached.

2.1 Standalone photovoltaic systems

Stand-alone photovoltaic power systems are electrical power systems that are energized by photovoltaic (PV) panels. In this way they do not have any connection to utility grid. These systems can have power from milliwats to kilowats. During of night or the time that radiation is low, for supplying the load, the electric power supply such as battery is needed in order to ensure the supplying of the standalone system. Some standalone systems are design only for the time that irradiation is sufficient and during this time load is supplied with electric power directly. In this condition a storage system is not necessary.

Nowadays, it can be seen that in each part, standalone systems are used. For example in systems for traffic control, watches, solar calculators and etc. They can be a dc system with or without battery or ac system with inverter. In figure 1 a simple standalone system can be seen that is including of battery.

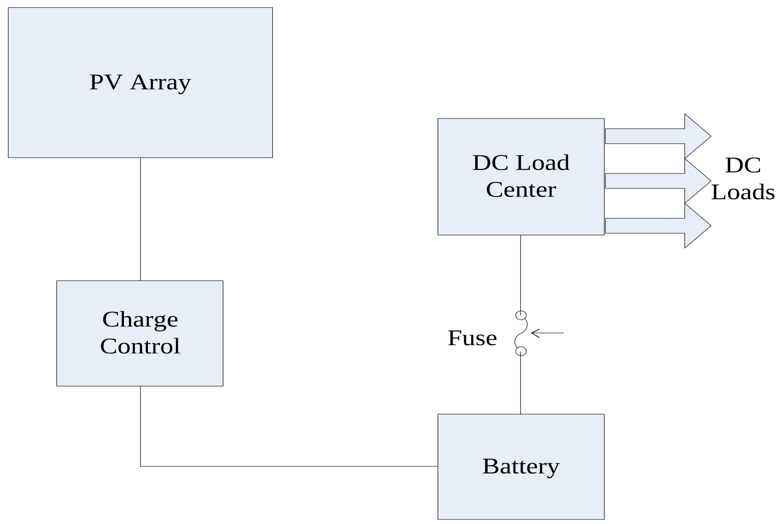

Figure 1: standalone system

2.2 PV Module

Electricity is generated directly by the conversion of the sun's energy into electricity by photovoltaic systems. This simple system involves advanced technology that is implemented to build efficient devices namely solar cells that are the main constituent of a PV system [1].

A photovoltaic system is a modular system because it is built by a number of pieces or elements, which have to be used to build larger system or to build smaller systems. The elements and components of a PV system are the photovoltaic devices and electronic equipment that are needed to interface the system to other system component, namely:

- A storage element in standalone systems
- The grid in grid-connected systems
- AC or DC loads, by suitable DCDC or DC/AC converters

In section 3, PV system will be described more in details

2.3 Maximum Power Point Tracker (MPPT)

Maximum power point tracking is a technique that some devices such as battery charger and other similar devices are used in order to get maximum possible power from one or more solar panels [2]. There are some factors that are effective in characteristic of the solar panel that can lead to have different characteristics. These factors are irradiation, temperature and total resistance that produce a non-linear output efficiency known as the I-V curve. It is the purpose of the MPPT technique that reaches to maximum power point by using some methods such as Perturb and Observation (P&O), Incremental conductance (IC), Constant Voltage (CV) and some other methods. In season 4, MPPT will be described in more details [3].

2.4 Step down converter

Buck converter is a step down DC to DC converter that in design is similar to step up boost converter and like a boost converter it is switched mode power supply .In both of the topologies, two switches are used; a transistor and a diode. In this thesis, voltage of the module is in range of the 36 V and it should be decreased to nominal voltage of the battery (12 V) so a buck converter is used in order to reaching to this goal.

There are some ways for reducing the dc output voltage such as a linear regulator, but it has some disadvantages. For example, linear regulators waste energy in operating time as a heat and leads to dissipating the power so for solving this problem, buck converter is used in order to decreased output voltage with minimum losses that can be remarkably efficient (95% or higher) making them useful for some tasks[4].

2.5 Battery

Rechargeable battery is a storage device that is a group of electrochemical cells. The electrochemical reactions of these batteries are electrically reversible so they are known as secondary cells. Nowadays, in markets there are different shapes of the rechargeable batteries and they are in different size. They are connected to stabilize an electrical distribution network. There are some different combinations of chemicals that are commonly used, including , lithium ion (Li-ion), lead–acid, nickel cadmium (NiCd), nickel metal hydride (NiMH)and lithium ion polymer (Li-ion polymer) [5].

In generally, rechargeable batteries in comparison with disposable batteries have lower total cost and also have lower environmental impact. The initial value of the rechargeable battery is higher than disposable batteries, but can be recharged very cheaply and used several times.

3 Photovoltaic Module

3.1 Introduction

Fossil fuel is very common choice in many countries worldwide that people use it and the main reason is that this kind of fuel has large sources, but nowadays by increasing concerns about some issues such as fossil fuel shortage, global warming, skyrocketing oil costs, and also damage to environment and ecosystem, the favorable stimulus to develop alternative energy with considering to high efficiency and low emission are of major importance. Among the renewable energy resources, the energy through the photovoltaic (PV) effect can be considered the most essential and prerequisite sustainable resource because of the profusion, ubiquity, and sustainability of solar radiant energy. For these reasons, it is mandatory to improve the know-how and skills in this field.

A photovoltaic (PV) system generates electricity by the direct conversion of the sun's energy into electricity. This simple principle involves advanced technology that is used to build efficient devices, namely solar cells, which are the key components of a PV system and require semiconductor processing techniques in order to be manufactured at low cost and high efficiency.

For designing and constructing of a PV power supply it is necessary to have enough knowledge about characteristics of PV panel .The output characteristics of PV module depends on the cell temperature, solar insolation and output voltage of PV module.

In following, after a briefly introduction about cell, module, and array, a cell is modeled and it can be used to predict the PV panel operation under different working conditions (i.e. surface temperature of the PV panel, irradiance and weather condition) .Data for modeling a PV module is according to SW 250 mono module data sheet.

3.2 PV cell

The PV cell is a specially designed pn junction or schottky barrier device. When the cell is illuminated, electron-hole pairs are produced by the interaction of the incident photons with the atoms of the cell. The electric field created by the cell junction causes the photon-generated-electron-hole pairs to separate, with the electrons drifting into the n-region of the cell and the holes drifting into the p-region.

The amounts of current and voltage available from the cell depend upon the cell illumination level. In the ideal case, the I-V characteristic equation is:

$$I = I_l - I_o\left(e^{\frac{qV}{kT}} - 1\right) \qquad (1)$$

where I_l is the component of cell current due to photons, q =1.6×10^{-19} coul(electron charge), k = 1.38×10^{-23} j/K (Boltzmann's constant) and T is the cell temperature in Kelvin (K). While the I-V characteristics of actual PV cells differ somewhat from this ideal version, provides a means of determining the ideal performance limits of PV cells [6].

3.3 Basic parameters of solar cells

There are certain parameters in the I-V characteristics of solar cell that are important for estimate the PV module that are mentioned in following notes [9].

3.3.1 Short Circuit Current (I_{sc})

Short circuit current is the light-generated current or photo current, I_l . It is the current in the circuit when the output is short circuited. It can be achieved by connecting the positive and negative terminals by copper wire.

3.3.2 Open Circuit Voltage (V_{oc})

To determine the open circuit voltage of the cell, the cell current is set to zero and first equation is solved forV_{oc}, yielding the result:

$$V_{oc} = \frac{kT}{q}\ln\frac{I_l + I_o}{I_o} \qquad (2)$$

The open circuit voltage is the voltage for maximum load (resistance) in the circuit. Note that the open circuit voltage is only logarithmically dependent on the cell illumination, while the short circuit current is directly proportional to cell illumination [7].

For a good solar cell, the series resistance, R_s (figure 5), should be very small and the shunt (parallel) resistance should be very large (figure 5). For commercial solar cells the shunt resistance is much greater than the forward resistance of a diode so that it can be neglected and only R_s is of interest [8].

3.3.3 Fill Factor (FF)

The fill factor, also known as the curve factor, is a measure of sharpness of the knee in an I-V curve. It indicates how well a junction was made in the cell and how low the series resistance has been made. The maximum value of the fill factor is one, which is not possible. Its maximum value in Si is 0.88.

$$FF = \frac{P_{max}}{V_{oc} \times I_{sc}} = \frac{V_{max} \times I_{max}}{V_{oc} \times I_{sc}} \qquad (3)$$

3.3.4 Maximum Power (P_{max})

No power is generated under short or open circuit. The power output is defined as:

$$P_{out} = V_{out} \times I_{out} \qquad (4)$$

The maximum power P_{max} provided by the device is achieved at a point on the characteristics, where the product IV is maximize. Thus:

$$P_{max} = V_{max} \times I_{max} \qquad (5)$$

The maximum possible output can also be given as

$$P_{max} = FF \times V_{oc} \times I_{sc} \qquad (6)$$

where FF is the fill factor.

3.3.5 Solar Cell Efficiency

The solar cell power conversion efficiency can be given as

$$\eta_{ce} = \frac{P_{max}}{P_{in}} = \frac{I_{max} \times V_{max}}{\text{Incident solar radiation} \times \text{Area of solar cell}} = \frac{V_{oc} \times I_{sc} \times FF}{I_{(t)} \times A_c} \quad (7)$$

where $I_{max}$and V_{max} are the current and voltage for maximum power, corresponding to solar intensity ($I_{(t)}$).

A maximum power point tracker (MPPT) is a high-efficiency DC-to-DC converter, which functions as an optimal electrical load for a photovoltaic (PV) cell, most commonly for a solar panel or array and converts the power to a voltage or current level which is more suitable to whatever load the system is designed to drive. PV cells have a single operating point where the values of the current (I) and Voltage (V) of the cell result in a maximum power output.

Note also that the voltage at which maximum power occurs is dependent upon the cell illumination level.

The PV cell I-V curve is also temperature sensitive. A quick look at second equation might suggest that the open circuit voltage is directly proportional to the absolute temperature of the cell.

It is important to remember that when a cell is illuminated, it will generally convert less than 20% of the irradiance into electricity. The balance is converted to heat, resulting in heating of the cell. As a result, the cell can be expected to operate above ambient temperature. If the cell is a part of a concentrating system, then it will heat even more, resulting in additional temperature degradation of cell performance [6].

The photocurrent developed in a PV cell is dependent on the intensity of the light incident on the cell. The photocurrent is also highly dependent on the wavelength of the incident light. PV cells are made of materials for which conversion to electricity of this spectrum is as efficient as possible. Depending on the cell technology, some cells must be thicker than others to maximize absorption. Cells are often coated with an antireflective coating to minimize reflection of sunlight away from the cells.

3.4 PV module

In order to obtaining adequate output voltage, PV cells are connected in series to form a PV module. Since PV systems are commonly operated at multiples of 12 volts, the modules are typically designed for optimal operation in these systems. With silicon single cell open-circuit voltages typically in the range of 0.5 – 0.6 volts; this suggests that a module should consist of 33–36 cells connected in series. With each individual cell capable of generating approximately 3.5-4 watts that it depends on size of the module.

When connecting a module into a system, one consideration is what happens when the module is not illuminated. This can happen at night, but can also happen during the day if any cell or portion of a cell is shaded by any means.

Under night time conditions, when none of the cells are generating appreciable photocurrent, it is necessary to consider the module as a series connection of diodes that may be forward biased by the system storage batteries.

When cells are mounted into modules, they are often covered with antireflective coating, then with a special laminate to prevent degradation of the cell contacts. The module housing is generally metal, which provides physical strength to the module. When the PV cells are mounted in the module, they can be characterized as having a nominal operating cell temperature (NOCT). The NOCT is the temperature the cells will reach when operated at open circuit in an ambient temperature of 20 ^{o}C at AM 1.5 irradiance conditions, G = 0.8 $\frac{KW}{m^2}$and a wind speed less than 1 $\frac{m}{s}$.

Since the open circuit voltage of a silicon cell decreases by 2.3 mV/^{o}C, the open circuit voltage of a module will decrease by 2.3n mV/^{o}C, where n is the number of series cells in the module.

3.5 PV Array

If higher voltages or currents than are available from a single module are required, modules must be connected into arrays. Series connections result in higher voltages, while parallel connections result in higher currents. When modules are connected in series, it is desirable to have each module's maximum power production occur at the same current. When modules are connected in parallel, it is desirable to have each module's maximum power production occur at the same voltage. Thus, during mounting and connecting modules, the installer should have this information available for each module.

Figure 2 shows how cells are configured into modules, and how modules are connected as arrays.

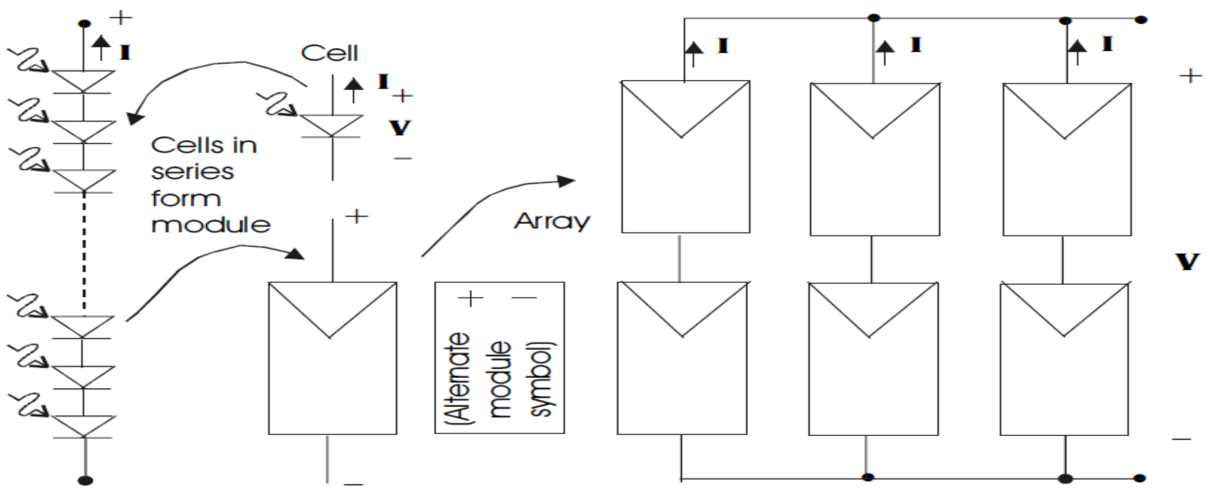

Figure 2: Cells, modules and arrays [6]

Since PV module has nonlinear characteristics, it is necessary to model it for the design and simulation of maximum power point tracking (MPPT) for PV system applications. The mathematical PV models used in computer simulation have been built for over the past four decades. Almost all well-developed PV models describe the output characteristics mainly affected by the solar insolation, cell temperature, and load voltage [10], [11], [12].

For survey and analyze the implementing of the solar cell the equivalents are needed in order to have I-V and P-V characteristics.

In following general model for PV cell is considered [13] and modeled it according to equations that are shown. Also, the nonlinearity of PV current versus voltage (I-V) and power versus voltage (P-V) characteristics are shown as well and influence of temperature and irradiance on them is analyzed.

3.6 Solar Panel

In photovoltaic systems, operating near the maximum power point is important. Maximum power operation is a challengeable issue, since the load should be capable to use all power available from PV system at all the times.

In figure 3, for different illumination levels, the operating point for ideal load is shown that will intersect the locus of maximum power pints on the I-V characteristic of the PV array.

According to above notes, it is desirable that operating point should be at intersection of the I-V characteristic of the load and PV source so, if the intersection of the I-V characteristic of a load with PV source depart from the maximum power point of the PV source, it is necessary to use a maximum power tracker between the array and the load.

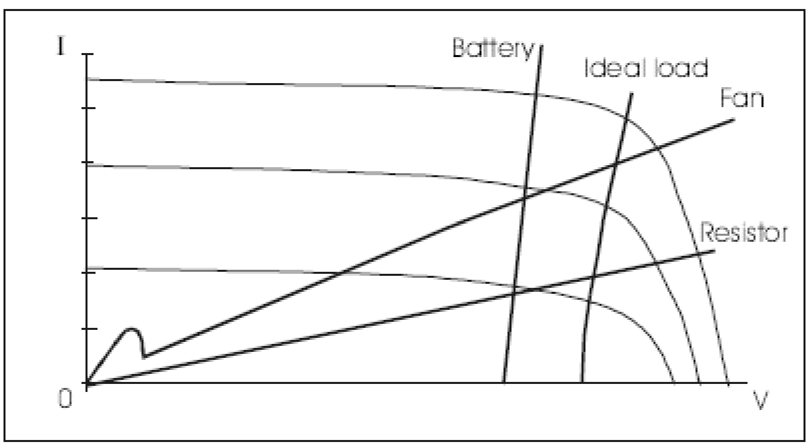

Figure 3: I-V characteristics for several common loads along with ideal load I-V characteristic for maximum power operation of a PV system

There are some techniques in order to reaching the maximum power point. These techniques generally employ pulse width modulation to switch from an input dc voltage to an output dc voltage at a different level. The MPPT employs a feedback loop to sense the output power and changes the output voltage until the maximum power is realized [6].

Most of the electrical power sources are constant voltage sources, such as the battery, but photovoltaic cell is an unusual power source and it is a constant current source. The PV cell displays the constant current characteristic up to a limiting voltage where the current collapses and the voltage where the current collapses would be at the open circuit voltage (V_{oc}) for an ideal PV module.

In figure 4, the typical I-V curve is shown. By passing some current through the internal resistance of the PV cell, the current is drop slightly .This slight current drop is shown between points M and A. Between points A and S, the load resistance increases forcing some of the current to follow through the diode (figure 5) that leads to fast drop in current to the load. This current-drop continues until point S where all the current flow through the diode and the internal resistance.

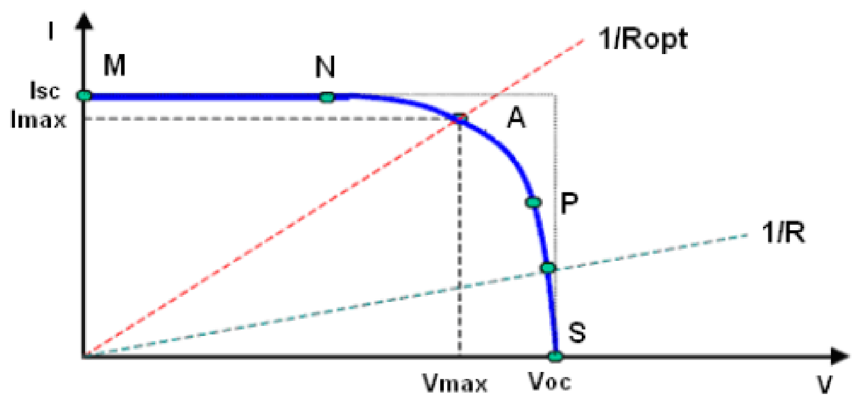

Figure 4: Typical current-voltage I-V curve

I-V and P-V characteristics of the PV are dependent more to irradiance and cell temperature. By altering the amount of sun light that is available to PV module, the current that the module can produce is also altered so the output power and current of solar panel is approximately proportional to irradiance.

The effect of the temperature on the current of the PV cell is small. In following, simulation results in order to showing the influence of the changing cell temperature and irradiance are shown. According to them, by increasing the temperature, the cell voltage is increased slightly however by increasing the temperature a slightly higher current is produced.

As it mentioned above, the PV operating point can be changed by variation of the load. This effect can be employed by Ohm low: $I = \frac{V}{R}$

In figure 4, the load lines are shown for different load resistance. In I-V characteristic, the slopes of these load lines are given by 1/R so, according to this slop (1/R), lower resistance leads to have steeper load lines and higher resistance results in flatter load lines. On the other hand, the operating point is specific by restriction point of load line and I-V curve so, if the irradiance is changed, the operating point is changed too, but for a given irradiance there is only one load resistance that will produced maximum power.

The irradiance is not constant and through the day is changed so, in order to operating at maximum power point in different irradiance, maximum power point trackers are needed to match the operating point to the load resistance.

3.7 Solar cell model

The equivalent circuit of a PV cell (figure 5) is a current source that is proportional to the incident radiation in parallel with a diode (D) and a shunt resistance (R_{SH}).This resistance is inversely related with shunt leakage current to the ground. The internal losses due to current flow and the connection between cells are modeled as a small series resistance R_S[14].

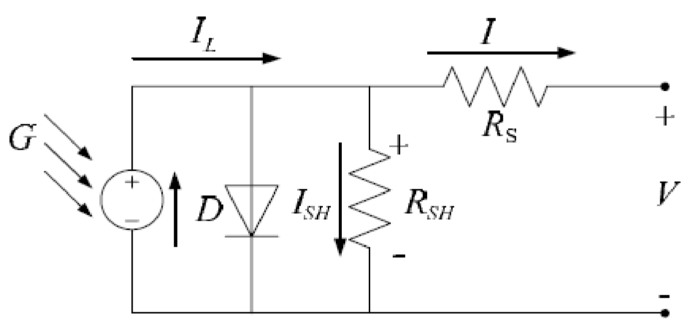

Figure 5: circuit diagram of PV module

The PV efficiency is not sensitive to variation in $R_{SH}$and the shunt-leakage resistance can be assumed to approach infinity without leakage current to ground. On the other hand, a small variation in R_S will significantly affect the PV output power so, by assuming $R_{SH}$to infinity it is changed to open circuit. Then equation (8) can be defined which shows the net current I of the cell and by this equation, the I-V characteristic is described.

$$I = I_l - I_o\left(e^{\frac{q(V+R_s.I)}{n.k.T}} - 1\right) \qquad (8)$$

Which $I_l$is a light-generated current or photocurrent, $I_o$is the cell saturation of dark current, n is ideality diode factor and its value ranges between 1 and 2, q (=1.6 $\times$ 10^{-19}C) is an electron charge, k (=1.38 $\times$ 10^{-23}J/K) is a Boltzmann's constant, T is the cell's working temperature, $R_{sh}$is a shunt resistance, and R_s (figure 5) is a series resistance. For drawing I-V curve, equation (8) should be solved, but it is nonlinear. For solving it, numerical method is used (Newton Raphson's method).

Photocurrent, saturation current and open circuit current depend on the temperature (same as other equation that can be seen in following) and are defined by these equations [14]:

$$I_L = I_L(T_1) + K_o(T - T_1) \qquad (9)$$

$$I_L(T_1) = I_{SC}(T_1)\frac{G}{G_{ref}} \qquad (10)$$

$$K_o = \frac{I_{SC}(T_2) - I_{SC}(T_1)}{(T_2 - T_1)} \qquad (11)$$

$$I_o = I_o(T_1) \times \left(\frac{T}{T_1}\right)^{\frac{3}{n}} . e^{\frac{q.V_g.(T_1)}{n.K.\left(\frac{1}{T}-\frac{1}{T_1}\right)}} \qquad (12)$$

$$I_o(T_1) = \frac{I_{sc}(T_1)}{\left(e^{\frac{q.V_{oc}(T_1)}{n.K.T_1}} - 1\right)} \qquad (13)$$

where V_g is the band gap energy (1.12ev for Si) and G is the irradiation. The subscript ref identifies the Standard Test Conditions (STC) defined in the IEC 61215 international standard [10]; in particular T_{ref} = 25 °C (T_1 in equations) and G_{ref} = 1000 $\frac{W}{m^2}$. I_{SC} (T_{ref}) and V_{oc} are specified in data sheet of the company.