Thesis

Study of By-Pass Diodes Behaviour in Photovoltaic Modules

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BACHELOR‘S THESIS ASSIGNMENT

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II. Bachelor’s thesis details

Bachelor’s thesis title in English:

Study of By-Pass Diodes Behaviour in Photovoltaic Modules

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Studium chování by-pass diod ve fotovoltaických modulech

Guidelines:

1. Process the research on the by-pass diodes and their functionality in photovoltaic modules.
2. In SPICE, create a model of a photovoltaic module simulating a variety of faults.
3. Measure modules with various defect types (defect levels) using available methods.
4. Compare the results of simulation and real measured data under different ambient conditions (irradiance, temperature).

Bibliography / sources:

[1] GRAY, J. L. The Physics of the Solar Cell. A. LUQUE and S. HEGEDUS. Handbook of Photovoltaic Science and Engineering. Chichester : John Wiley & Sons, Ltd., 2003, 3.
[2] DALSASS, M., H. SCHEUERPFLUG, F.W. FECHER, C. BUERHOP-LUTZ, CH. CAMUS a CH.J. BRABEC. Correlation between the generated string powers of a photovoltaic: Power plant and module defects detected by aerial thermography. 2016 IEEE 43rd Photovoltaic Specialists Conference (PVSC) [online]. IEEE, 2016, , 3113-3118. DOI: 10.1109/PVSC.2016.7750239. ISBN 978-1-5090-2724-8. Available at: http://ieeexplore.ieee.org/document/7750239/

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Date of bachelor’s thesis assignment: **27.02.2018** Deadline for bachelor thesis submission: __________

Assignment valid until: **30.09.2019**

Ing. Ladislava Černá, Ph.D. Supervisor’s signature	Head of department’s signature	prof. Ing. Pavel Ripka, CSc. Dean’s signature

III. Assignment receipt

The student acknowledges that the bachelor’s thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the bachelor’s thesis, the author must state the names of consultants and include a list of references.

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Abstract

This project studies the influence of temperature of bypass diodes on photovoltaic module behaviour. Various experiments in laboratory, as well as outside, were carried out to assess the influence of diverse shading conditions on module performance. A special stress has been placed in analysing the behaviour of bypass diodes under different conditions. The results are compared with the simulations in LT SPICE.

Keywords: Solar Energy, PV Module, Bypass Diode, Cell Shading

I would especially like to thank my supervisor, Ing. Ladislava Černá, Ph.D. and also Ing. Tomáš Finsterle and Ing. Pavel Hrzina, Ph.D. for their help in this project. And I would like to dedicate this thesis to all my family and friends, that have supported and helped me through all these years of study before and during university.

Salvador Fco. Villanueva Moreno

Affirmation

I confirm that I wrote the Bachelor thesis *“Study of By-Pass Diodes Behaviour in Photovoltaic Modules“* based on my individual efforts and I used to complete a list of the references that I mention in the list annexed to the thesis in accordance with Methodological guideline number 1/2009 on the observance of ethical principles in the preparation of university thesis.

In Prague on 24 May 2018 ....

Signature

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1 Introduction

Photovoltaics (PV) happen to be very popular in recent years for multiple reasons: they are a free-pollutant energy; with relatively low costs of manufacturing, installation and maintenance of the facilities; have a great efficiency, only surpassed as renewable source of energy by aeolic energy; and are a technology in continuous development. One of the key aspects is the reliable operation of PV systems which includes also diagnostics. Although many diagnostic methods exist, there are some of their features which are still unknown. One of them is the difference between the results obtained under different conditions by thermography, which is very popular diagnostic tool.

This project is focused primarily on the study of the influence of temperature of a bypass diode installed within a photovoltaic module through different experiments. These experiments consist of modifying the temperature and the projected shadow on real and simulated photovoltaic module and analysing the *I-V* and *P-V* curves obtained.

Part I: Theoretical Part

2 Photovoltaic Module

2.1 Description

The photovoltaic modules or panels are a set of photovoltaic cells, interconnected to each other and protected from the outside by a structure of glass and encapsulants. The photovoltaics cells are the components that allow the transformation of the solar radiation into electric energy by means of the photovoltaic effect.

These modules are used in photovoltaic solar installations, which can be classified into two categories depending on of the application they are made for. We can distinguish between autonomous applications and applications connected to the grid.

- The autonomous applications produce electricity with no connection to the electrical grid, with the purpose of supplying energy to the place where they are located. We can differentiate between two different blocks [1].

    - In space devices, photovoltaic modules are used as a way of providing electric energy to devices located in space. Some examples would include communication satellites, the International Space Station (ISS), etc. The research in this area is responsible for the development of the photovoltaic equipment as we know it today.

- On terrestrial devices we could highlight telecommunications (telephony, radio, signal repeaters, etc.), electrification of rural and isolated areas, traffic signalling and illumination of public spaces amongst other things.

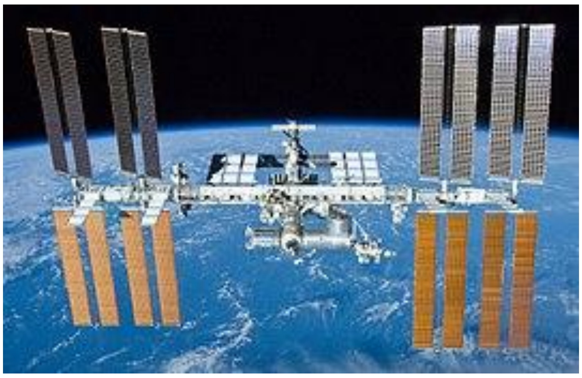

Figure 1 ISS Solar Panels [2]

- Applications connected to the network are those where the producer does not use the energy directly, but instead it is sold to the organization responsible for the energy management of that country. It has the benefit that the electricity is produced when the electricity demand curve rises, this is highly important to have kilowatts produced in this way [1]. We can distinguish:

    - Photovoltaic plants and small solar farms are areas where a determined number of photovoltaic installations of different owners are concentrated, with the purpose of selling the electricity produced to the electric company with whom they have signed a contract. The concentration of these photovoltaic installations with various owners located in the same place allows the improvement of the installation maintenance, vigilance, insurance policy, etc.

    - Photovoltaic buildings are one of the last applications developed in the photovoltaic energy sector. Solar energy is more appropriate as a renewable source of energy for the urban electric generation, with no adverse environmental effects. The integration of photovoltaic technology in architecture is the combination of both functions, as a constructive element and as an electrical producer – for the photovoltaic modules.

Figure 2 Photovoltaic Facade in a Building [1]

The voltage produced by the photovoltaic modules is a direct current (DC) and other components of the photovoltaics systems are needed to manage and transform this voltage into an alternating current (AC) [3].

There are different types of photovoltaic modules depending on the characteristics we are looking for (efficiency, durability, price…), but a great part of this technology is based on and depends on silicon, as shown in the following paragraphs:

- Monocrystalline Silicon Solar Module: This module is the most efficient, comparing the output wattage with the panel size, with an efficiency between 13.3 % and 15.9 % in the commercial panels and a maximum efficiency of 25 %, but this advantage come with a higher cost compared to the rest of the module types.
  The module is made from a single silicon crystal, cut into wafers. Complete modules have blue colour and no grain marks. They have the best purity and highest efficiency levels in the photovoltaic industry [4], [5],[6].

Figure 3 Monocrystalline Silicon PV Module [7]

- Multicrystalline (or Polycrystalline) Silicon Solar Module: This module has levels of efficiency close to the monocrystalline silicon solar modules, with an efficiency in the commercial modules between 9.5 % and 15.3 % and a maximum efficiency of 20.4 %, but at lower costs.

  The module is made by pouring molten silicon into a cast. During the solidification, defects in the crystal appear as vacancies and grains (grain boundaries with high surface recombination velocity), this being the main reason for the lower efficiency by comparison to the monocrystalline PV module [4], [5], [6].

Figure 4 Multicrystalline Silicon Solar Module [8]

- Thin Film Solar Modules: This type of module has several disadvantages, but it can be a good choice for projects without big demands of power which needs to be lightweight and portable (the electric production for houses self-consumption is his best market). Due to materials and technologies used in the production of this modules, the price is much lower in comparison with the other modules, but on the other hand, it has a low average efficiency around 12 % (with a maximum of 28.8 %) [4], [5], [9], [10].

Figure 5 Thin Film Solar Modules [11]

- Hybrid Solar Modules: These modules refer to new technologies combined with photovoltaic elements, with the purpose of increasing their efficiency.

  The most common and popular hybrid solar modules are modules that allow the combination of electric energy and thermal energy production. The solar technology absorbs solar radiation, which is transformed partially into heat. While the common PV module is not able to utilise this energy, the solar heater uses it, thanks to a heat exchanger, for heating e.g. water. The resulting efficiency of the whole system is then significantly heightened [4], [12].

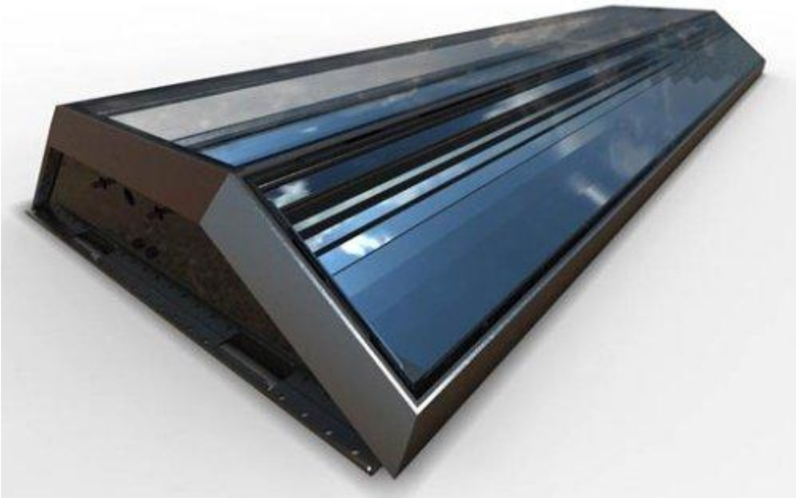

Figure 6 Hybrid Solar Module [12]

2.2 Parameters

When the module's solar cells are irradiated while connected to an external load, they work as an energy generator, generating current and voltage, which vary with the temperature and irradiance.

The characteristic parameters of the photovoltaic modules are shown in the Figure 7 [13], [14], [15].

- **Short Circuit Current:** The value of current that goes through the module when the terminals voltage is zero, obtaining (an ideal circuit) the maximum value of the current while the module works as generator (I_{SC} on the graph).
- **Open Circuit Voltage:** The higher voltage that the system can polarize while is working as generator (V_{OC} on the graph).
- **Maximum Power:** The work point, where the power delivered by the module to the external load is maximum. As the system delivers direct current, the electric power follows the equation $P_{M}=V_{MP}\cdot I_{MP}$, where V_{MP} and I_{MP} are the nominal values of voltage and current in the maximum power point (P_{M} on the graph).

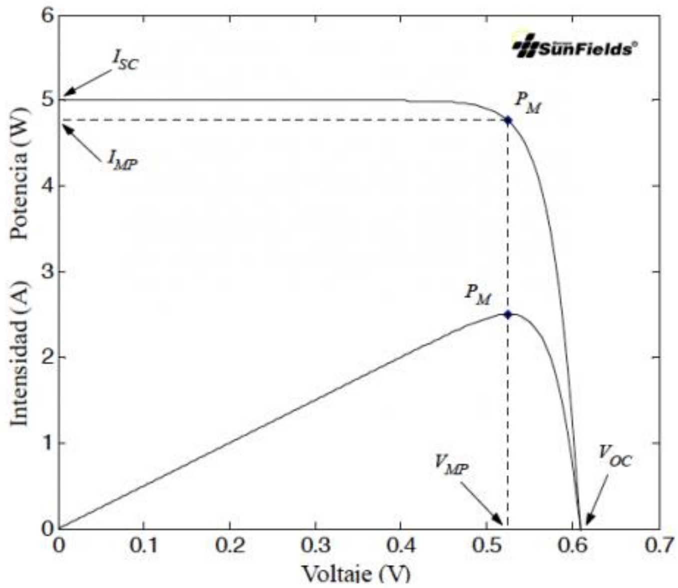

Figure 7 I-V Curve Parameters Graph [13]

- **Fill Factor:** The relation between Maximum Power and the virtual product of Short Circuit Current and Open Circuit Voltage. This value is related with the quality of the PV module, so if solar cells have low values of Fill Factor it means that the system is suffering with efficiency losses. Usual value is approx. 0.8 for crystalline PV modules and 0.7 for thin-film ones.
- **Efficiency:** The relation between the electric power delivered by the module and the solar radiation power that hits the photovoltaic cells expressed as a percentage.

2.3 Basic Construction

First, we must compare the different photovoltaic technologies which are used in the construction of the solar cells. These technologies are based on different active materials for absorbing light and collecting electric charge. We can differentiate three categories: Wafer-based cells based on traditional crystalline silicon technologies or alternatives like gallium-arsenide; commercial thin film cells including amorphous non-crystalline silicon, cadmium telluride and copper indium gallium (di)selenide; and the emerging thin film technologies including perovskites, organic and quantum dot solar cells.

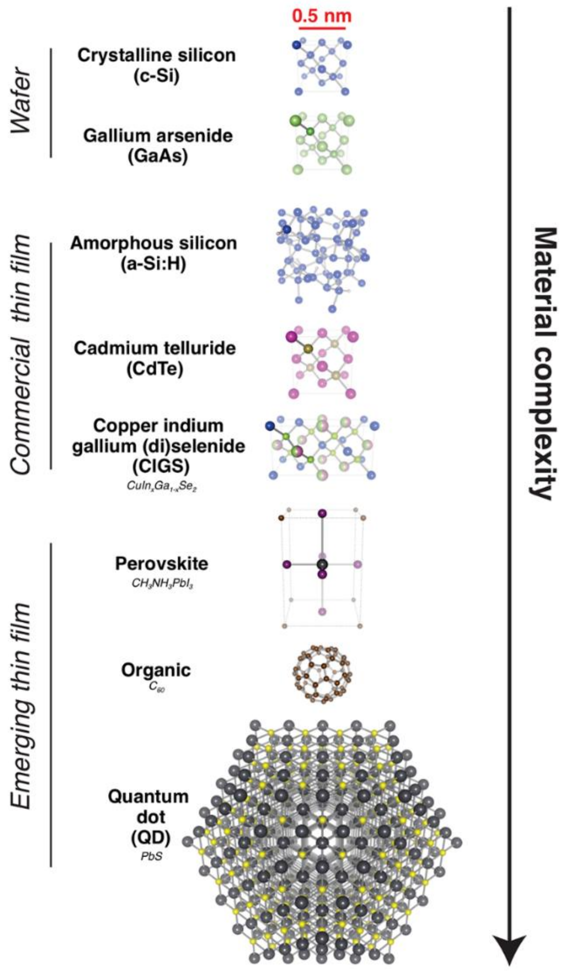

Figure 8 PV Technology Classification Based on Material Complexity [16]

Because the distribution of PV modules technologies based on the efficiencies may not be the most accurate, an MIT team came up with a new way of dividing based on the complexity of the light-absorbing material (defined as the number of atoms in the molecule or crystal unit that forms the building block for the material). In addition, it was found that there is some correlation between complexity and the performance measurements [16].

The way photovoltaic modules are constructed differs case-by-case depending on the type of photovoltaic module. In the following paragraphs, the basic construction of the most common modules, monocrystalline and polycrystalline silicon solar modules will be explained.

Modules based on silicon technology use quartzite as raw material, which contains 90 % or more silica (SiO_2), that must be refined, and its impurities removed. From all these processes polycrystalline silicon material is obtained which is made of numerous randomly packed “grains” of monocrystalline silicon. If we want to obtain a monocrystalline silicon material, the polycrystalline silicon must be melted and allowed to solidify naturally, to allow the atoms to find their preferred positions (usually by the Czochralski method).

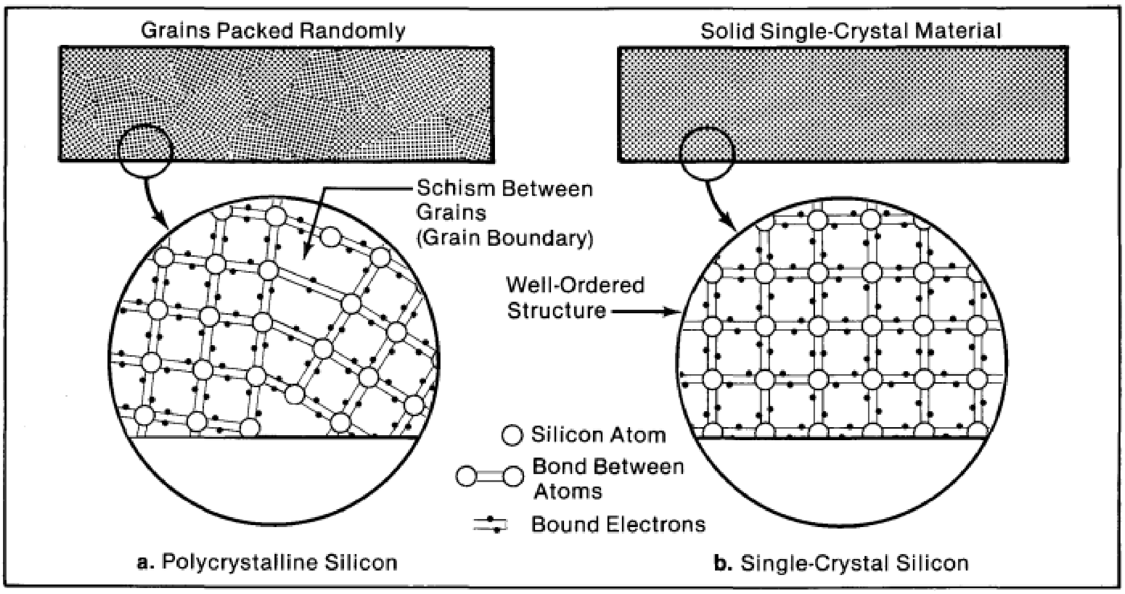

Figure 9 a) Polycrystalline Silicon. b) Single-Crystal Silicon [17]

Once ingots of monocrystalline silicon have been made, they must be cut and processed into wafers, which form the base layers of solar cells. Wafers are typically 0.25 millimetres thick. Then the PN junction is formed, composed by a N-layer and a P-layer. In a typical cell a N-doped surface layer is formed by diffusion of phosphorus.

The region in which the phosphorus penetrates becomes the N-type collector layer. Below the N-type layer, a very narrow transition region to the p-type layer is. Both layers together form the PN junction. The surface of the layer, through which light passes, has to be treated (with titanium dioxide and silicon oxide) so that it reflects minimally, this reflective layer is also called antireflective layer (ARC – Anti Reflective Coating). Untreated silicon reflects more than 30 % of the incident light, while one treated surface reduces the reflection to 10 % or even less. Electrical contacts must connect cells between each other and with an electrical circuit. It is usual to design the top surface contacts as grids. The grid fingers must be thick enough to conduct well and to not block light, which would create the consequent shading phenomenon.

Individual PV cells have limited power and must be tied together electrically, forming strings, in order to produce enough electricity for most applications. The final PV cells strings are then encapsulated, being sealed into ethylene vinyl acetate (EVA) or silicon rubber. A glass or plastic cover is then added to protect the module from the stressing factors (moisture,…). Usually, the front cover is hardened glass and the back of the module is protected by a backsheet foil – Tedlar or Mylar. Finally the module must be structurally self-supporting, so it usually has a supporting frame, which usually is made of aluminium [18], [19], [17], [20], [21].

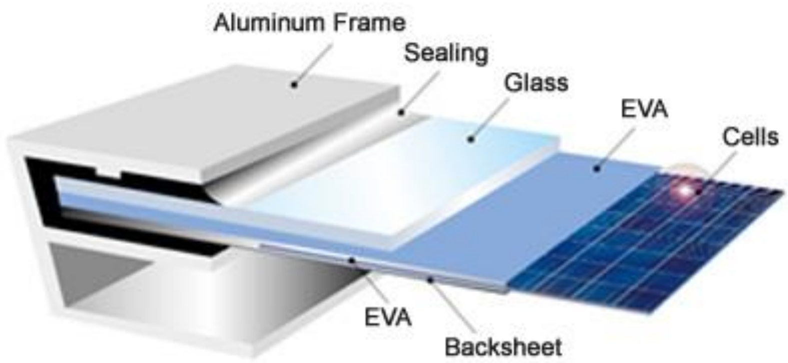

Figure 10 Photovoltaic Silicon Module Elements [22]

2.4 I-V Curves

I-V curves show the course of current depending on voltage of a particular photovoltaic cell, module or array. Thanks to these graphs we are able to obtain, through some calculations, the nameplate values and other important parameters of the module.

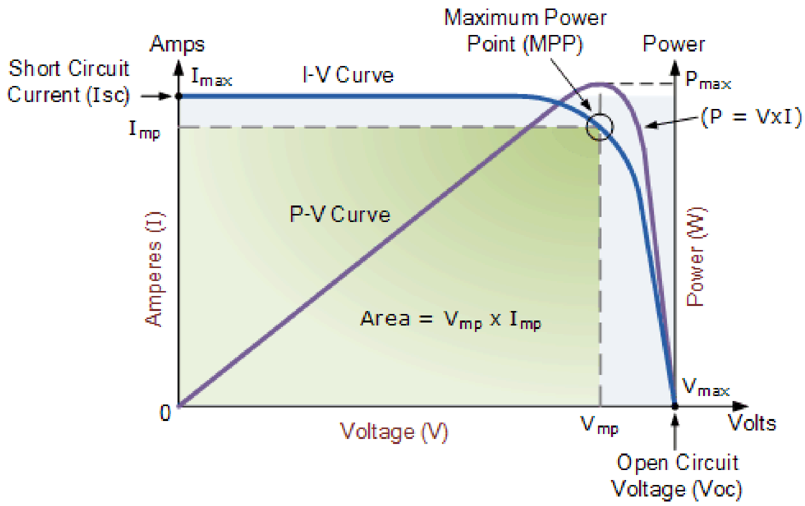

Figure 11 I-V Curve Parameters Graph 2 [3]

The parameters obtained by the *I-V* curves measurement are described in the section **2.2 Parameters.** In the following paragraphs, the changes of these curves when connecting multiple modules, cells respectively, forming cell arrays in different connections as series, parallel and series-parallel are explained.

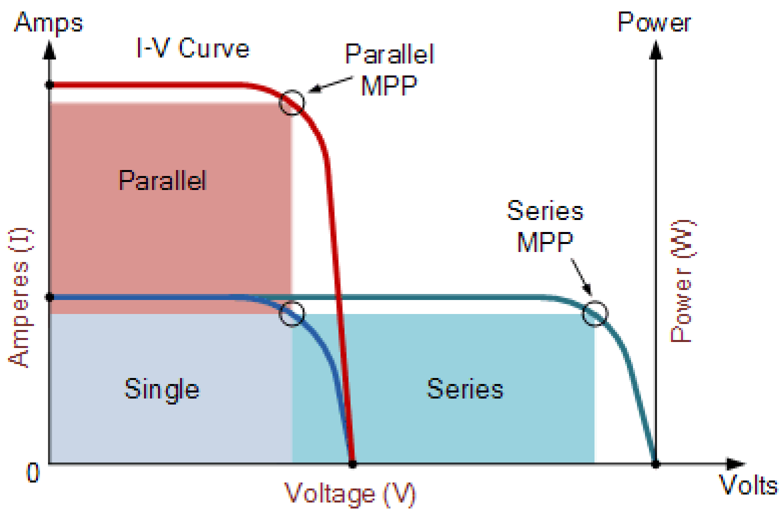

Figure 12 Series and Parallel PV Connection Graphs [3]

When various cells are connected into series, as shown in the last picture, the voltage delivered by the photovoltaic modules increases (this configuration is most common), while when various cells are connected in parallel, the current of the array increases (not so commonly used). The main objective of cells connection is to obtain as much electrical power as possible (maintaining a high efficiency in the system) [3].

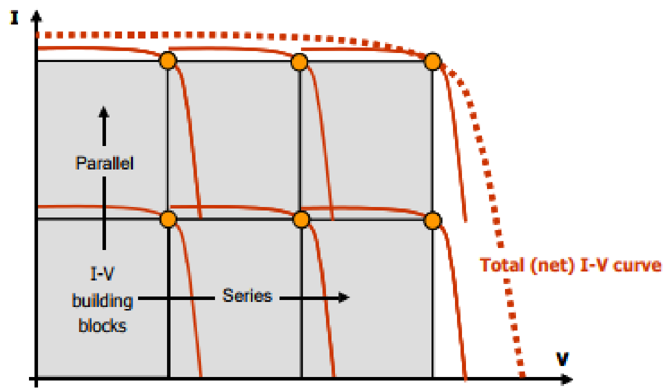

Figure 13 Series/Parallel Module Combination Graph [23]

For this reason, in some cases it is recommendable to connect the cells combining the series and parallel connections. This is the usual case for systems and module connections which greatly increases the system Maximum Power Point, as shown in the picture above [23].

2.5 Influence of Shading

As stated in the previous section **2.1 Description** "The photovoltaics cells are the components that allow the transformation of the solar radiation into electric energy…" Therefore, when solar radiation falling onto the photovoltaic module is decreased due to shading phenomenon, the electric energy produced by the system decreases and also some irregularities in the *I-V* and *P-V* curves appear.

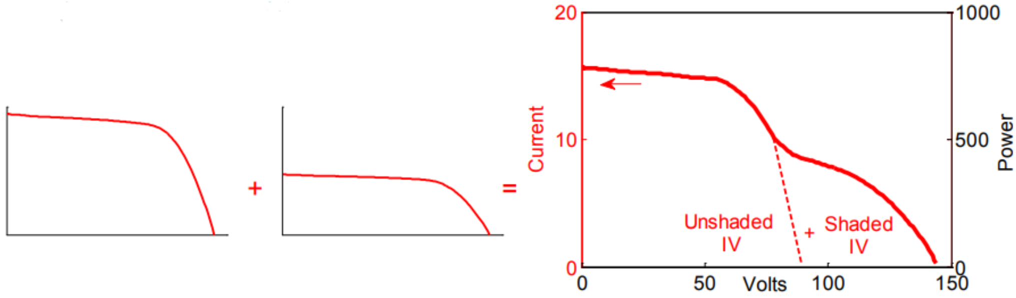

Figure 14 Partial Module Shading Effect on Graphs [24]

This shading phenomenon is usually caused by nearby shade obstructions like trees, telephone poles, buildings, other photovoltaic modules, incorrect orientation, aging, dirty or damaged surface etc. The shading impact depends on some factors of the module like fill form or bypass diode position, severity of the shade and string configuration [24].

When one cell in a photovoltaic module is shaded, the current produced in this cell is lower than in the unshaded ones. But, due to the photovoltaic cells usually being connected in series, the same amount of current must flow through each.

This results in the shaded cell being forced, by the unshaded cells, to pass more current than the short circuit current (I_{SC}) of the shaded one. The only possible way is to have it operating in a negative voltage region that will cause a net voltage loss in the system. The shaded cell will dissipate power as heat, that causes hot spots, generating at the same time drops in the *I-V* curves of the photovoltaic module [24], [25].

In the following pictures, the variations of the *I-V* and *P-V* curves produced by the shading are shown in comparison with the curves of an unshaded photovoltaic module.

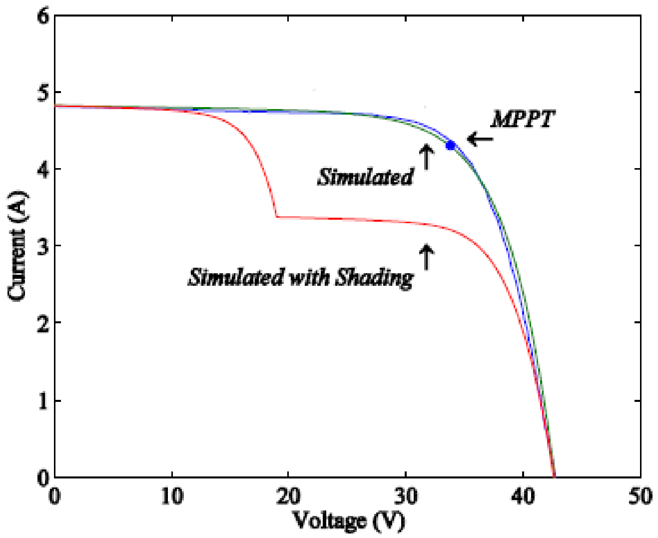

Figure 15 Simulated Shaded and Unshaded I-V Curves [26]

Here the position of the Maximum Power Point on two serially connected modules has changed due to shading. Despite this, there are also two inflection points, one is the new *MPP* and the other one is the maximum power point of the shaded cells graph. This can suppose a difficulty and lead to an error, to find the correct *MPP* and it also contributes in forming energy losses during the conversion [26].

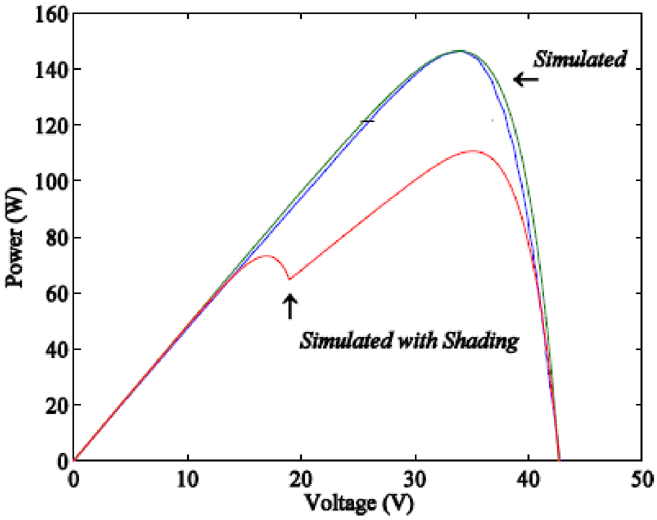

Figure 16 Simulated Shaded and Unshaded P-V Curves [26]

The same situation is also apparent at *P-V* curves where the relation between both power peaks of the shading curve with the *MPPs* of the previous picture is shown [26].

3 By-Pass Diode

3.1 Utilization in Photovoltaics

As explained in the previous section **2.5.- Influence of Shading** and observed in their pictures, when part of a photovoltaic module is shaded and the photovoltaic cells are connected in series, an equal current must flow through them.

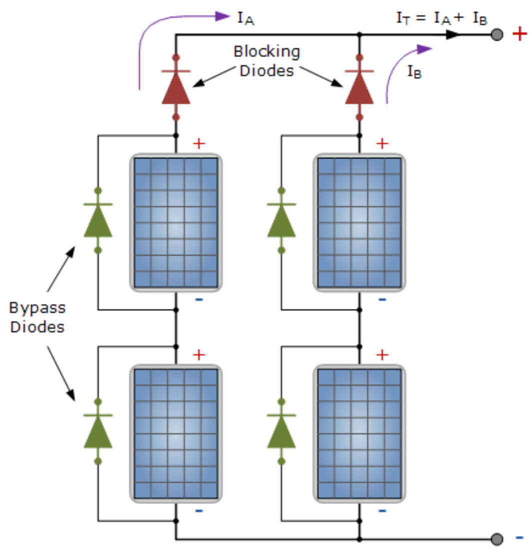

Figure 17 Schematic Photovoltaic Module/Bypass Diode Circuit [25]

If more defective cells occur, this current is reduced to zero and thus it should be compensated by some additional means. For minimising these effects on the photovoltaic modules, bypass diodes are used which allow the current to pass around shaded cells, decreasing the losses on the module.

This diode has a much higher current density than an ordinary PN junction. This means that voltage drops are lower, making the diode ideal for use in photovoltaic modules (because it does not represent large additional losses to the system), avoiding the appearance of "Hot spots" or even the breakdown of the PV cells [27], [28].

All the current higher than the short circuit current is bypassed through the diode, greatly reducing the heating in the affected area. The ideal construction of photovoltaic modules would utilise one bypass diode per cell, however this is too expensive and complicated to realise, so instead of this, they are placed across groups of solar cells (as shown in the **Figure 17** of this section) [25].

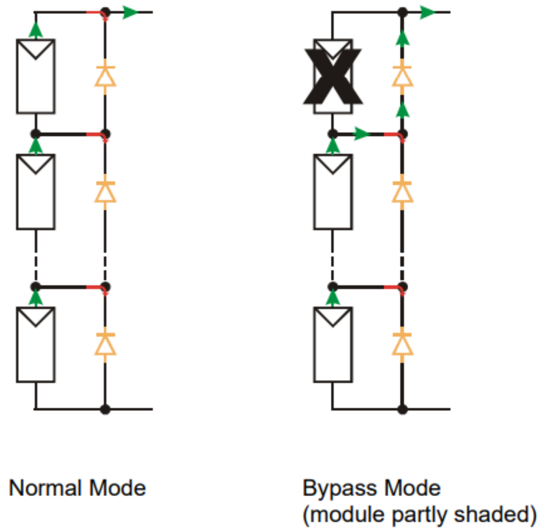

Figure 18 Activation of the Bypass Diode by Partial Module Shaded [28]

3.2 Bypass Diodes Parameters

The *I-V* curve of a Schottky diode (Bypass diode) is quite distinctive in comparison with other diodes. In the forward direction the current rises exponentially, having a turn-on voltage of around 0.2 V. In the reverse direction, there is a greater level of reverse current than that experienced using a PN junction diode [27].

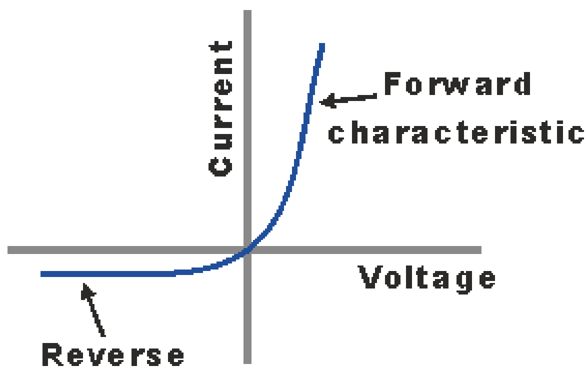

Figure 19 Bypass Diode I-V Curve [27]

It is necessary to define some parameters related with the Schottky diodes to be able to compare them with more common diodes [27].

- **Forward voltage drops:** As can be seen on the Schottky diode *I-V* curve, the voltage across the diode varies according to the current being carried. Typically, the turn-on voltage is assumed to be around 0.2 V.
- **Reverse breakdown:** Schottky diodes do not have a high breakdown voltage. Values relating to this include the maximum Peak Reverse Voltage, maximum Blocking DC Voltage and other similar parameter names. If these values are exceeded, then there is a possibility the diode will enter into reverse breakdown. The upper limit for reverse breakdown is not high when compared to normal PN

junction diodes. Maximum values, even for rectifier diodes, reach approx.100 V only. Schottky diode rectifiers seldom exceed this value because devices that would operate above this value even by moderate amounts would exhibit forward voltages equal to or greater than equivalent PN junction rectifiers.

- **Capacitance:** This parameter has a great importance for small signal RF applications. Normally, the junction area of Schottky diodes is small and consequently the capacitance is small as well, with values around a few picofarads (pF). As the capacitance is dependent upon any depletion areas, the capacitance must be specified at a given voltage.

- **Reverse Recovery Time:** This parameter is important when a diode is used in a switching application. It is the time needed by the diode to switch from its forward state or ON state to the reverse or OFF state. The charge that flows within this time is referred to as the 'Reverse Recovery Charge'. The duration for a Schottky diode is normally measured in nanoseconds (ns), in some cases it arrives to 100 ps. In fact, such a small recovery time mainly arises from the capacitance rather than the majority carrier recombination. As a result, there is very little reverse current overshoot when switching from the forward conducting state to the reverse blocking state.

- **Working temperature:** The maximum working temperature of the junction, *Tj* is normally limited between 125 to 175 °C. This is less than what can be achieved with ordinary silicon diodes. Care should be taken to ensure heatsinking of power diodes does not allow to exceed these values.

- **Reverse leakage current:** The reverse leakage parameter can be an issue with Schottky diodes. It is found that increasing temperature significantly increases the reverse leakage current parameter. Typically for every 25 °C increase in the diode junction temperature, there is an increase in reverse current of an order of magnitude for the same level of reverse bias.

In the following table, a summarized comparison of the characteristics of the bypass or Schottky diode, explained just before, and a common diode with PN junction is shown [27].

COMPARISON OF CHARACTERISTICS OF SCHOTTKY DIODE AND PN DIODE		
CHARACTERISTIC	SCHOTTKY DIODE	PN JUNCTION DIODE
Forward current mechanism	Majority carrier transport.	Due to diffusion currents, i.e. minority carrier transport.
Reverse current	Results from majority carriers that overcome the barrier. This is less temperature dependent than for standard PN junction.	Results from the minority carriers diffusing through the depletion layer. It has a strong temperature dependence.
Turn on voltage	Small - around 0.2 V.	Comparatively large - around 0.7 V.
Switching speed	Fast - as a result of the use of majority carriers because no recombination is required.	Limited by the recombination time of the injected minority carriers.

Figure 20 Comparison Schottky /PN Junction Diode Table [27]

3.3 Influence of Temperature

Every semiconductor device suffers irregularities in its behaviour with the variations of temperature, including bypass diodes. Generally, in the PN junction diodes, increasing temperature causes a decrease in the cut off voltage in the forward bias region, whereas in the reverse bias exactly the opposite occurs. In the following graphs, this phenomenon in different types of diodes is shown [29].

- PN Junction diode

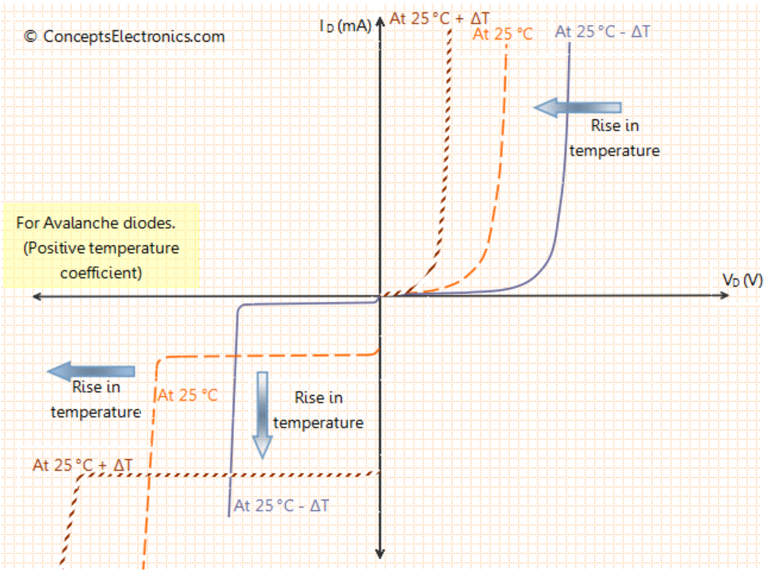

Figure 21 Effect of Temperature on PN Junction Diodes [29]

- Zener diode

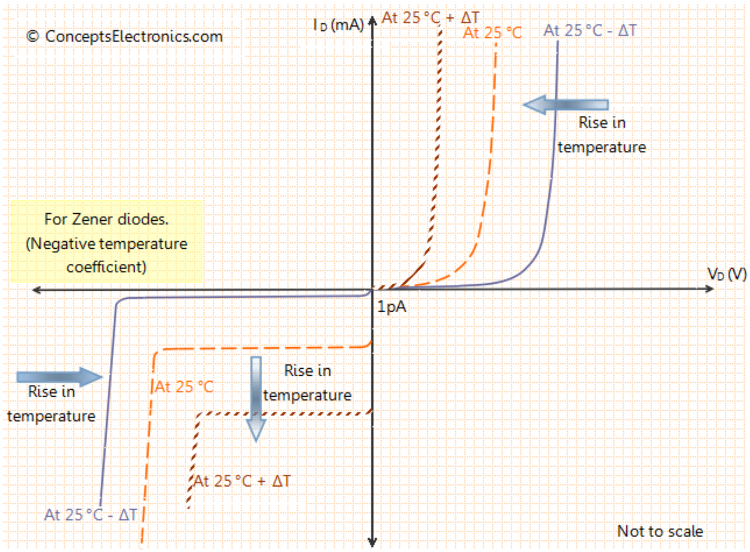

Figure 22 Effect of Temperature on Zener Diodes [29]

These effects are due to all diodes being made from semiconductor materials. This means they do not conduct properly current at low temperatures, but as temperature increases so too does their conductivity [29].

Part II: Practical Part

4 Modelling Photovoltaic Module

4.1 LT Spice

LT Spice is freeware computer software created, developed and distributed by the company Linear Technology (LT), now part of Analog Devices, released on November 18th, 2016.

Figure 23 LT Logotype [30]

LT Spice is defined by his developers as a high-performance SPICE (Simulation Program with Integrated Circuits Emphasis) simulator, schematic capture and waveform viewer with enhancements and models for easing the simulation of switching regulators. LT enhancements to SPICE have made simulating switching regulators extremely fast compared to normal SPICE simulators, allowing the user to view waveforms for most switching regulators in just a few minutes [30].

To study the behaviour of electronic components or circuits, it is useful to have simulation software, with which the equations that model the behaviour of the studied circuit can be evaluated under different situations, helping to confirm or discard the theory behind it.

4.2 Photovoltaic Module Simulation

The main objective in this part of the experimentation was to create and develop an equivalent circuit of a photovoltaic module with an assignable number of defective cells. In order to be able to properly simulate the circuit, it was necessary to develop a new and specific component and matching equivalent sub-circuit (Shown in the **Figure 28**).

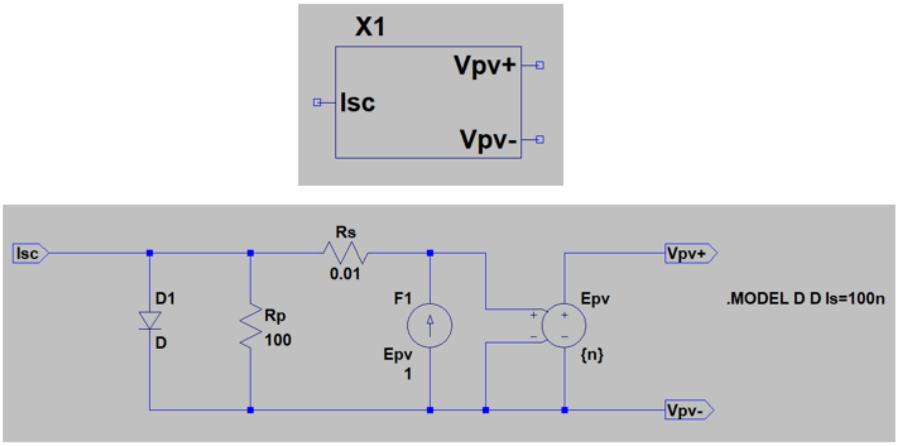

Figure 24 Component Developed (Up). Sub-Circuit Developed (Down)

Once the components were created, obtaining simulated *I-V* and *P-V* curves from the finished photovoltaic panel circuit was possible under the desired conditions. Results obtained in the outdoor experiments with real photovoltaic modules, could be compared with the simulated results and conclusions drawn [31], [32], [33].

For simulating various defects, the blocks were connected using the following circuit. Two substrings are considered to be "healthy" and upper substring is divided into two sections – one representing the defect by lower supplying current and the second one representing the "healthy" part of the sub-string.

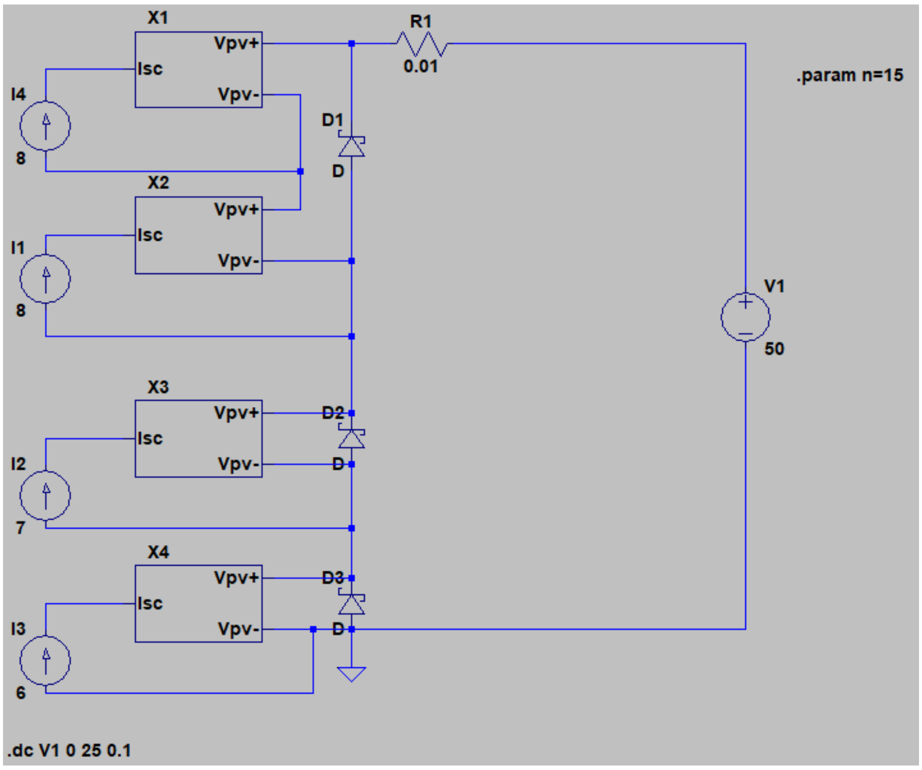

Figure 25 Simulated Photovoltaic Solar Panel with LT Spice

4.3 Simulation results

When simulating the various defects, it is sufficient to affect the required number of the cells by the defect – hot spot affect only one cell, shading influence more cells, but not totally. The results of simulation of most common defects follow.

4.3.1 Hot-spot

This defect appears in single cells and gradually leads to destruction of the module.

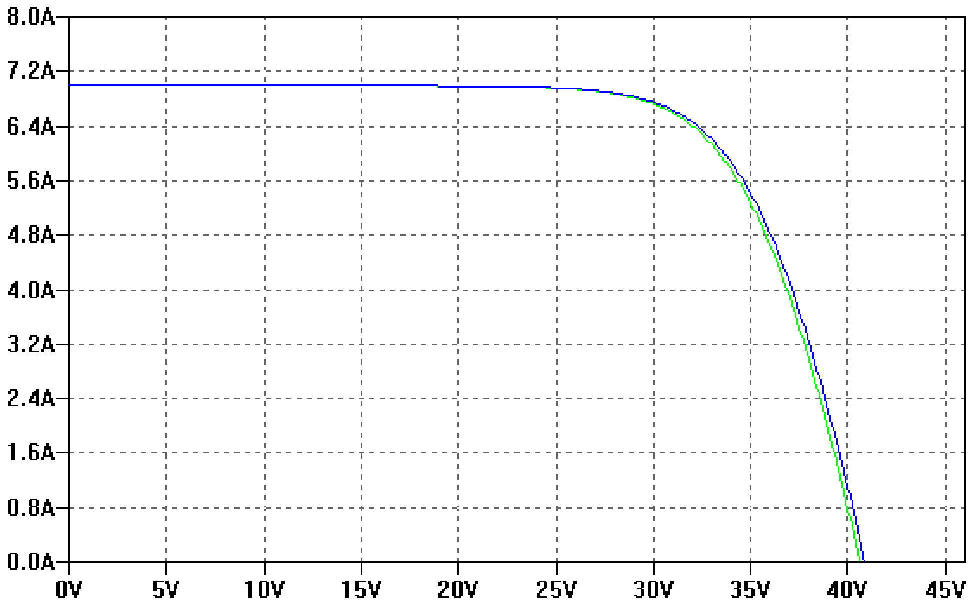

Figure 26 Simulation of PV module with hot-spot defect with different temperature of the hot-spot – 50 °C blue curve, 100 °C green curve.

Results show that the hot-spot will not influence the PV module performance much. This is due to fact that only local heating of cell appears at affected module, so the resulting curve is not influenced.

4.3.2 Shaded block of cells in one substring (local shading)

For simulation, shading of 1, 2, 3 and 4 cells with transparency is assumed. Transparency means that the shading is not total, but only limiting, in this case the decrease of generated current was set to 60 % of its original value.

The result shows that one cell will not affect the performance much but 2, 3 and 4 cells have the same impact on the resulting curve. This is caused by the bypass diode behaviour, which switched in the case of more shaded cells, but in the case of one shaded cell remains closed.

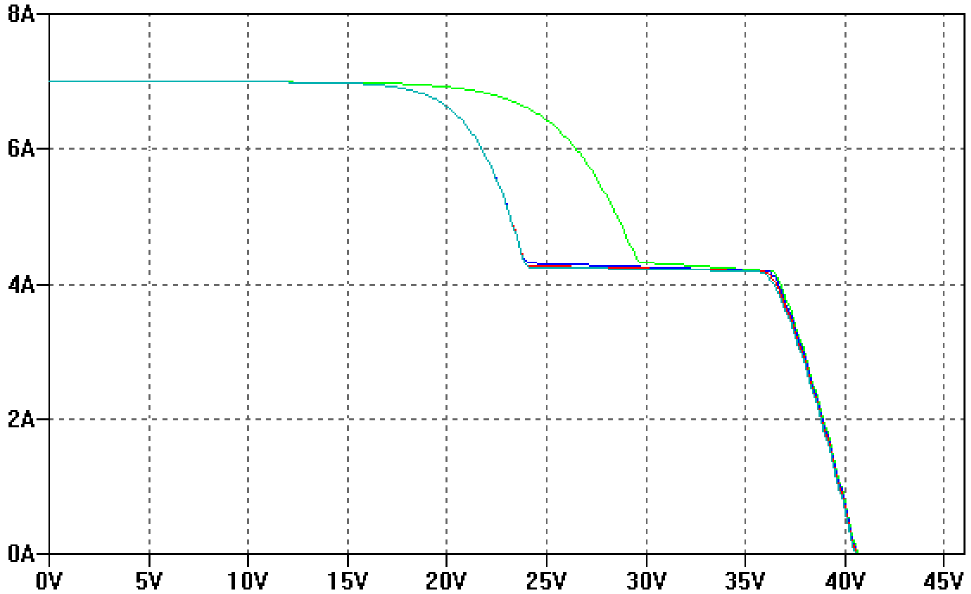

Figure 27 Simulation of PV module with local shading of 1 cell (green) and more cells (other curves)

4.3.3 Cracked half of cell

The cracked half of the cell can be simulated using the shading of one cell with the half supplying current.

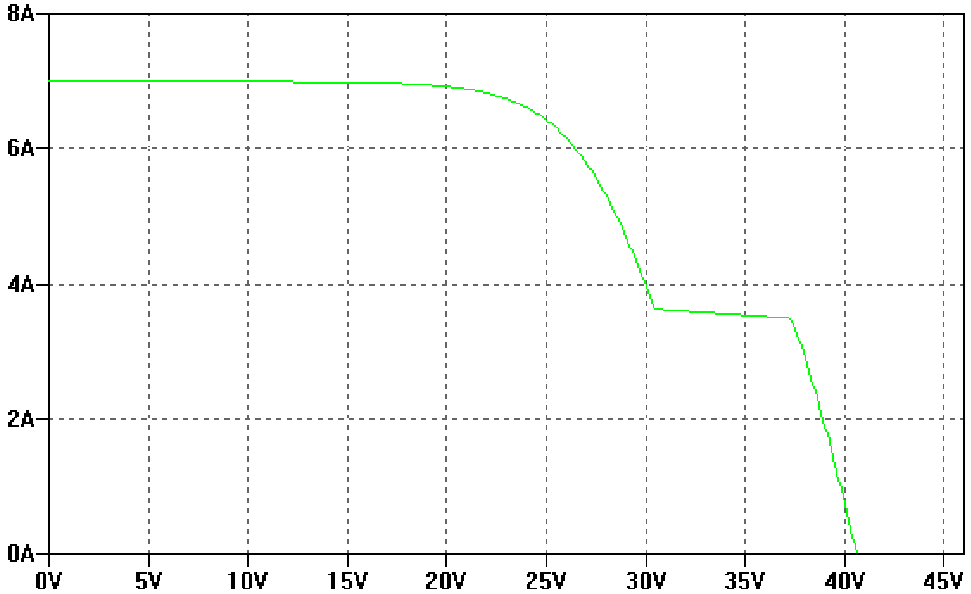

Figure 28 Simulation of PV module with cracked half of cell

At the ambient temperature, the bypass diode is closed. This situation is the same as the previous one for 1 shaded cell. However, it changes with rising temperature of the bypass diode rapidly. If higher temperature of the diode is presumed, it can switch on and bypass the affected substring. The simulation results for temperature of the bypass diode of 100 °C (blue curve) and 150 °C (green curve) are given below.

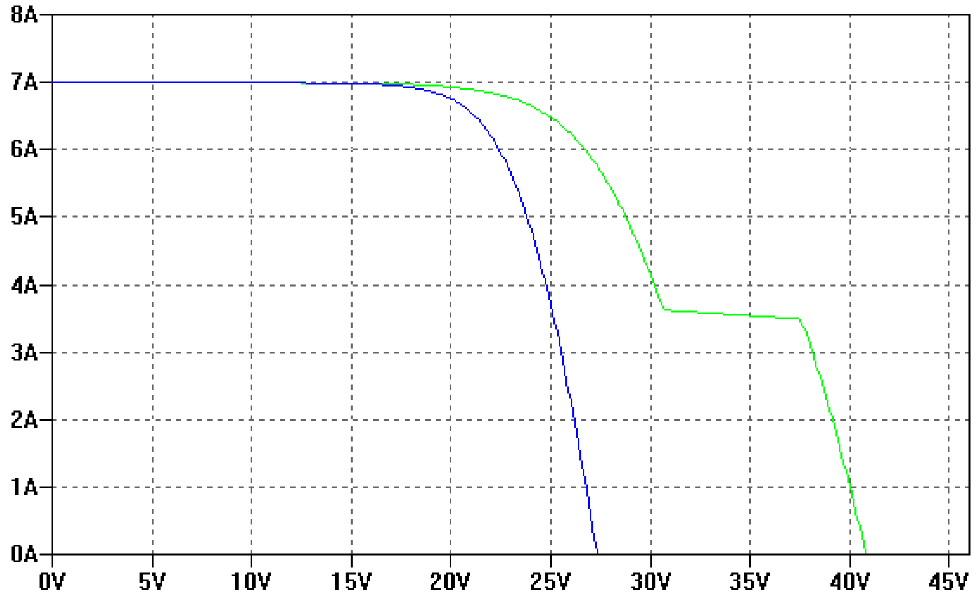

Figure 29 Simulation of PV module with cracked half of cell – different bypass diode temperature

4.3.4 Unconnected cells

This situation is very similar to the previous one, the only resulting current in affected part of the curve is in the case of non switched diode zero from the beginning. The situation is the same regardless the number of affected cells and the whole string behaves like a short-circuited bypass diode.

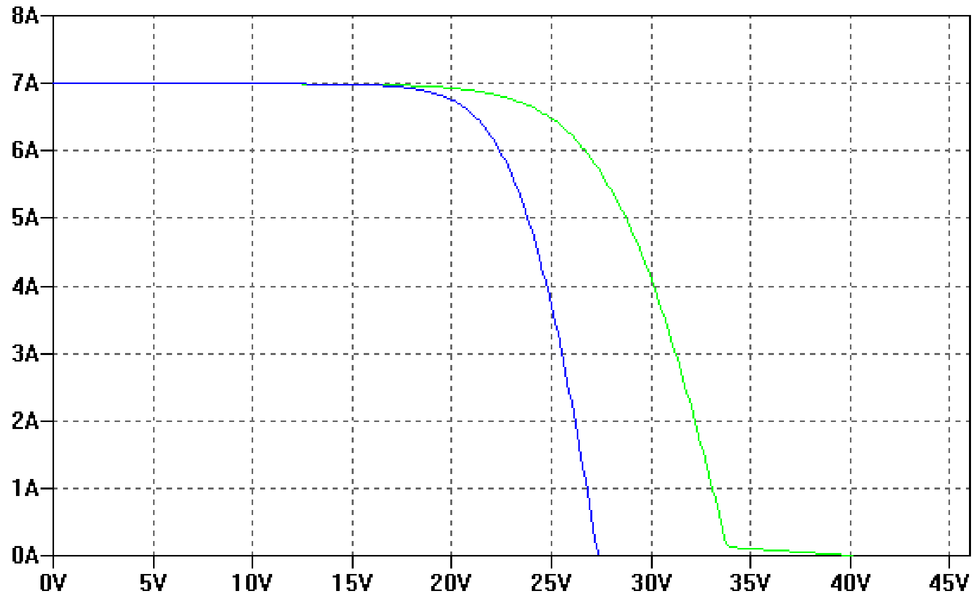

Figure 30 Simulation of PV module with more unconnected – different bypass diode temperature

5 Experiments

5.1 Laboratory experiments

5.1.1 Bypass Diode Disbalancing

Measurement setup

This experiment consisted of the disbalancing of a diodes box under variable temperatures. The disbalancing and variation of temperatures simulate the effects of a shaded PV module. The advantage of this experiment is that when working in a laboratory indoors, it is easier to control the conditions of the experimentation than when using a real photovoltaic module outdoors.

To develop the experiment, some devices were used in order to simulate the photovoltaic module behaviour. The main devices are three independent power sources, which supply current to the diodes box (simulating the PV module). This PV module simulator is connected to a junction box that allows the connection of the measurement equipment and a heater to progressively raise the temperature of the bypass diodes box.

After the equivalent circuit has been made, the experiment consists of setting certain temperatures in the bypass diodes box, which are increased in intervals of 10 °C (from 20 °C to approximately 100 °C). Once the desired temperature has been reached, and the bypass diodes are balanced (1 A), the current is reduced step by step in 0.1 A until the value of 0.2 A is reached. In each of these steps, the variable resistors values are modified to measure whole unbalanced (or balanced) *I-V* curve by the datalogger.

Results

The simulation using diodes did not work as expected, as no changes of the I-V curves are apparent in dependence on the temperature, presumably due to too low level of supplying current (with a range of 1 A to 0.2 A approximately). Consequently, the results obtained are not valid to this research. So, the conclusions will be obtained from the outdoor experiments. Some of the graphs obtained are shown as examples below.

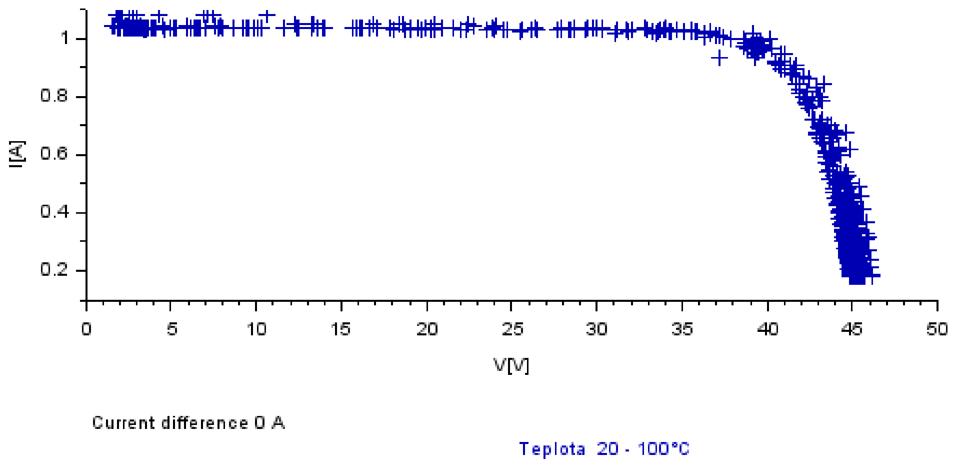

Figure 31 Balance I-V Curves from 20 to 100 °C

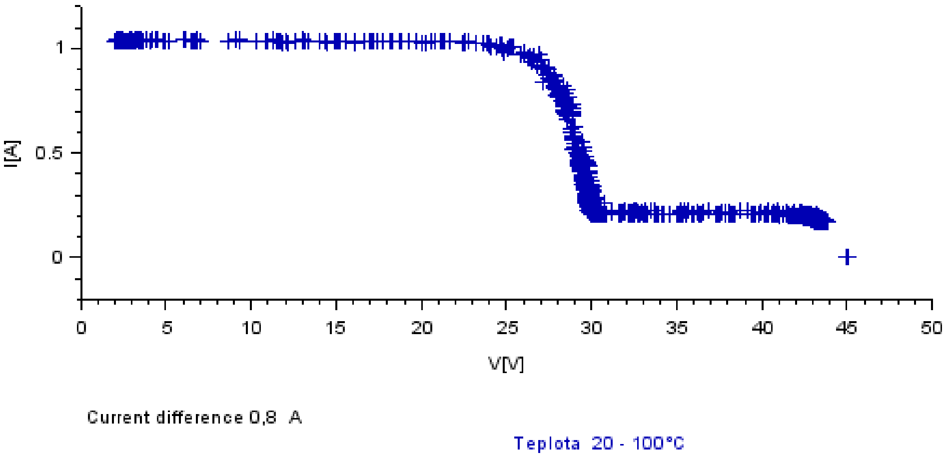

Figure 32 Unbalance I-V Curves from 20 to 100 °C

5.2 Outdoor experiments

5.2.1 Measurement setup

In this part of the experimentation, the main objective was to measure under real conditions. All experiments were performed under clear-sky weather on the morning of April the 3rd 2018 (designated as Exp1) and May the 19th 2018 (designated as Exp2).

In order to prepare the experiment to produce the highest possible amount of energy, the photovoltaic module was placed oriented to the sun. Ambient temperature, temperature in the photovoltaic module and in the bypass diode, as well as the irradiance were measured, and the *I-V* curves graphed. For these measurements a thermocouple digital thermometer, a solar irradiation sensor and a solar analyser were used - shown in the pictures below.

Figure 33 Left: Thermometer (Up), Irradiance Sensor (Down); Right: Solar Analyzer

Figure 34 Irradiance Sensor (Left) and Thermometer (Right) used on the Experiment

The experiment was then carried out, with nine different measurements of *I-V* and *P-V* curves being taken in different conditions: without shading, with partial shading and with complete shading of one or two of the PV cells of the photovoltaic module with cardboard.

Figure 35 Photovoltaic Module with Different Levels of Shading

Maximum Power Point operation

To test the photovoltaic module in real operation at higher temperatures, a load was connected to it, allowing it to operate at the Maximum Power Point (*MPP).* A change in the *I-V* and *P-V* curves was expected due to the defective part behaviour.

Figure 36 Load used on the Experiment

Multiple measures of the solar irradiance and environmental and panel glass temperatures were taken during the realisation of the experiment, in order to increase the accuracy of the results. Finally, a total of eight measurements were obtained. Obtained measurements are properly analysed in section **5.2.2 Experimentation Analysis.**

Operation under short circuit conditions

To test under different conditions, not only was a different date with lower irradiance chosen, but also a different operation, foregoing the measurement, was set up. The module was short-circuited and taken in this state for approximately 10 minutes before measurement. This led to a higher current flowing through the bypass diode and consequently also its higher temperature.

Operation with heated junction box

The experiment (Exp 2) was performed practically like the previous one - with one exception. The bypass diodes box was heated by a Hakko FR-801 Hot Air Station and a thermal camera (Shown in the **Figure 27**) was used in order to track the temperature of defective cells.

Figure 37 Hakko FR-801 Hot Air Station (Left) and Testo Thermal Imager (Right)

The bypass diode box was heated for approximately five minutes before each measure with the solar analyser. It is quite possible that the differences between the *I-V* and *P-V* curves are not significant due to their working area. Five measurements, with and without load, were taken in the experiment.

5.2.2 Experiments results

Comparing the data obtained in both outdoor experiments gives various graphs that compile the *I-V* and *P-V* curves of the different measurements according to the shading of the module (unshaded, one cell shaded, one and a half shaded, etc). For better comparison, data was corrected to the STC irradiance value of 1000 W/m^2, neglecting the temperature of the photovoltaic modules glass, as its value was within the range of 10 °C which is not significant difference for evaluation.

The obtained graphs show some interesting results. In a total of five graphs, with eight *I-V* and *P-V* curves from the outdoor experiments (one unshaded and four shaded), it can be observed how critical the defect is on the module (as a greater surface is shaded), the behaviour of the bypass diodes box is more stable.

Unshaded module

The first curves were measured for the unshaded PV module:

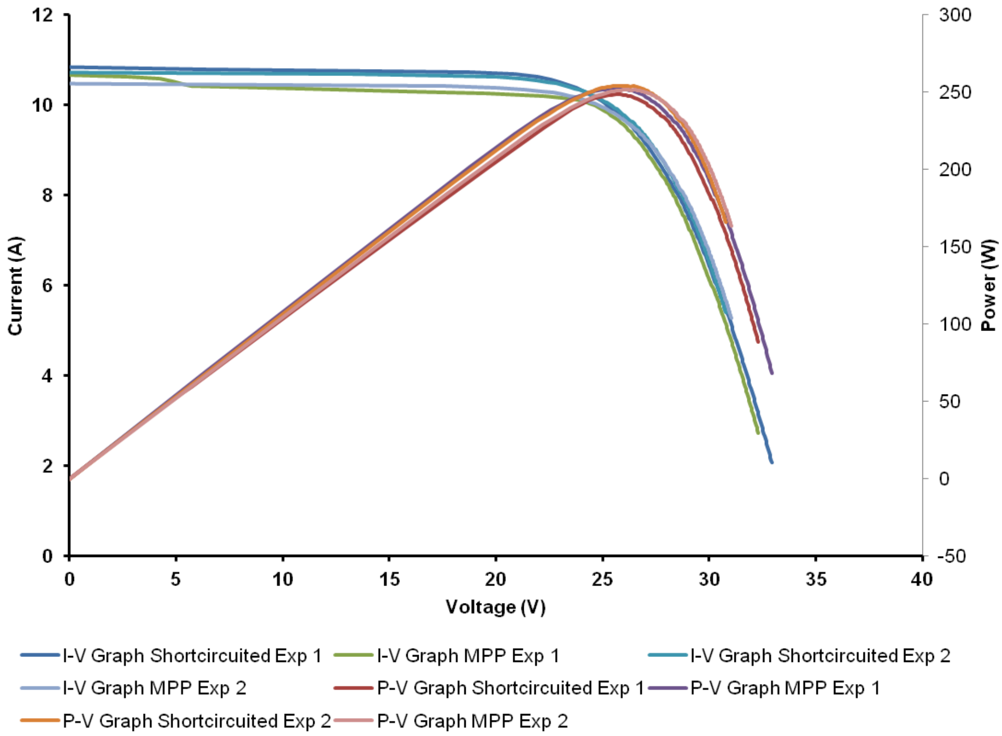

Figure 38 Unshaded I-V and P-V Curves

Half-shaded cell

The most critical situation takes place in the half-shaded cell graph. In these curves, it can be observed that the *I-V* curves are very unstable. Although the by-pass diode is closed in the case of the first outdoor experiment (Exp 1) and MPP conditions, it heated up through the short-circuit operation and switched on. During the next experiment (Exp 2), the bypass diode was heated, but only to 65 °C which didn't cause any significant difference, because the irradiance was about approximately 30 % lower than in the first experiment, meaning the current flowing through the diode was insufficient.

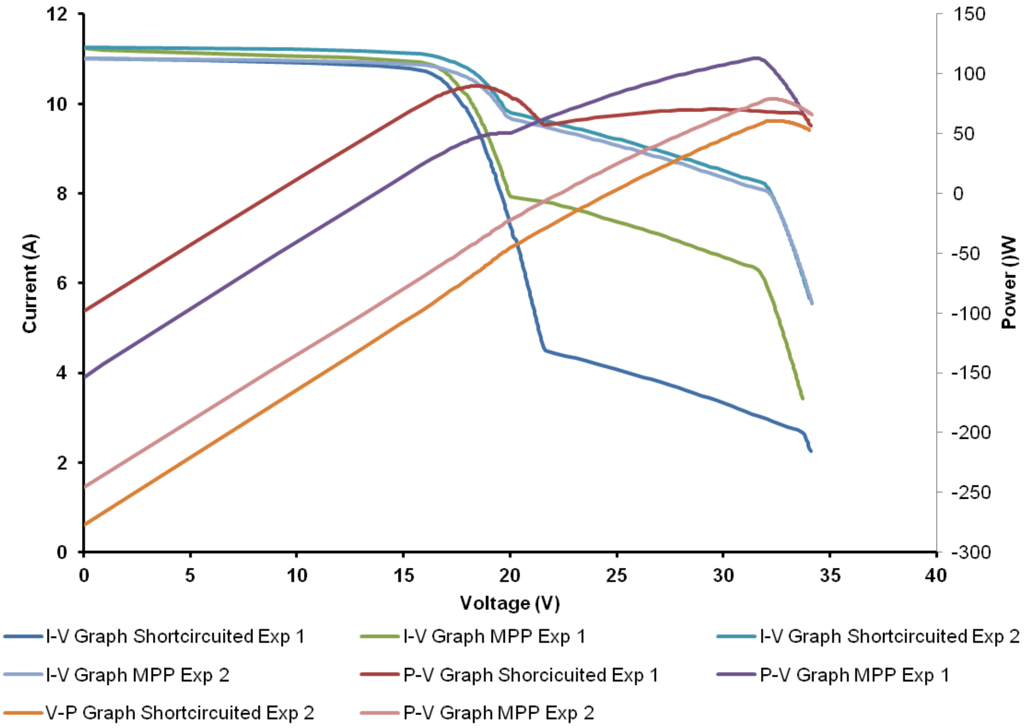

Figure 39 Half Cell Shaded I-V and P-V Curves

Observing the data obtained in these experiments, we can see that the main factors that differ from one experiment to another are the irradiance and temperature. In the first experiment, the temperature of the glass in the short-circuited measure was 32.1 °C and in the MPP the measure was 31.9 °C, while the bypass diode box was at ambient temperature. The irradiance was approximately 800 W/m^2. However, in the second experiment, in both measures the temperature of the glass was 38.9 °C (lower irradiance – approximately 700 W/m^2, but with a much higher ambient temperature) whilst the temperature in the bypass diode box was approximately 60 °C due to the heat applied by the hot air station.

One or more shaded cells

In the case of one or more shaded cells, it is not necessary to correct the data to STC and it is obvious that the behaviour in the right part of the *I-V* curve is the same regardless of the temperature of bypass diode or any other component of the module under experiment. The differences observed are caused only by the unequal conditions, but no other additional effect of bypass diode behaviour appeared.

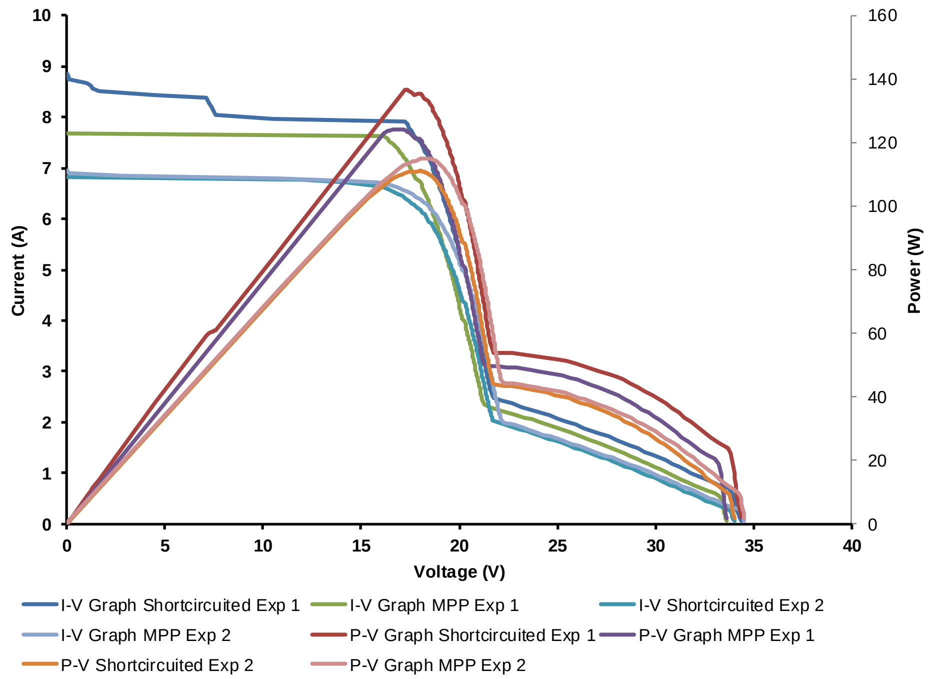

Figure 40 One Cell Shaded I-V and P-V Curves

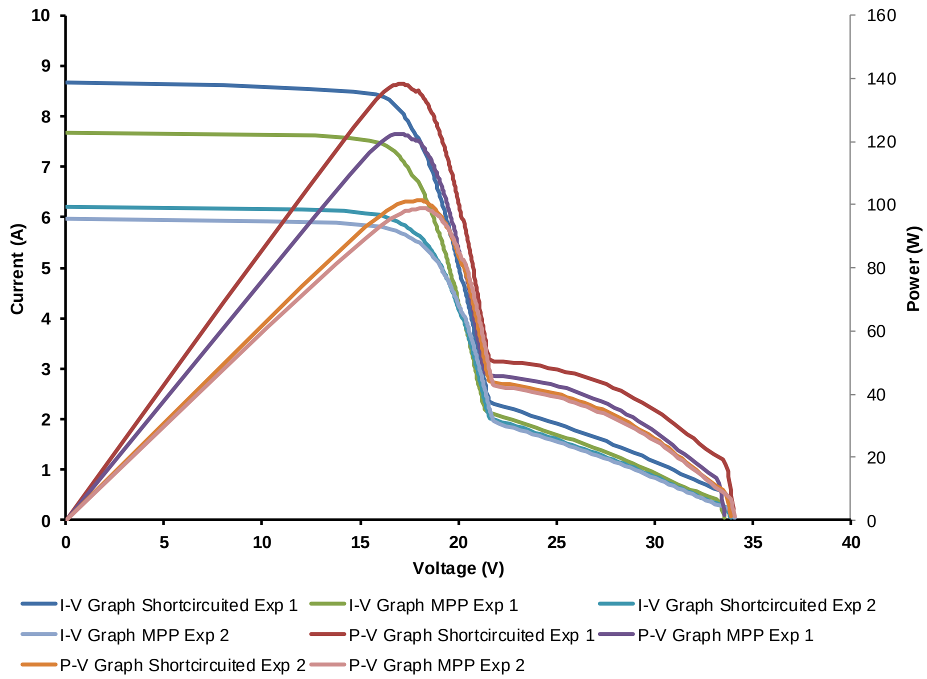

Figure 41 One Cell and a Half Shaded I-V and P-V Curves

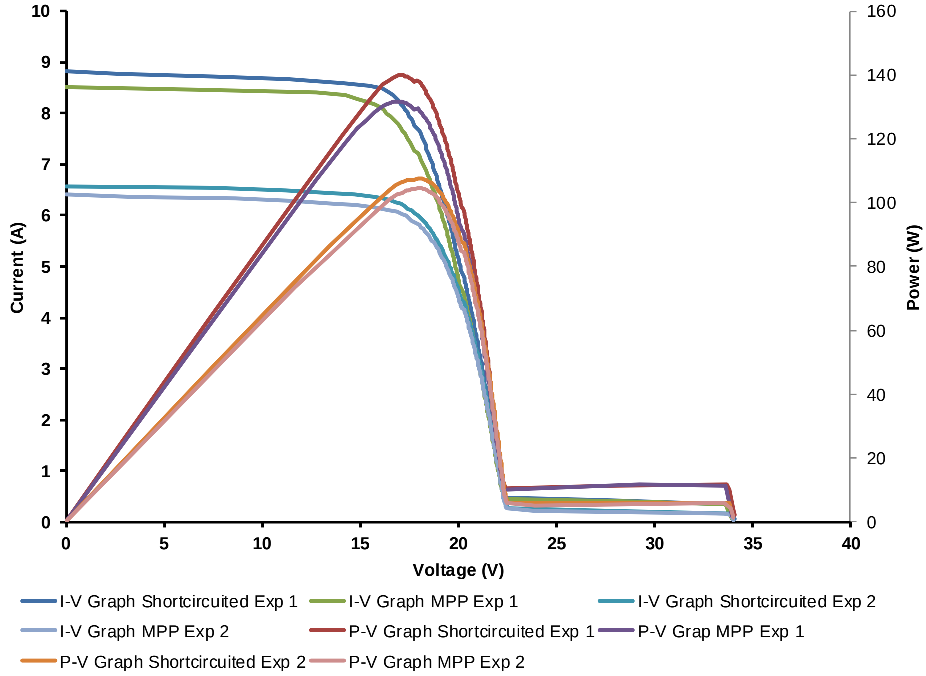

Figure 42 Two Cells Shaded I-V and P-V Curves

6 Conclusions

The presented thesis summarises the behaviour of bypass diodes within the PV module. Set of simulations and measurements has been performed.

The experiments in the laboratory proved that the configuration, which is too far from the real values (too low current level), is not suitable for a behaviour study of bypass diodes, because of their current limits and thus heating is too low to be able to affect the resulting *I-V* curves values.

On the other hand, the simulation and also outdoor experiments proved that the non-standard behaviour exists. When the defect of the PV module is less serious – half of the cell is affected; then the module exhibits non-standard behaviour in comparison with more serious defects – more cells are affected. Such defects with the combination of bypass diode behaviour can give different results than expected and the bypass diode behaviour should then be taken into account when evaluating *I-V* curves of PV modules in laboratory and natural conditions.

In the case of more defective cells, bypass diode temperature does not play an important role.

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8 List of Figures