MODELING OF PHOTOVOLTAIC SYSTEMS

A Thesis

Presented in Partial Fulfillment of the Requirements for
the Degree Master of Science in the
Graduate School of The Ohio State University

By

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* * * * *

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Distributed generation (DG) offers great potential in meeting future global energy needs. The dwindling supplies of crude oil and natural gas and the global challenges of climatic change and other environmental concerns have resulted in rapid growth of alternative energy sources. This thesis investigates various approaches to the modeling of photovoltaic systems. The mathematical model of the current-voltage characteristics of solar cells is an implicit nonlinear equation that is very difficult to solve. The complexity in modeling solar cells is further compounded by the fact that the solar cell parameters vary with changes in environmental conditions. Analytical methods and empirical methods used in modeling are presented.

Key words: Photovoltaics, Modeling, Neural Networks, Power Converters, Distributed Generation.
To the memory of my mother,
Our Guardian Angel
R. Dzimano
1939-2000
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CHAPTER 1

INTRODUCTION

1.1 Background

Of late, the interest in Distributed Energy Systems (DES) is increasing \cite{1}. Photovoltaic systems have become increasingly popular and are ideally suited for distributed systems. Because of strict environmental regulations, the lack of corridors for building high voltage transmission systems and security issues, larger power plants have become uneconomical in many regions. Additionally, recent technological advances in small generators, power electronics, and energy storage devices have provided a new opportunity for distributed energy resources that are located closer to loads. Many governments have provided the much needed incentives to promote the utilization of renewable energies, encouraging a more decentralized approach to power delivery systems.

In spite of their relatively high cost, there has been very remarkable growth in installed Photovoltaic systems. Recent studies show an exponential increase in the worldwide installed photovoltaic power capacity \cite{2}. There is ongoing research aimed at reducing the cost and achieving higher efficiency. Furthermore, new regulatory laws mandating the use of renewable energy have expanded this market around the world.
Currently, photovoltaic generation systems are actively being promoted in order to mitigate environmental issues such as the greenhouse effect and air pollution. Solar energy is the world’s major renewable energy source and is available everywhere in different quantities. Photovoltaic panels do not have any moving parts, operate silently and generate no emissions. Another advantage is that solar technology is highly modular and can be easily scaled to provide the required power for different loads.

1.2 Motivation of thesis

Modeling is a very important part of any engineering practice. Nowadays with the use of computers and powerful software extremely complex systems can be simulated and their performance can be predicted and monitored. A typical photovoltaic system may consist of the solar generator itself and other components that maybe any one of the following: storage elements (especially in stand alone systems); the utility grid; power converters (DC/DC or Inverters) and associated control circuitry.

Availability of models of all these components (especially for the photovoltaic generator itself) at all stages in system development is very important in system sizing, cost analysis and monitoring. Moreover, such models may be tested together with other distributed system models in order to evaluate and predict the overall system performance. This thesis presents various techniques, challenges and directions in modeling photovoltaic systems. Special design considerations are needed for photovoltaic systems. Environmental conditions have a huge influence on the characteristics and performance of a photovoltaic module.
For a power electronics engineer working with renewable energies, it is therefore imperative to have an accurate model at one’s disposal as it aids in testing and development of optimal power converters together with their associated control algorithms. Because the efficiency of photovoltaic generators is relatively low, converters must be designed in such a way that they can harvest as much power as possible from the modules. This in turn requires accurate models to ensure that designs can be easily tested for performance through simulations.

1.3 Outline of the thesis

The thesis was prepared with every effort to ensure clarity and to make it easier to read. The rest of the thesis is organized as follows. Chapter 2 presents some background knowledge on photovoltaic materials and the solar resource required to understand future parts of the thesis. Photovoltaic materials that are currently in use are described and performance measures of photovoltaics and some solar related terms are defined. Chapter 3 describes in detail the various components that constitute photovoltaic systems as they are configured today. The different types of systems are outlined and the balance of system components are also described. Chapter 4 describes the Sandia model, a very accurate empirical model developed over 12 years. Chapter 5 delves into the modeling of the photovoltaic generators. It describes the various modeling techniques for photovoltaics. The single and double exponential models are presented as lumped circuit models of PV modules. Parameter extraction techniques are presented. Some results are presented in Chapter 6 and Chapter 7 concludes the thesis. The results and contributions are summarized and discussed. Furthermore some future directions in research are identified.
1.4 Thesis contribution

This thesis presents in detail challenges and modeling approaches of photovoltaic systems. It presents in a clear way the different techniques that are used to model photovoltaics. The thesis also explains how the Sandia points can be used to regenerate a close approximation of the I-V curve of a photovoltaic module.
CHAPTER 2

PRELIMINARIES

Photovoltaics generate electric power when illuminated by sunlight or artificial light. They directly convert the sun’s energy into electricity which can be easily transported and converted to other forms for the benefit of society. In terms of power they come in various sizes from $mW$ to $MW$ ranges. This modular structure allows one to scale them depending on application. Practically, they may consist of one or more solar modules in combination with other balance of system components (BOS) covered by the National Electric Code (NEC). The balance of system components include mounting materials for the modules, wire and all wiring components, lightning protectors, grounding connections, power converters and battery storage.

2.1 Solar resource

2.1.1 Introduction

Knowledge of the sun is very important in the optimization of photovoltaic systems[3]. Solar energy is the most abundant renewable resource. The electromagnetic waves emitted by the sun are referred to as solar radiation. The amount of sunlight received by any surface on earth will depend on several factors including; geographical location, time of the day, season, local landscape and local weather. The light’s angle
of incidence on a given surface will depend on the orientation since the Earth’s surface is round and the intensity will depend on the distance that the light has to travel to reach the respective surface. The radiation received by a surface will have two components one which is direct and will depend on the distance the rays travel (air mass). The other component is called diffuse radiation and is illustrated in figure 2.1. The range of wavelengths of light that reach the earth varies for 300 nm to 400 nm approximately. This is significantly different from the spectrum outside the atmosphere, which closely resembles ‘black body’ radiation, since the atmosphere selectively absorbs certain wavelengths.
2.1.2 Spectrum of the sun

Two different spectral distributions have been defined for the sun. The AM0 spectrum relates to radiation in outer space and the AM 1.5 G spectrum is at sea level at certain standard conditions. The photovoltaic (PV) industry and the American Society for Testing and Materials (ASTM), American government research and development laboratories have developed and defined two standard terrestrial solar spectral irradiance distributions: a standard direct normal and a standard total spectral irradiance. An instrument called the pyranometer is used to measure global radiation. This instrument is designed to respond to all wavelengths and therefore gives an accurate value of the total power in any incident spectrum.

The solar spectrum is shown in 2.2. Important terms are defined as follows [4].

1. Spectral irradiance $I_\lambda$ has units of $W/m^2\mu m^{-1}$ and refers to the power received by a unit surface area in a wavelength differential $d\lambda$.

2. Irradiance - has units of $Wm^{-2}$ and refers to the integral of the spectral irradiance over all the respective wavelengths.

3. Radiation - refers to the integral of Irradiance over a specified time period.

2.1.3 Standard test conditions (STC)

Uniform conditions are usually specified so that a performance comparison can be made between different PV units (cell, modules). The parameters obtained from the testing are usually provided on the manufacturer’s datasheet. Measurements are performed under these standard test conditions and the electrical characteristics
obtained characterize the module accurately under these conditions. The conditions are specified as follows:

1. The reference vertical irradiance $E_o$ with a typical value of 1000W/m$^2$

2. Reference cell temperature for performance rating, $T_o$ with a typical value of 25°C and a tolerance of ±2°C;

3. A specified light spectral distribution with an air mass, AM =1.5. Air mass figures provide a relative measure of the path the sun must travel through the atmosphere.
In addition to supplying performance parameters at the Standard Test Conditions manufacturers also provide performance data under the Nominal Operating Cell Temperature (NOCT) \[5\]. This is defined as the temperature reached by the open-circuited cells in a module under the following conditions:

- Irradiance on cell surface is 800\text{W/m}^2
- The ambient temperature is 20°C (293 K)
- is 1\text{m/s} and the mounting is open back side

To account for other ambient conditions the approximate expression below may be used:

\[ T_{\text{cell}} = T_{\text{amb}} + \frac{\text{NOCT} - 20}{0.8} S \]  \hspace{1cm} (2.1)

where \(T_{\text{cell}}\) is cell temperature (°C), \(T_{\text{amb}}\) is the ambient temperature, (NOCT) is the Nominal Operating Cell Temperature and \(S\) is the solar insolation (kW/m\(^2\)).

2.2 Photovoltaic performance

2.2.1 PV characteristics

There are three classic parameters that are very important on the PV characteristics namely short-circuit current \((I_{sc})\), open-circuit voltage \((V_{oc})\) and the maximum power point \((I_{mp}, V_{mp})\). The power delivered by a PV cell attains a maximum value at the points \((I_{mp}, V_{mp})\). The classical points are shown in Figure 2.3 and are usually given as part of a manufacturer’s data sheet for a PV module as shown in Table 2.1. This information is enough to build a simple model of the module to test power converters, but for a more accurate model more information is required.
Another important parameter of the PV characteristics is called the Fill Factor (FF) is shown in Figure 2.4. It is a term that describes how the curve fills the rectangle that is defined by \((V_{oc})\) and \((I_{sc})\). It gives an indication of the quality of a cell’s semiconductor junction and measures of how well a solar cell is able to collect the carriers generated by light. It is defined as:

\[
FF = \frac{V_{mpp}I_{mpp}}{V_{oc}I_{oc}} \tag{2.2}
\]

After a simple manipulation the following equation results:

\[
V_{oc}I_{oc} \cdot FF = V_{mpp}I_{mpp} = P_{max} \tag{2.3}
\]
It can be easily observed that $FF$ is always $< 1$ and ranges from material to material. The closer the value of the fill factor is to unity, the better the operation of the PV cell. For high quality cells, fill factors over 0.85 can be achieved (see Table 2.2). For typical commercial devices the value lies around 0.68.

2.2.2 PV efficiency

The efficiency $\eta$ is defined as the ratio of the maximum output power $P_{mp}$ to the solar power received by the cell surface, $P_L$:

$$\eta = \frac{V_{mp}I_{mp}}{P_L} \quad (2.4)$$
Table 2.1: Electrical characteristics provided on a datasheet

<table>
<thead>
<tr>
<th>General Specs</th>
<th>Thermal Characteristics:</th>
</tr>
</thead>
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<tr>
<td>Open Circuit Voltage ((V_{oc}))</td>
<td>Temp. coefficient of (Voc) ((V/\circ C))</td>
</tr>
<tr>
<td>Short Circuit Current ((I_{sc}))</td>
<td>Temp. coefficient of (Isc) ((A/\circ C))</td>
</tr>
<tr>
<td>Maximum Power, Watts ((P_{max}))</td>
<td></td>
</tr>
<tr>
<td>Maximum Power Voltage ((V_{mp}))</td>
<td></td>
</tr>
<tr>
<td>Maximum Power Current ((I_{mp}))</td>
<td></td>
</tr>
<tr>
<td>Maximum System Voltage</td>
<td></td>
</tr>
</tbody>
</table>

Equation 2.4 can be rewritten as:

\[
\eta = FF \frac{V_{oc} I_{sc}}{P_L} = FF \frac{V_{oc} I_{sc}}{\int_{0}^{\infty} P(\lambda)d\lambda}
\]  

(2.5)

where \(P(\lambda)\) is the solar power density at wavelength \(\lambda\). If different loss factors are taken into account the following results [3],

\[
\eta = \frac{\int_{0}^{\lambda_g} P(\lambda)d\lambda}{\int_{0}^{\infty} P(\lambda)d\lambda} \cdot \frac{E_g \int_{0}^{\lambda_g} N(\lambda)d\lambda}{\int_{0}^{\infty} P(\lambda)d\lambda} \cdot \frac{q V_{oc}}{E_g} \cdot FF \cdot \frac{1}{v} \cdot \frac{Af}{A_L} \cdot \frac{\eta_d}{v_i} \cdot \frac{\eta_{col}}{v_{ii}}
\]  

(2.6)

The terms in equation 2.6 above account for different loss factors in the solar energy conversion. Long wavelengths have energy smaller than \(E_g - E_{phonon}\) and can not contribute to the creation of electron-hole pairs accounting for (i). The term (ii) accounts for loss due to the excess energy of photons which is dissipated as heat.

Term (iii) is the voltage factor and is the ratio of the maximum voltage developed by the cell \(V_{oc}\) to the bandgap voltage \((\frac{E_g}{q})\) is limited by Auger recombination giving an upper bound of 0.65 for thick silicon cells. The fill factor (FF-term (iv)) is ideally 0.89 but assumes a lower value due to carrier recombination, series resistance and shunt resistance losses. The preceding terms all represent fundamental losses.

Losses due to limits in technology are accounted for by the terms v-viii. The surface
of the cell reflects part of the incident light resulting in term (v). The use of anti-reflective coatings and surface texturing considerably improves performance. Term (vi) accounts for loss by metal coverage where $A_f$ is the area of the front surface not covered by metal contacts and $A_t$ is the total area. Incomplete absorption is accounted for by term (vii); special light trapping techniques are used to increase absorption. The last term (viii) represents collection efficiency: not all the generated carriers reach the junction and are collected, they may recombine in the bulk or at the surface.

2.3 PV materials

2.3.1 Introduction

PV cells are made of semiconductor materials with crystalline and thin films being the dominant materials. The majority of PV-cells are silicon-based but in the near future other thin film materials are likely going to surpass silicon PV cells in terms of cost and performance [6]. PV materials may fall into one or more of the following classes: crystalline, thin film, amorphous, multi-junction, organic or photochemical.

2.3.2 Crystalline materials

Single-crystal silicon

Mono-crystalline silicon cells have in the past dominated the PV market but have now been overtaken by poly-crystalline silicon. The popularity of mono-crystalline silicon was due to the good stability and desirable electronic, physical and chemical properties of silicon. Moreover, silicon was already successful in microelectronics and the enormous industry thus created would benefit the smaller PV industry with regards to economy of scale [3].
Poly-crystalline silicon

This is the currently most dominant material and has surpassed the mono-crystalline because it is cheaper. The cost of silicon is a significant portion of the cost of the solar cell. The manufacturing processes of poly-crystalline silicon reduces the cost of silicon by avoiding pulling in the manufacturing process and it results in a block with a large crystal grain structure. This results in cheaper cells with a somewhat lower efficiency. The assembly of multi-crystal wafers is easier and therefore offsets the low efficiency disadvantage.

Gallium Arsenide

This material is a compound semiconductor made of gallium and arsenic. It has a crystalline structure and has a high level of light absorptivity. GaAs has higher efficiency than silicon but its main drawback is its cost. It is used in space applications and in concentrator systems.

2.3.3 Thin-film materials

Since the 1990s development of thin-film, processes for manufacturing solar cells have increased. These PV devices are made using very thin semiconductor films deposited on some type of low-cost structural substrate such as glass, metal or plastic. Epitaxial processes (such as vapor deposition, sputter processes and electrolytic baths) are used to achieve this. Because thin-film materials have high absorptivity, the deposited layer of PV material is extremely thin. This results in the reduction of the dominating material cost although thin-film PV cells suffer from poor cell conversion efficiency. There are several types of thin-film materials.
Amorphous silicon

This material has a significant advantage of higher light absorptivity, about 40 times that of crystalline silicon. It can be deposited on a low cost substrate and the manufacturing process requires low temperature and therefore less energy. It has lower material and manufacturing costs. Amorphous hydrogenated silicon (a-Si:H) has been widely used by the Japanese to power small consumer goods such as watches and calculators \[6\]. This material is a non-crystalline for silicon and does not form a regular crystal structure, but an irregular network. The material is highly defective even with hydrogenation so the minority carrier lifetimes are very low resulting in low conversion efficiency. A major drawback of this material is that it degrades under sun exposure, a mechanism called the Staebler-Wroski effect.

Cadmium Telluride (CdTe)

This is one of the most promising thin film solar cells. The material is a polycrystalline semiconductor compound made of cadmium and tellurium. CdTe has the lowest production cost among the current thin-film technologies. Low-cost soda-lime glass is used as the substrate. The manufacturing processes have greatly improved over the past few years. The CdS film is grown either by chemical bath deposition (CBD), close space sublimation (CSS), chemical vapor deposition (CVD), sputtering, or vapor transport deposition (VTD). This material has a very high absorption coefficient.

Copper Indium Diselenide (CIGS)

CIGS is a polycrystalline semiconductor compound of copper, indium and selenium, and has been a major research area in the thin film industry. It is another
promising material for thin-film solar cells. It can achieve high energy conversion efficiency and does not suffer from outdoor degradation problem and has demonstrated that thin film PV cells are a viable and competitive choice for the solar industry in the future. This material also has a high absorption coefficient with only 0.5 micrometers needed to absorb 90% of the solar spectrum. However it is a very complex material making it difficult to manufacture. Moreover its manufacturing process involves hydrogen selenide, an extremely toxic gas raising safety concerns.

2.3.4 Future of the PV industry

The future of the Photovoltaic industry is promising as the efficiency of the cell and submodules continues to increase. The table 2.2 shows the most recent confirmed efficiency of modules of various photovoltaic materials [8]. As technology and manufacturing processes continue to improve higher efficiencies are expected in the near future.

<table>
<thead>
<tr>
<th>Material</th>
<th>Efficiency</th>
<th>$V_{oc}$</th>
<th>$I_{oc}$</th>
<th>Fill Factor (FF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si (crystalline)</td>
<td>22.7 ± 0.6</td>
<td>5.6</td>
<td>3.93</td>
<td>80.3</td>
</tr>
<tr>
<td>Si (large crystalline)</td>
<td>20.1 ± 0.6</td>
<td>66.1</td>
<td>6.30</td>
<td>78.7</td>
</tr>
<tr>
<td>Si (multicrystalline)</td>
<td>15.3 ± 0.4</td>
<td>14.6</td>
<td>1.36</td>
<td>78.6</td>
</tr>
<tr>
<td>Si (thin-film polycrystalline)</td>
<td>8.2 ± 0.2</td>
<td>25.0</td>
<td>0.328</td>
<td>68.0</td>
</tr>
<tr>
<td>CIGSS</td>
<td>13.4 ± 0.7</td>
<td>31.2</td>
<td>2.16</td>
<td>68.9</td>
</tr>
<tr>
<td>CdTe (thin film)</td>
<td>10.7 ± 0.5</td>
<td>26.21</td>
<td>3.205</td>
<td>62.3</td>
</tr>
<tr>
<td>a-sI/A-SiGe/a-SiGe (tandem)</td>
<td>10.4 ± 0.5</td>
<td>4.353</td>
<td>3.285</td>
<td>66.0</td>
</tr>
</tbody>
</table>

Bulk crystalline Si devices are likely going to remain dominant for the next decade. Thin-film technologies are maturing fast and may soon challenge the market share
of crystalline Silicon devices. The dominant future technology will be determined largely by material availability and costs.
CHAPTER 3

PHOTOVOLTAIC SYSTEMS

Photovoltaic systems are composed of interconnected components designed to accomplish specific goals ranging from powering a small device to feeding electricity into the main distribution grid. Photovoltaic systems are classified according to the diagram in Figure 3.1. The two main general classifications as depicted in the figure are the stand-alone and the grid-connected systems [9]. The main distinguishing factor between these two systems is that in stand-alone systems the solar energy output is matched with the load demand.

To cater for different load patterns, storage elements are generally used and most systems currently use batteries for storage. If the PV system is used in conjunction with another power source like a wind or diesel generator then it falls under the class of hybrid systems. The balance of system (BOS) components are a major contribution to the life cycle costs of a photovoltaic system. They include all the power conditioning units, storage elements and mechanical structures that are needed. They especially have a huge impact on the operating costs of the PV system.
3.1 PV hierarchy

3.1.1 PV cell

PVs generate electric power when illuminated by sunlight or artificial light. To illustrate the operation of a PV cell the p-n homojunction cell is used. PV cells contain a junction between two different materials across which there is a built in electric field. The absorption of photons of energy greater than the bandgap energy of the
semiconductor promotes electrons from the valence band to the conduction band, creating hole-electron pairs throughout the illuminated part of the semiconductor [6]. These electron and hole pairs will flow in opposite directions across the junction thereby creating DC power.

The cross-section of a pv cell is shown in Figure 3.2. The most common material used in pv cell manufacture is mono-crystalline or poly-crystalline silicon. Each cell is typically made of square or rectangular wafers of dimensions measuring about 10\text{cm} \times 10\text{cm} \times 0.3\text{mm} [6]. In the dark the PV cell’s behavior is similar to that of a diode and the well known Shockley-Read equation can be used to model its behavior i.e $i = I_s[e^{\frac{qV}{nkT}} - 1]$. 

![Figure 3.2: Structure of a PV cell](image)
3.1.2 Module

For the majority of applications multiple solar cells need to be connected in series or in parallel to produce enough voltage and power. Individual cells are usually connected into a series string of cells (typically 36 or 72) to achieve the desired output voltage. The complete assembly is usually referred to as a module and manufacturers basically sell modules to customers. The modules serves another function of protecting individual cells from water, dust etc. as the solar cells are placed into an encapsulation of single or double flat glasses.

![Figure 3.3: Structure of a PV module with 36 cells connected in series](image)

Within a module the different cells are connected electrically in series or in parallel although most modules have a series connection. Figure 3.3 shows a typical connection of how 36 cells are connected in series. In a series connection the same current flows through all the cells and the voltage at the module terminals is the sum of the
individual voltages of each cell. It is therefore, very critical for the cells to be well matched in the series string so that all cells operate at the maximum power points. When modules are connected in parallel the current will be the sum of the individual cell currents and the output voltage will equal that of a single cell.

3.1.3 Array

An array is a structure that consists of a number of PV modules, mounted on the same plane with electrical connections to provide enough electrical power for a given application. Arrays range in power capacity from a few hundred watts to hundreds of kilowatts. The connection of modules in an array is similar to the connection of cells in a single module. To increase the voltage, modules are connected in series and to increase the current they are connected in parallel. Matching is again very important for the overall performance of the array. The structure of an array is shown in figure 3.4 which has 4 parallel connections of 4 module strings connected in series.

The voltages for \( n \) modules in series is given as:

\[
V_{\text{series}} = \sum_{j=1}^{n} V_j = V_1 + V_2 + \ldots + V_n \quad \text{for } I > 0 \tag{3.1}
\]

\[
V_{\text{seriesOC}} = \sum_{j=1}^{n} V_j = V_{oc1} + V_{oc2} + \ldots + V_{ocn} \quad \text{for } I = 0 \tag{3.2}
\]

The current and voltage for \( m \) modules in parallel is given by:

\[
I_{\text{parallel}} = \sum_{j=1}^{m} I_j = I_1 + I_2 + \ldots + I_m
\]

\[
V_{\text{parallel}} = \quad V_1 = V_2 = \ldots = V_m \tag{3.3}
\]

For an array to perform well all the modules must not be shaded otherwise it will act as a load resulting in heat that may cause damage. Bypass diodes are usually
used to avoid damage although they result in further increase in cost. Integration of bypass diodes in some large modules during manufacturing is not uncommon and reduces the extra wiring required. It must be pointed out though that it becomes very difficult to replace the diode if it fails.

3.1.4 Standalone systems

Historically the first cost-effective application of photovoltaics were stand-alone systems especially in remote areas where it was not feasible or prudent to connect to the main utility grid. Solar power is also seeing growth in small applications, the majority of which, are portable electronic goods such as calculators, watches, flashlights just to name a few. A stand-alone system is shown in Figure 3.5.
In the developing world stand-alone systems will go a long way in rural electrification. They can also be used for mobile equipment and communication systems and water pumping systems. Typically a stand-alone system comprises of the solar module(s), some power conditioning and control units (converters: dc-dc, inverter), some storage elements and the load.

### 3.1.5 Hybrid systems

In cases where it is not feasible economically or practically to supply the requisite energy from PV modules other means are used. In most cases the PV system is used in conjunction with a Diesel generator. Such a hybrid system ensures that energy demands are met while fully utilizing the PV supply. A typical hybrid system is shown in Figure 3.6.
3.1.6 Grid connected systems

Grid connected PV systems provides a person or business the opportunity to be self sufficient in terms of energy while protecting the environment. Installed grid connected systems have increased considerably over the recent years with Germany alone boasting close to (1 GW) of installed PV power by the year 2004 \[10\]. More installations are going to be witnessed as governments are putting in place more legislations to promote the use of renewable energy and the cost of PV systems continues to reduce.

Most technical issues with regards to connection of PV systems to the utility grid have been solved; IEEE adopted standard 929-2000 in 2000 \[9\]. In the standard the integration of PV systems to electricity networks is covered in two main categories: safety and power quality. The IEEE Std 929 states that the limits on the total harmonic distortion caused by the PV system at the point of common coupling (PCC)
must comply with Clause 10 of IEEE Std 519-1992. These limits are shown in Table 3.1. These limits apply to six pulse converters and for general distortion situations for pulse numbers greater than six a conversion formula is given [11].

With regards to safety, an important issue that has been extensively studied is the issue of islanding whereby the inverter is supposed to automatically shut down if the source of power is disconnected from the network. If this does not happen the safety of the utility staff and public will be critically compromised. Another issue is Radio Frequency Suppression which demands proper filtering and shielding.

Table 3.1: Distortion limits as recommended in IEEE Std 519-1992 for six-pulse converters

<table>
<thead>
<tr>
<th>Odd harmonics</th>
<th>Distortion limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$3^{rd} - 9^{th}$</td>
<td>$&lt; 4%$</td>
</tr>
<tr>
<td>$11^{th} - 15^{th}$</td>
<td>$&lt; 2%$</td>
</tr>
<tr>
<td>$17^{th} - 21^{st}$</td>
<td>$&lt; 1.5%$</td>
</tr>
<tr>
<td>$23^{rd} - 33^{rd}$</td>
<td>$&lt; 0.6%$</td>
</tr>
<tr>
<td>above $33^{rd}$</td>
<td>$&lt; 0.3%$</td>
</tr>
</tbody>
</table>
3.2 Power electronic converters

The role of power electronic converters is to provide power to the user in a suitable form at high efficiency. Power electronic converters are needed in PV systems to convert DC voltage to the required values and to convert from DC to AC and vice versa [12]. In addition they control the charging and discharging of batteries in systems where batteries are storage elements.

3.2.1 Buck converter

The Buck converter is one of the simplest power electronics circuits and basically consists of an inductor, a power electronic switch (usually a MOSFET or an IGBT) and a diode. It may have a capacitor to smooth the output. Its function is to step down DC voltage and is shown in Figure 3.8.

![Figure 3.8: Functional circuit of a buck converter](image.png)
If the switch is turned on and off repeatedly at very high frequencies (\(10kHz \rightarrow 100MHz\)) and assuming that in the steady state the output will be periodical then:

\[
v_o(t + T) = v_o
\]

\[
i_o(t + T) = i_o
\] (3.4)

The current in the load is given by \(I_R = V_o/R\). The average DC component of the capacitor current must be equal to zero otherwise the capacitor voltage will be increasing and there will be no periodic steady state. If the switch is turned on and off repeatedly at very high frequencies (\(10kHz \rightarrow 100MHz\)) and assuming that in the steady state the output will be periodical then:

\[
\langle i_C \rangle = I_C = 0
\]

\[
\langle i_L \rangle = I_L = I_R = V_o/R
\] (3.5)

Likewise the DC component of voltage across the inductor has to be zero:

\[
\langle v_L \rangle = \frac{1}{T} \int_T v_L dt = 0
\] (3.6)

The duty ratio \(D\) is defined as the fraction of the switch period during which the switch is on:

\[
D \equiv \frac{t_{on}}{T}
\] (3.7)

The average voltage across the inductor will be given by:
\[
\langle v_L \rangle = \frac{1}{T} \left( \int_{DT} v_{on} dt + \int_{(1-D)T} v_{off} dt \right) \\
= \frac{1}{T} \left( \int_{DT} (V_s - V_o) dt + \int_{(1-D)T} -V_o dt \right) \\
= \frac{1}{T} [(V_s - V_o)DT + (-V_o)(1 - D)T] \\
= \frac{1}{T} (V_s DT - V_o T) \\
= V_s D - V_o = 0 
\] (3.8)

After solving we get:

\[
\frac{V_o}{V_s} = D
\] (3.9)

It can be seen that the output voltage is always less than or equal to the input voltage \((0 \leq D \leq 1)\). The converter may operate in the continuous conduction mode CCM or the discontinuous conduction mode DCM. In the CCM the inductor current is always greater than zero while in the DCM the inductor current is zero during certain portions of the switching period. In some applications both modes may be mixed. The filter inductor that determines the boundary is given by

\[
L_{boundary} = \frac{(1-D)R}{2f} \] (3.10)

Typically \(D = 0.5\), \(R = 10\Omega\), and \(f = 100kHz\), the boundary is \(L_b = 25\mu H\) [12].

Thus for any inductance larger than this value the buck converter will operate in the continuous conduction mode.

To limit the ripple across the dc output voltage \(V_o\) to a value below a specific value \(V_r\), the filter capacitance \(C\) must be greater than

\[
C_{min} = \frac{(1-D)V_o}{8V_r Lf^2} \] (3.11)

The two preceding equations are the key design equations for buck converters.
3.2.2 Boost converter

The Boost converter is another simple power electronic converter and basically consists of a voltage source, an inductor, a power electronic switch (usually a MOSFET or an IGBT) and a diode. It usually also has a filter capacitor to smoothen the output. Its function is to step up DC voltage to bring it to a desired level and is shown in Figure 3.9.

![Functional circuit of a boost converter](image)

Figure 3.9: Functional circuit of a boost converter

If the switch is turned on and off repeatedly at very high frequencies and assuming that in the steady state the output will basically be DC(large capacitor):

\[
\langle i_C \rangle = I_C = 0
\]

\[
\langle i_L \rangle = I_L = I_R - I_{\text{switch}}
\]

\[
= I_R - DI_L
\]

\[
\therefore I_L = \frac{V_o}{R(1 - D)} \quad (3.12)
\]

The DC component of voltage across the inductor has to be zero if losses are neglected. The average voltage across the inductor is given by:
\[ \langle v_L \rangle = 0 = \frac{1}{T} \left( \int_{DT} v_{on} dt + \int_{(1-D)T} v_{off} dt \right) \]

\[ = \frac{1}{T} [V_s DT + (V_s - V_o)(1 - D)T] \]

\[ = V_s - (1 - D)V_o = 0 \quad (3.13) \]

After solving we get:

\[ \frac{V_o}{V_s} = \frac{1}{1 - D} \quad (3.14) \]

The fraction to the right is always greater than one since the duty is always less than one thus the voltage is stepped up. The filter inductor that determines the boundary is given by

\[ L_{\text{boundary}} = \frac{(1 - D)^2 DR}{2f} \quad (3.15) \]

For \( D = 0.5, R = 10 \Omega, \) and \( f = 100kHz, \) the boundary is \( L_b = 6.25\mu H \) \[12\]. For any inductance larger than this value the boost converter will operate in the continuous conduction mode. A much larger filter capacitance \( C \) is required as the current supplied to the output \( RC \) circuit is discontinuous. The limiting value is given by

\[ C_{\text{min}} = \frac{DV_o}{V_r Rf} \quad (3.16) \]

### 3.2.3 Inverters

Inverters convert direct current to alternating current, which may be single or multi-phase. Several topologies exist for both single phase and multi-phase inverters. An example is a full bridge single phase inverter in Figure 3.10. It consists of four
switches that are turned is such a way that within a branch the upper and lower switches are never on at the same time to avoid short-circuiting the DC source.

![Figure 3.10: Fullbridge VSI inverter](image)

The inverter consist of four defined states and one undefined state as shown in Table 3.2. Various modulating techniques can be used to control the switching of the inverter switches but all of them must avoid the undefined state and the short circuit conditions. There are two general types of inverters namely, square wave inverters (line frequency switching) and pulse width modulation PWM inverters (high frequency switching) depending on the switching techniques used. To avoid the short circuit condition (shoot-through) a very small time interval must be inserted between turning off one switch and turning on the other. This short time interval is referred to as the blanking time and largely depends on the type of semiconductor switch employed.
Table 3.2: Switch states for a full-bridge single-phase VSI

<table>
<thead>
<tr>
<th>State</th>
<th>State</th>
<th>( v_{an} )</th>
<th>( v_{bn} )</th>
<th>( V_o )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( S_{1+} ) and ( S_{2-} ) are on and ( S_{1-} ) and ( S_{2+} ) are off</td>
<td>( V_{dc}/2 )</td>
<td>( -V_{dc}/2 )</td>
<td>( V_{dc} )</td>
</tr>
<tr>
<td>2</td>
<td>( S_{1-} ) and ( S_{2+} ) are on and ( S_{1+} ) and ( S_{2-} ) are off</td>
<td>( -V_{dc}/2 )</td>
<td>( V_{dc}/2 )</td>
<td>( -V_{dc} )</td>
</tr>
<tr>
<td>3</td>
<td>( S_{1+} ) and ( S_{2+} ) are on and ( S_{1-} ) and ( S_{2-} ) are off</td>
<td>( V_{dc}/2 )</td>
<td>( V_{dc}/2 )</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>( S_{1-} ) and ( S_{2+} ) are on and ( S_{1+} ) and ( S ) are off</td>
<td>( -V_{dc}/2 )</td>
<td>( -V_{dc}/2 )</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>( S_{1-} ), ( S_{1+} ), ( S_{2-} ) and ( S_{2+} ) are all off</td>
<td>( -V_{dc}/2 )</td>
<td>( V_{dc}/2 )</td>
<td>( -V_{dc} )</td>
</tr>
</tbody>
</table>

3.2.4 Maximum power point tracking

The photovoltaic module operates at on the I-V characteristics that is determined by the load. Since the power harvested from the photovoltaic module is different at different operating points it is important that the load is matched in such a way that maximum power is obtained from the photovoltaic module [13]. The simplest and widely known algorithm is the perturb and observe algorithm. It works by periodically changing the array terminal voltage and comparing the calculated power with that from the previous samples as shown in Figure 3.11. There are other numerous and more complex and efficient algorithms and a comparative study has been done on these algorithms [14].
Figure 3.11: Perturb and observe algorithm
4.1 Introduction

This model has been developed at the Sandia National Laboratories and is based on empirical data and the equations used in the model are derived from the individual solar cell characteristics \[15\]. The model is very useful for designing and monitoring photovoltaic systems. Sandia also maintains a module database that contains the parameters for modules from different manufacturers. In addition to the expressions for the classic points on a module current-voltage (I-V) curve (short-circuit current \(I_{sc}\), open-circuit voltage \(V_{oc}\) and the maximum power point \((I_{mp}, V_{mp})\)), this model also gives expressions for two other points that better define the shape of the curve are given (see figure 4.1).

4.2 Performance equations for photovoltaic modules

Many factors influence a photovoltaic system and a complete model of a photovoltaic system must quantify how these environmental factors individually influence the performance of the system. The following are the defining equations of the Sandia model. They describe the electrical performance for individual photovoltaic modules...
but can be scaled for series or parallel combinations of modules. The coefficients and constants for modules from different manufacturers that are used in the equations are kept in a database maintained by Sandia that can be downloaded for free. The database contains more information than what is provided on the datasheet by manufacturers.
4.2.1 Basic equations

\[ I_{sc} = I_{sco} \cdot f_1(AM_a) \cdot \left\{ \left( E_b \cdot f_2(AOI) + f_d \cdot E_{diff} \right) / E_o \right\} \cdot \left\{ 1 + \alpha_{Isc} \cdot (T_c - T_o) \right\} \]  
(4.1)

\[ I_{mp} = I_{mpo} \cdot \left\{ C_0 \cdot E_e + C_1 \cdot E_e^2 \right\} \cdot \left\{ 1 + \alpha_{Imp} \cdot (T_c - T_o) \right\} \]  
(4.2)

\[ V_{oc} = V_{oco} + N_s \cdot \delta(T_c) \cdot \ln(E_e) + \beta_{Voc}(E_e) \cdot (T_c - T_o) \]  
(4.3)

\[ V_{mp} = V_{mpo} + C_2 \cdot N_s \cdot \delta(T_c) \cdot \ln(E_e) + C_3 \cdot N_s \cdot \{ \delta(T_c) \cdot \ln(E_e) \}^2 + \beta_{Vmp}(E_e) \cdot (T_c - T_o) \]  
(4.4)

\[ I_x = I_{xo} \cdot \left\{ C_4 \cdot E_e + C_5 \cdot E_e^2 \right\} \cdot \left\{ 1 + \alpha_{Isc} \cdot (T_c - T_o) \right\} \]  
(4.5)

\[ I_{xx} = I_{xxo} \cdot \left\{ C_6 \cdot E_e + C_7 \cdot E_e^2 \right\} \cdot \left\{ 1 + \alpha_{Imp} \cdot (T_c - T_o) \right\} \]  
(4.6)

\[ P_{mp} = I_{mp} \cdot V_{mp} \]  
(4.7)

\[ FF = P_{mp} / I_{sc} \cdot V_{oc} \]  
(4.8)

where:

\[ E_e = \frac{I_{sc}}{I_{sco} \cdot \left\{ 1 + \alpha_{Isc} \cdot (T_c - T_o) \right\}} \]  
(4.9)

\[ \delta(T_c) = \frac{n \cdot k(T_c + 273.15)}{q} \]  
(4.10)

4.2.2 Module parameters definitions

The different parameters used in the equations above are defined as follows [15]:

- \( I_{sc} = \) Short circuit current

- \( I_{mp} = \) Current at maximum power

- \( I_x = \) Current at module voltage \( V = 0.5 \cdot V_{oc} \)
• $I_{xx} =$ Current at module voltage $V = 0.5 \cdot (V_{oc} + V_{mp})$

• $V_{oc} =$ Open-circuit voltage $V$

• $V_{mp} =$ Voltage at maximum-power point $V$

• $P_{mp} =$ Power at maximum-power point $W$

• $FF =$ Fill Factor

• $N_s =$ Number of cells in series in a module’s cell-string

• $N_p =$ Number of cells in parallel in a module

• $k =$ Boltzmann’s constant, $1.38 \times 10^{-23} \text{J/K}$

• $q =$ Electronic charge, $1.6 \times 10^{-19} \text{C}$

• $T_c =$ Cell temperature inside module in °C

• $T_o =$ Reference cell temperature, typically 25°C

• $E_o =$ Reference solar irradiance, typically 1000$W/m^2$

• $E_{diff} =$ Diffuse component of solar irradiance incident on the module surface, $W/m^2$

• $E_{dni} =$ Beam component of solar irradiance incident on the module surface, $W/m^2$

• $f_d =$ Fraction of diffuse radiation used by the cell typically 1.

• $AM_a =$ Absolute air mass
• **AOI** = Angle of incidence ie. the angle between the a line perpendicular to the module surface and the beam component of the sunlight.

• \( \delta(T_c) \) = 'Thermal voltage' per cell at temperature \( T_c \)

### 4.3 Variation of parameters with environmental conditions

#### 4.3.1 Variation of parameters with irradiance

The 'effective' solar irradiance gives an indication of the fraction of the total irradiance incident on a module to which the cells inside actually respond. The variation of the key voltage points with the effective irradiance is shown in Figure 4.2.

![Figure 4.2: Variation of voltage with effective irradiance](image-url)

- **Open circuit voltage**
- **Maximum power point voltage**
The variation of the currents with effective irradiance is linear and is shown in Figure 4.3.

Figure 4.3: Variation of current with effective irradiance

The coefficients used in plotting the curves were obtained through linear regression on empirical data by the Sandia researchers. They were read from the database that is available from their site.
4.3.2 Modeling the solar resource

The two functions $f_1(AM_a)$ and $f_2(AOI)$ account for the influence of the solar spectrum and the optical losses respectively.

\[ f_1(AM_a) = a_0 + a_1 \cdot AM_a + a_2 \cdot (AM_a)^2 + a_3 \cdot (AM_a)^3 + a_4 \cdot (AM_a)^4 \]  (4.11)

\[ f_2(AOI) = b_0 + b_1 \cdot AOI + b_2 \cdot (AOI)^2 + b_3 \cdot (AOI)^3 + b_4 \cdot (AOI)^4 \]  (4.12)

The plots in 4.4 show the variation of the relative response with air mass.

Figure 4.4: Relative response with respect to air mass
The variation of the relative response with the angle of incidence is also shown in Figure 4.5. As can be observed from the plots the AOI does not have a significant on the relative response until the angle reaches about $57^\circ$.

![Variation of the relative response $f_2(AOI)$](image)

Figure 4.5: Relative response with respect to the Angle of Incidence

### 4.3.3 Temperature dependent parameters and the thermal model

Four temperature coefficients are used so that the model can apply to different technologies and different operation conditions. The coefficients are also available in the online database. The normalized short circuit temperature coefficient $\alpha_{I_{sc}}$ and the normalized temperature coefficient for $I_{mp}$ give an indication of how the currents
vary with temperature. The coefficients for voltages are denoted as $\beta_{V_{oc}}$ and $\beta_{V_{mp}}$ and their irradiance dependence is neglected in most cases.

The thermal model is used to obtain the module and cell temperatures given the ambient conditions.

$$T_m = E \cdot \exp(a + b \cdot WS) + T_a$$  \hspace{1cm} (4.13)

$T_m$, $T_a$ are the back-surface module temperature and the ambient temperature respectively, ($^\circ$C). $E$ is the solar irradiance incident on module surface, ($W/m^2$) and $WS$, the wind speed. The coefficients $a$, $b$ are obtained empirically and are given as in Table 4.1. The dependency on wind speed is shown in Figure 4.6, wind direction is neglected. The cell temperature is obtained from the back-surface temperature as:

$$T_c = T_m + \frac{E}{E_o} \cdot \Delta T$$  \hspace{1cm} (4.14)

<table>
<thead>
<tr>
<th>Module type</th>
<th>Mount</th>
<th>$a$</th>
<th>$b$</th>
<th>$\Delta T^\circ$C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass/cell/glass</td>
<td>Open rack</td>
<td>-3.47</td>
<td>-0.594</td>
<td>3</td>
</tr>
<tr>
<td>Glass/cell/glass</td>
<td>Close roof mount</td>
<td>-2.98</td>
<td>-0.0471</td>
<td>1</td>
</tr>
<tr>
<td>Glass/cell/polymer sheet</td>
<td>Open rack</td>
<td>-3.56</td>
<td>-0.0750</td>
<td>3</td>
</tr>
<tr>
<td>Glass/cell/polymer sheet</td>
<td>Insulated back</td>
<td>-2.81</td>
<td>-0.0455</td>
<td>0</td>
</tr>
<tr>
<td>Polymer/thin-film/steel</td>
<td>Open rack</td>
<td>-3.58</td>
<td>-0.113</td>
<td>3</td>
</tr>
<tr>
<td>22X Linear Concentrator</td>
<td>Tracker</td>
<td>-3.23</td>
<td>-0.130</td>
<td>13</td>
</tr>
</tbody>
</table>
Figure 4.6: Response with respect to wind speed
CHAPTER 5

MODELING OF PHOTOVOLTAIC MODULES

5.1 Modeling and system identification procedure

The modeling process varies from system to system (see Figure 5.1). Depending on the a priori knowledge of the system structure three different classes of models of the system can be produced as listed below [16] [17].

Figure 5.1: Modeling conceptual sketch

1. "White Box": For this type of model the structure and parameters can be deduced from physical principles and information is available a priori. The identification of such a system does not require experimental data and can be characterized based on first engineering principles.
2. ”Gray Box”: For this class of models the structure is usually known and in most cases certain physical parameters need to be determined from measured data. The amount of information known a priori in these models usually varies from case to case but the system structure will not be replaced by artificial structures as seen in generic black-box approximators. Grey box design needs both modeling and identification, since the result obtained from modeling is not certain and must be verified by identification.

3. ”Black Box” : This usually uses nonlinear neural network modeling (NN). The model complexity is determined from a generalized NN model. The identification in such a case is performed exclusively from measured data. With this type of model structural information is usually lost.

In the case of PV cells the structure is known so what only remains is to fine tune the model:

- Matching between data and parameters
- Use of statistical relationships
- Use of numerical methods that heavily rely on computers and software tools such as MATLAB™.

5.1.1 Grey Box Modeling process for a PV cell/module

Firstly, for any given temperature and irradiance the parameters of the model equation must be determined. Once these parameters are determined the solution of the equation can be obtained using a simple numerical solution like the Newton-Raphson method. The modeling process for a PV cell as described in [18] is shown
in Figure 5.2.

Figure 5.2: Modeling process for a PV

The PV cell or module is usually represented by the single exponential model or the double exponential model. The single exponential circuit model [19] is shown in Figure 5.3. The current is expressed in terms of voltage and other parameters as shown in Equation 5.1. Although this model is widely used and accepted in the simulation and testing of photovoltaic modules the double exponential model (see Figure 5.4) is more accurate and more difficult to solve and the parameters also vary with temperature and irradiance [18]. Models that use constant parameters have been proposed [20, 21] but these models are inaccurate as they do not account for temperature variation. Recently, a lot of researchers have developed single exponential models that neglect
the shunt resistance \[22\] \[23\] \[24\]. Other researchers have developed models that take account of temperature and irradiance based on datasheet information \[25\].

Figure 5.3: The single exponential model of photovoltaic cell

\[
I = I_{ph} - I_o \left\{ \exp \left[ \frac{q(V + IR_s)}{AkT} \right] - 1 \right\} - \frac{V + IR_s}{R_p} \tag{5.1}
\]

Figure 5.4: The double exponential model of photovoltaic cell

\[
I = I_{ph} - I_{s1} \left\{ \exp \left[ \frac{q(V + IR_s)}{kT} \right] - 1 \right\} - I_{s2} \left\{ \exp \left[ \frac{q(V + IR_s)}{AkT} \right] - 1 \right\} - \frac{V + IR_s}{R_p} \tag{5.2}
\]

where

- \(I_{ph}\) - the photo-generated current
• $I_o$ - the dark saturation current

• $I_{s1}$ - saturation current due to diffusion

• $I_{s2}$ - is the saturation current due to recombination in the space charge layer

• $I_{R_p}$ - current flowing in the shunt resistance

• $R_s$ - cell series resistance

• $R_p$ - the cell (shunt) resistance

• $A$ - the diode quality factor

• $q$ - the electronic charge, $1.6 \times 10^{-19} C$

• $k$ - the Boltzmann’s constant, $1.38 \times 10^{-23} J/K$

• $T$ - the ambient temperature, in Kelvin

Equations 5.1 and 5.2 are both nonlinear and implicit [18]. Moreover the parameters ($I_{ph}$, $I_{s1}, I_{s2}$, $R_s$, $R_{sh}$ and $A$) vary with temperature and irradiance and depend on manufacturing spread. Some work has already been done to develop a complete model based on the double exponential. These methods have relied heavily on numerical methods and curve fitting. For example the Levenberg-Marquardt method has been used to solve the double exponential model [18].

5.2 Single diode model

This model assumes that the dark current of a solar cell can be described by a single exponential dependence modified by a diode quality factor (see Equation 5.1). The values of the five parameters in the equation must be determined to reproduce
the IV curve. This requires five equations containing five unknowns that will be solved simultaneously to obtain the parameter values \([26]\). Some authors have further simplified this model by removing the shunt resistance to obtain a model of moderate complexity \([24]\).

There are are three key points on the IV curve of a photovoltaic cell: the short circuit point, maximum power point and the open circuit point.

At the open-circuit point on the IV curve, \(V = V_{oc}\) and \(I = 0\). After substituting these values in the single exponential equation \([5.1]\) the first needed equation is obtained:

\[
0 = I_{ph} - I_o \left\{ \exp \left[ \frac{qV_{oc}}{AkT} \right] - 1 \right\} - \frac{V_{oc}}{R_p} \tag{5.3}
\]

At the short-circuit point on the IV curve, \(I = I_{sc}\) and \(V = 0\). After substituting these values in the single exponential equation \([5.1]\) the second needed equation is

\[
I_{sc} = I_{ph} - I_o \left\{ \exp \left[ \frac{qI_{sc}R_s}{AkT} \right] - 1 \right\} - \frac{I_{sc}R_s}{R_p} \tag{5.4}
\]

At the maximum-power point on the IV curve, \(I = I_{mpp}\) and \(V = V_{mpp}\). After substituting these values in the single exponential equation \([5.1]\) a third equation is obtained

\[
I_{mpp} = I_{ph} - I_o \left\{ \exp \left[ \frac{q(V_{mpp} + I_{mpp}R_s)}{AkT} \right] - 1 \right\} - \frac{V_{mpp} + I_{mpp}R_s}{R_p} \tag{5.5}
\]

More equations can be obtained by obtaining the derivative of \([5.1]\) with respect to \(V\):

\[
\frac{dI}{dV} = -I_o \left\{ \frac{q}{AkT} \left( 1 + \frac{dI}{dV}R_s \right) \exp \left[ \frac{q(V + IR_s)}{AkT} \right] \right\} - \frac{1}{R_p} \left( 1 + \frac{dI}{dV}R_s \right) \tag{5.6}
\]

Again at the open-circuit point on the IV curve \(V = V_{oc}\) and \(I = 0\) therefore,

\[
\frac{dI}{dV} = \frac{dI}{dV} \bigg|_{I=0}
\]
Substituting in \[5.6\] the following results

\[
\left. \frac{dI}{dV} \right|_{I=0} = -I_o \left\{ \frac{q}{A k T} \left[ 1 + \left. \frac{dI}{dV} \right|_{I=0} R_s \right] \cdot \exp \left( \frac{q V_{oc}}{A k T} \right) \right\} - \frac{1}{R_p} \left[ 1 + \left. \frac{dI}{dV} \right|_{I=0} R_s \right] (5.7)
\]

Again at the short-circuit point on the IV curve, \( I = I_{sc} \) and \( V = 0 \).

\[
\frac{dI}{dV} = \left. \frac{dI}{dV} \right|_{V=0}
\]

After substituting in \[5.6\] the following results

\[
\left. \frac{dI}{dV} \right|_{V=0} = -I_o \left\{ \frac{q}{A k T} \left[ 1 + \left. \frac{dI}{dV} \right|_{V=0} R_s \right] \cdot \exp \left( \frac{q I_{sc} R_s}{A k T} \right) \right\} - \frac{1}{R_p} \left[ 1 + \left. \frac{dI}{dV} \right|_{V=0} R_s \right] (5.8)
\]

The power transferred from the pv at any point is given by:

\[
P = IV (5.9)
\]

The power equation \[5.9\] can be differentiated with respect to the voltage, \( V \),

\[
\frac{dP}{dV} = \left( \frac{dI}{dV} \right) V + I (5.10)
\]

To find the value of voltage that gives the maximum power the derivative is equated to 0.

\[
\frac{dP}{dV} = 0 (5.11)
\]

Substituting in equation \[5.10\]

\[
\frac{dI}{dV} = -\frac{I_{mpp}}{V_{mpp}} (5.12)
\]
Substituting in (5.6) the following equation is obtained

\[ -\frac{I_{mpp}}{V_{mpp}} = -I_o \left\{ \frac{q}{AkT} \left( 1 - \frac{I_{mpp}}{V_{mpp}} R_s \right) \exp \left[ \frac{q(V_{mpp} + I_{mpp}R_s)}{AkT} \right] \right\} - \frac{1}{R_p} \left[ 1 - \left( \frac{I_{mpp}}{V_{mpp}} \right) R_s \right] \]  

(5.13)

The equations obtained in the preceding analysis are independent and are sufficient to solve for the five parameters \( I_{ph}, I_o, \alpha, R_s, \) and \( R_p \). To start with, the values of \( V_{oc}, I_{sc}, V_{mpp}, I_{mpp} \), \( \frac{dI}{dV} \bigg|_{V=0} \) and \( \frac{dI}{dV} \bigg|_{I=0} \) are plugged in to the independent equations. A solution of the resulting equation may then be solved by a digital computer using iterative methods for solving nonlinear equations such as the Newton-Raphson method. The Sandia points form an additional two sets of equations that can also be used. For notational convenience the following can be defined:

\[ R_{so} = \frac{dV}{dI} \bigg|_{V=V_{oc}} \]
\[ R_{sho} = \frac{dV}{dI} \bigg|_{I=I_{sc}} \]
\[ V_T = \frac{kt}{q} \]  

(5.14)

The equations can also be summarized as \([27]\):

\[ \begin{align*}
0 &= I_o \left( \exp \left( \frac{V_{oc}}{AV_T} \right) - \exp \left( \frac{I_{sc}R_s}{AV_T} \right) \right) - I_{sc} \left( 1 + \frac{R_s}{R_p} \right) + \frac{V_{oc}}{R_p} \\
0 &= (R_{so} - R_s) \left( \frac{1}{R_p} + \frac{I_o}{AV_T} \exp \left( \frac{V_{oc}}{AV_T} \right) \right) - 1 \\
0 &= \frac{1}{R_p} - \frac{1}{R_{sho} - R_s} + \frac{I_o}{AV_T} \exp \left( \frac{I_{sc}R_s}{AV_T} \right) \\
0 &= I_o \exp \left( \frac{V_{oc}}{AV_T} \right) + \frac{V_{oc} - V_{mpp}}{R_p} - \left( 1 + \frac{R_s}{R_p} \right) I_{mpp} - I_o \exp \left( \frac{V_{mpp} + I_{mpp}R_s}{AV_T} \right)
\end{align*} \]  

(5.15)

To obtain initial values the algorithm uses expressions similar to the analytical expressions obtained from \([27][28]\). Based on that work the initial values can be calculated.
by calculating the diode quality factor first as follows:

\[
A = \frac{V_{mpp} + I_{mpp}R_{so} - V_{oc}}{V_T \left\{ \ln \left( I_{sc} - \frac{V_{mpp}}{R_{sho}} - I_{mpp} \right) - \ln \left( I_{sc} - \frac{V_{oc}}{R_p} \right) + \frac{I_{mpp}}{I_{sc} - (V_{oc}/R_{sho})} \right\}}
\] (5.16)

The rest of the initial values of the parameters can then be found from the following equations:

\[
R_p = R_{sho}
\] (5.17)

\[
I_o = \left( I_{sc} - \frac{V_{oc}}{R_p} \right) \exp \left( -\frac{V_{oc}}{AV_T} \right)
\] (5.18)

\[
R_s = R_{so} - \frac{AV_T}{I_o} \exp \left( -\frac{V_{oc}}{AV_T} \right)
\] (5.19)

\[
I_{ph} = I_{sc} \left( 1 + \frac{R_s}{R_p} \right) + I_o \left( \exp \frac{I_{sc}R_s}{AV_T} - 1 \right)
\] (5.20)

Starting with the values obtained a numerical solution can be obtained using the Newton-Raphson method or other algorithms that solve systems of nonlinear equations.

### 5.3 Newton-Raphson method

The Newton-Raphson method is used to solve systems of nonlinear equations. It finds the roots of a nonlinear function by computing the Jacobian linearization of the function around an initial guess point, and using this linearization to move closer to the nearest zero. A set of nonlinear equations in matrix form is given by:

\[
f(x) = \begin{bmatrix} f_1(x) \\ f_2(x) \\ \vdots \\ f_N(x) \end{bmatrix} = y
\] (5.21)
where \( y \) and \( x \) are \( N \) vectors and \( f(x) \) is an \( N \) vector of functions. The aim is to find \( x \) given \( y \) and \( f(x) \). If equation (5.21) is rewritten as

\[
0 = y - f(x)
\]  

(5.22)

and adding \( Dx \) to both sides of equation (5.22), where \( D \) is a square \( N \times N \) invertible matrix,

\[
Dx = Dx + y - f(x)
\]  

(5.23)

And if we premultiply by \( D^{-1} \) we get,

\[
x = x + D^{-1}[y - f(x)]
\]  

(5.24)

The Newton-Raphson method specifies the matrix \( D \) based on the Taylor series expansion of \( x \) about a point \( x_0 \).

\[
y = f(x_0) + \left. \frac{df}{dx} \right|_{x=x_0} (x - x_0) \ldots
\]  

(5.25)

If higher order terms are neglected in (5.25) and solving for \( x \),

\[
x = x_0 + \left[ \left. \frac{df}{dx} \right|_{x=x_0} \right]^{-1} [(y - f(x_0)]
\]  

(5.26)

The value \( x_0 \) is replaced by the old value \( x(i) \) and \( x \) by the new value \( x(i+1) \):

\[
x(i + 1) = x(i) + J^{-1}(i)\{y - f(x(i))\}
\]  

(5.27)

and the Jacobian matrix \( J \) is given for each iteration as,

\[
J(i) = \left. \frac{df}{dx} \right|_{x=x(i)} =
\begin{bmatrix}
\frac{\partial f_1}{\partial x_1} & \frac{\partial f_1}{\partial x_2} & \ldots & \frac{\partial f_1}{\partial x_N} \\
\frac{\partial f_2}{\partial x_1} & \frac{\partial f_2}{\partial x_2} & \ldots & \frac{\partial f_2}{\partial x_N} \\
\vdots & \vdots & \ddots & \vdots \\
\frac{\partial f_N}{\partial x_1} & \frac{\partial f_N}{\partial x_2} & \ldots & \frac{\partial f_N}{\partial x_N}
\end{bmatrix}
\]  

(5.28)
For example if five of the equations are used directly then the elements of the Jacobian Matrix will be as follows. Considering \( f_1(x) \) we get:

\[
\begin{align*}
J(1, 1) & = 1 \\
J(1, 2) & = -\exp\left(\frac{qV_{oc}}{AkT}\right) + 1 \\
J(1, 3) & = -\frac{qI_o V_{oc} \exp\left(\frac{qV_{oc}}{AkT}\right)}{A^2 kT} \\
J(1, 4) & = 0 \\
J(1, 5) & = -\frac{V_{oc}}{R_p^2} \\
\end{align*}
\]

(5.29)

Considering \( f_2(x) \) we get:

\[
\begin{align*}
J(2, 1) & = 1 \\
J(2, 2) & = -\exp\left[\frac{qI_{sc} R_s}{AkT}\right] + 1 \\
J(2, 3) & = \frac{qI_o I_{sc} R_s \exp\left[\frac{qI_{sc} R_s}{AkT}\right]}{A^2 kT} \\
J(2, 4) & = -\frac{qI_o I_{sc} \exp\left[\frac{qI_{sc} R_s}{AkT}\right]}{AkT} - \frac{I_{sc}}{R_p} \\
J(2, 5) & = \frac{I_{sc}}{R_p^2} \\
\end{align*}
\]

(5.30)
Considering \( f_3(x) \) we get:

\[
\begin{align*}
J(3,1) &= 0 \\
J(3,2) &= -q \left( 1 - \frac{R_s}{R_{so}} \right) \exp \left( \frac{qV_{oc}}{AKT} \right) \\
J(3,3) &= \frac{qI_o (R_{so} - R_s) \exp \left( \frac{qV_{oc}}{AKT} \right) (AKT + qV_{oc})}{A^3k^2T^2R_{so}} \\
J(3,4) &= \frac{qI_o (R_s - R_{so}) \exp \left( \frac{qV_{oc}}{AKT} \right) + 1}{AKTR_{so}} \\
J(3,5) &= 1 - \frac{R_s}{R_{so}} \\
J(4,1) &= 0 \\
J(4,2) &= -q \left( 1 - \frac{R_s}{R_{so}} \right) \exp \left( \frac{qI_{sc} R_s}{AKT} \right) \\
J(4,3) &= \frac{qI_o (R_{sho} - R_s) \exp \left( \frac{qI_{sc} R_s}{AKT} \right) (AKT + qI_{sc} R_s)}{A^3k^2T^2R_{sho}} \\
J(4,4) &= \frac{qI_o (R_{sho} - R_s) \exp \left( \frac{qI_{sc} R_s}{AKT} \right)}{AKTR_{sho}} - \frac{q^2I_o \left( 1 - \frac{R_s}{R_{sho}} \right) I_{sc} \exp \left[ \frac{qI_{sc} R_s}{AKT} \right]}{A^2k^2T^2} + \frac{1}{R_pR_{sho}} \\
J(4,5) &= \frac{R_{sho} - R_s}{R_pR_{sho}}
\end{align*}
\]

\[(5.31)\]

Considering \( f_4(x) \) we get:

\[
\begin{align*}
J(4,1) &= 0 \\
J(4,2) &= -q \left( 1 - \frac{R_s}{R_{so}} \right) \exp \left( \frac{qI_{sc} R_s}{AKT} \right) \\
J(4,3) &= \frac{qI_o (R_{sho} - R_s) \exp \left( \frac{qI_{sc} R_s}{AKT} \right) (AKT + qI_{sc} R_s)}{A^3k^2T^2R_{sho}} \\
J(4,4) &= \frac{qI_o (R_{sho} - R_s) \exp \left( \frac{qI_{sc} R_s}{AKT} \right)}{AKTR_{sho}} - \frac{q^2I_o \left( 1 - \frac{R_s}{R_{sho}} \right) I_{sc} \exp \left[ \frac{qI_{sc} R_s}{AKT} \right]}{A^2k^2T^2} + \frac{1}{R_pR_{sho}} \\
J(4,5) &= \frac{R_{sho} - R_s}{R_pR_{sho}}
\end{align*}
\]

\[(5.32)\]
Finally considering \( f_5(\mathbf{x}) \) we get:

\[
\begin{align*}
J(5, 1) &= 0 \\
J(5, 2) &= -q \left(1 - \frac{I_{mp}R_s}{V_{mp}}\right) \exp\left(\frac{q(V_{mp} + I_{mp}R_s)}{AkT}\right) \\
J(5, 3) &= \frac{(V_{mp} - I_{mp}R_s)[AkT + q(V_{mp} + I_{mp}R_s)]qI_o \exp\left(\frac{q(V_{mp} + I_{mp}R_s)}{AkT}\right)}{V_{mp}A^2k^2T^2} \\
J(5, 4) &= \frac{qI_oI_{mp} \exp\left(\frac{q(V_{mp} + I_{mp}R_s)}{AkT}\right) q^2I_o \left(1 - \frac{I_{mp}R_s}{V_{mp}}\right) I_{mp} \exp\left(\frac{q(V_{mp} + I_{mp}R_s)}{AkT}\right)}{V_{mp}AkT} + \frac{I_{mp}}{R_pV_{mp}} \\
J(5, 5) &= \frac{1 - \frac{I_{mp}R_s}{V_{mp}}}{R_p^2}
\end{align*}
\]

\((5.33)\)

The Jacobian can easily be evaluated in Matlab using the Symbolic toolbox and a numerical solution can be obtained by using the Optimization toolbox.

### 5.4 Neural network modeling

Developing an accurate PV-module model based on analytical models or numerical simulations is very difficult due to the influence of environmental factors. Artificial neural networks are currently used in tackling complex problems in diverse areas including modeling of nonlinear systems and mapping, time series processing, pattern recognition, signal processing, automatic control, engineering, business and applied sciences. An ANN consists of simple, adaptive processing units called neurons that are interconnected to form a large network. This structure makes them well suited for Very Large Scale Integration (VLSI) technology. The general structure of a neuron is shown in 5.5.
5.4.1 Neuron structure

The neuron shown in Figure 5.5 consists of four basic elements. The first is a set of synapses or connecting links that are characterized by synaptic weights (also called strengths). If $x_j$ denotes the $k$th element of the input vector $x$ and is the input signal to the synapse $j$. If it is connected to neuron $k$, then $x_j$ is multiplied by the synaptic weight $w_{kj}$ where $w_{kj}$ is usually a real number. The second element is the summing junction or linear combiner, which sums the weighted inputs $w_{kj}x_j$. The third element is the activation function which is usually a sigmoid function (a family of curves that includes logistic and hyperbolic tangent curves. An example of these function is the logistic function shown in Figure 5.6, which is the most widely used sigmoid function. The functions are typically nonlinear functions. An additional externally applied bias $b_k$ is usually included and constitutes the fourth element.

Figure 5.5: Structure of a neuron
Mathematically the following equations describe the \( k \)th neuron.

\[
v(k) = \sum_{j=1}^{m} w_{kj} x_j (5.34)
\]

\[
y(k) = \phi (v(k) + b_k) (5.35)
\]

Where

- \( v(k) \) is the output of the linear combiner
- \( \phi(.) \) is the activation function
- \( y(k) \) is the output signal of neuron \( k \)
- \( x_1, x_2, \ldots, x_m \) are the \( m \) input signal to neuron \( k \)
- \( w_{k1}, w_{k2}, \ldots, w_{km} \) are the \( m \) synaptic weights

### 5.4.2 Multilayer perceptron structure

Neural networks (NN) can be used to model photovoltaics. The feed forward multilayer perceptron (MLP) is the most widely used neural network structure today. It yields very good results if properly trained. The MLP consists of an input layer, a number of hidden layers and an output layer \[29\] \[30\]. It has no feedback connections and the signals proceed layer by layer through the network, which is fully connected. The MLP training attempts to minimize the mean-square output error. The training methods used is the back propagation type of learning algorithms or other faster converging algorithms. The structure of a MLP neural network is shown in Figure 5.7. The input to the Artificial Neural Network (ANN) is a vector, \( \mathbf{x} \) consisting of a number of input signals \( x_1, x_2, \ldots, x_{n0} \). The neurons are connected by synapses
or connecting links which are assigned a value called the synaptic weight or strength.

In supervised learning there are available some $K$ known training pairs $\{x(k), d(k)\}, k = 1, 2, \ldots, K$. These represent the input and desired response respectively. The output vector $y(k)$ produced by the MLP network for the input vector $x(k)$ is compared to the desired response $d(k)$. Initial weights are usually set at random and therefore, the initial error will be high. The error signals are then propagated backwards through the MLP network layer by layer from the output to the first hidden layer. The Mean
Square Error (MSE) is the most commonly used error indicator given by:

\[ E = \frac{1}{2N} \sum_{i}^{N} (d_i - z_i)^2 \]  

(5.36)

\( E \) denotes the MSE and \( d_i \) and \( z_i \) denote the target and the predicted output for the \( i \)th training patterns. A complete pass through the whole training dataset is called an epoch, and training can take many epochs to complete learning.
CHAPTER 6

SIMULATION RESULTS

6.1 Variation of characteristics with temperature

The performance of a photovoltaic module at a constant level of irradiance (1000 W/m² or 1 Sun in this case) is depicted as a three dimensional graph shown in Figure 6.1. There is a clear reduction in the open circuit voltage as the temperature increases. Figure 6.2 provides a clear view on how the curves vary with temperature and constitutes a typical set of curves that are displayed on a manufacturer’s datasheet.

There is significant reduction in the power output of the photovoltaic system as cell temperature increases. This relationship is clearly depicted in Figure 6.3 where the power is plotted as a function of voltage for 4 different temperatures.

6.2 Variation of characteristics with irradiance

To show the effect of irradiance on the performance of a module the temperature is kept fixed at 25 °C and the values of irradiance are changed to different values. The variation of the current-voltage characteristics with irradiance are shown in Figure 6.4. It is quite clear that irradiance has a major effect on the short circuit current and indeed the relationship between irradiance and the short circuit current is a linear
one. Power was also calculated at different levels of irradiation as shown in 6.5. To obtain the maximum possible output from the photovoltaic module, it has to operate at the voltage corresponding to maximum power as shown by the dotted lines.

6.3 Parameter extraction for the BPMSX120

Sandia points were used to extract the parameters for the BP MSX120 solar module. The MATLAB Symbolic toolbox and the Optimization Toolbox were used and the calculated parameters were used to model the PV. Figure 6.6 show the resulting waveform obtained at 25 °C. It can be seen that this waveform closely resembles the one provided by the manufacturer on the datasheet. The Maximum power point (Nb. in Figure 6.6 the values have been rounded) coincided with that on the manufacturer’s datasheet.
Figure 6.1: Three dimensional IVT curve for a photovoltaic module
Figure 6.2: IV curves for a photovoltaic module at different temperatures
Figure 6.3: Variation of power output with temperature for a photovoltaic module
Figure 6.4: Variation of current and voltage with irradiance. One Sun is defined as incident irradiance of 1000W/m². Therefore 0.8 Sun = 800W/m², 0.6 Sun = 600W/m², 0.4 Sun = 400W/m² and 0.2 Sun = 200W/m²
Figure 6.5: Variation of power and voltage with irradiance. One Sun is defined as incident irradiance of 1000W/m$^2$. Therefore 0.8 Sun = 800W/m$^2$, 0.6 Sun = 600W/m$^2$, 0.4 Sun = 400W/m$^2$ and 0.2 Sun = 200W/m$^2$
Photovoltaic single exponential model

\[ I = I_{ph} - I_{s1} \left\{ \exp \left[ \frac{q(V + IR_s)}{kT} \right] - 1 \right\} - V + IR_s \]

\( R_p \)

Current, I (A)
Voltage, V (V)

Figure 6.6: I-V characteristics of the BPMSX120 panel
CHAPTER 7

CONCLUSION

7.1 Summary

Challenges and approaches to the modeling of photovoltaic systems have been presented. In particular the thesis has presented in a very clear way how electrical parameters can be extracted from information provided on the datasheet and from the Sandia database. The Sandia database contains more information than a manufacturer’s datasheet and makes it easy to model photovoltaics. The points given by the Sandia model are sufficient to formulate a set of independent analytical equations that can be used to accurately extract electrical parameters of a module or array.

7.2 Future directions

In future there is a need to develop an model that can perform very accurate system-wide simulations involving all the individual subsystems that constitute a photovoltaic system. Neural network models can be built based on a portion of measurements and validated using a different subset of measurements. The author can easily demonstrate how the nonlinearities on the IV characteristics can be modeled
by a neural network. After building a rigorous model different Maximum power point tracking algorithms may be tested.

New maximum power point tracking algorithms can be developed and tested on this simulation testbed. Other renewable energy systems such as wind energy maybe modeled and a complete system with photovoltaics and wind energy may be developed and monitored.

[2] [s.n.], “Trends in photovoltaic applications. survey report of selected iea countries between 1992 and 2006.”.


APPENDIX A

DATA SHEETS

Figure A.1: MSX60 Picture

Figure A.2: MSX120 Picture
**Electrical Characteristics**

<table>
<thead>
<tr>
<th></th>
<th>BP MSX 60</th>
<th>BP MSX 64</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Maximum power (P&lt;sub&gt;max&lt;/sub&gt;)</strong></td>
<td>60W</td>
<td>64W</td>
</tr>
<tr>
<td><strong>Voltage at P&lt;sub&gt;max&lt;/sub&gt; (V&lt;sub&gt;mp&lt;/sub&gt;)</strong></td>
<td>17.1V</td>
<td>17.5V</td>
</tr>
<tr>
<td><strong>Current at P&lt;sub&gt;max&lt;/sub&gt; (I&lt;sub&gt;mp&lt;/sub&gt;)</strong></td>
<td>3.5A</td>
<td>3.66A</td>
</tr>
<tr>
<td><strong>Minimum P&lt;sub&gt;max&lt;/sub&gt;</strong></td>
<td>58W</td>
<td>62W</td>
</tr>
<tr>
<td><strong>Short-circuit current (I&lt;sub&gt;sc&lt;/sub&gt;)</strong></td>
<td>3.8A</td>
<td>4.0A</td>
</tr>
<tr>
<td><strong>Open-circuit voltage (V&lt;sub&gt;oc&lt;/sub&gt;)</strong></td>
<td>21.1V</td>
<td>21.3V</td>
</tr>
<tr>
<td><strong>Temperature coefficient of I&lt;sub&gt;sc&lt;/sub&gt;</strong></td>
<td>(0.065±0.015)%/°C</td>
<td></td>
</tr>
<tr>
<td><strong>Temperature coefficient of V&lt;sub&gt;oc&lt;/sub&gt;</strong></td>
<td>-(80±10)mV/°C</td>
<td></td>
</tr>
<tr>
<td><strong>Temperature coefficient of power</strong></td>
<td>-(0.5±0.05)%/°C</td>
<td></td>
</tr>
<tr>
<td><strong>NOCT&lt;sup&gt;1&lt;/sup&gt;</strong></td>
<td>47±2°C</td>
<td></td>
</tr>
<tr>
<td><strong>Maximum system voltage</strong></td>
<td>600V (U.S. NEC rating)</td>
<td>1000V (TUV Rheinland rating)</td>
</tr>
<tr>
<td><strong>Maximum series fuse rating</strong></td>
<td>20A</td>
<td></td>
</tr>
</tbody>
</table>

**Notes**

1. These data represent the performance of typical MSX 60 and MSX 64 modules as measured at their output terminals, and do not include the effect of such additional equipment as diodes or cables. The data are based on measurements made in accordance with ASTM E1636 corrected to SRC (Standard Reporting Conditions), also known as STC or Standard Test Conditions, which are:
   - Illumination of 1 kW/m² (1 sun) at spectral distribution of AM 1.5 (ASTM E892 global spectral irradiance);
   - cell temperature of 25°C.
2. During the stabilization process, which occurs during the first few months of deployment, module power may decrease approximately 3% from typical P<sub>max</sub>.
3. The cells in an illuminated module operate hotter than the ambient temperature. NOCT (Nominal Operating Cell Temperature) is an indicator of this temperature differential, and is the cell temperature under Standard Operating Conditions: ambient temperature of 20°C, solar irradiation of 0.8 kW/m², and wind speed of 1 m/s.
4. The power of solar cells varies in the normal course of production; the MSX 64 is assembled in limited quantities using cells of slightly higher power than the MSX 60.

---

**Figure A.3:** MSX60 electrical characteristics provided on datasheet
Electrical Characteristics

<table>
<thead>
<tr>
<th></th>
<th>BP MSX 60</th>
<th>BP MSX 64</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum power (P_{max})</td>
<td>60W</td>
<td>64W</td>
</tr>
<tr>
<td>Voltage at P_{max} (V_{mp})</td>
<td>17.1V</td>
<td>17.5V</td>
</tr>
<tr>
<td>Current at P_{max} (I_{mp})</td>
<td>3.5A</td>
<td>3.66A</td>
</tr>
<tr>
<td>Minimum P_{max}</td>
<td>58W</td>
<td>62W</td>
</tr>
<tr>
<td>Short-circuit current (I_{sc})</td>
<td>3.8A</td>
<td>4.0A</td>
</tr>
<tr>
<td>Open-circuit voltage (V_{oc})</td>
<td>21.1V</td>
<td>21.3V</td>
</tr>
<tr>
<td>Temperature coefficient of I_{sc}</td>
<td>(0.065±0.015)%/°C</td>
<td></td>
</tr>
<tr>
<td>Temperature coefficient of V_{oc}</td>
<td>-(80±10)mV/°C</td>
<td></td>
</tr>
<tr>
<td>Temperature coefficient of power</td>
<td>-(0.5±0.05)%/°C</td>
<td></td>
</tr>
<tr>
<td>NOCT†</td>
<td>47±2°C</td>
<td></td>
</tr>
<tr>
<td>Maximum system voltage</td>
<td>600V (U.S. NEC rating)</td>
<td>1000V (TUV Rheinland rating)</td>
</tr>
<tr>
<td>Maximum series fuse rating</td>
<td>20A</td>
<td></td>
</tr>
</tbody>
</table>

Notes

1. These data represent the performance of typical MSX 60 and MSX 64 modules as measured at their output terminals, and do not include the effect of such additional equipment as diodes or cables. The data are based on measurements made in accordance with ASTM E1636 corrected to SRC (Standard Reporting Conditions), also known as STC or Standard Test Conditions, which are:
   - illumination of 1 kW/m² (1 sun) at spectral distribution of AM 1.5 (ASTM E892 global spectral irradiance);
   - cell temperature of 25°C.
2. During the stabilization process, which occurs during the first few months of deployment, module power may decrease approximately 3% from typical P_{max}.
3. The cells in an illuminated module operate hotter than the ambient temperature. NOCT (Nominal Operating Cell Temperature) is an indicator of this temperature differential, and is the cell temperature under Standard Operating Conditions: ambient temperature of 20°C, solar irradiation of 0.8 kW/m², and wind speed of 1 m/s.
4. The power of solar cells varies in the normal course of production; the MSX 64 is assembled in limited quantities using cells of slightly higher power than the MSX 60.

Figure A.4: MSX120 electrical characteristics provided on datasheet
Figure B.1: A simple Simulink implementation of a module MSX60
APPENDIX C

PWM

Figure C.1: Three phase sinusoidal PWM in Matlab
Figure C.2: Space vector PWM Simulink Implementation
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