WORK END OF MASTER

MASTER IN ENERGY ENGINEERING

ENERGY APPROACH TO NEW RECONFIGURABLE PV SYSTEMS: THE TEAM SYSTEM

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Abstract

In years in which energy is essential for daily life, the photovoltaic system is now well known but not only for its positive aspects. If on the one hand it guarantees the generation of energy from a renewable source such as the sun, on the other hand its high cost and low efficiency do not make it so convenient. In this regard, research is attempting to make such a resource more competitive with cutting-edge solutions.

The goal of this study is in fact to analyze a new type of technology called *Team system*, which is part of the reconfigurable PV systems. It mainly concerns the use of a relay which, suitably programmed through software such as Matlab and Arduino, allows the system to change its configuration basing on the climatic conditions. And so, instead of a static structure, the system will have the possibility to change it in order to maximize the energy produced. In particular, two solar array simulators and two inverters will be considered in this project: the first configuration is that in which the two SAS are connected to a single inverter while the second where each simulator is connected to its own.

In this regard, a study will be carried out on the year 2006 in Barcelona considering real time values of irradiance and temperatures of three limit days: the sunniest, the most cloudy and the one characterized by more variations of the values in the 24 hours.

The aim is to conduct these simulations in order to understand the actual effectiveness of the Team system in terms of energy compared to a conventional one and the results obtained show a slight increase, giving way to hope for future developments.

Contents

List of abbreviations and symbols

AC:……alternating current
aSI:……amorphous silicon
B:……boron
CdTe:……cadmium telluride
CIGS:……copper indium gallium selenide
DC:……direct current
E:……electric field
E_c:……conduction band
E_v:……valence band
EVA:……ethylene vinyl acetate
G:……irradiance
GHGs:……greenhouse gas emissions
I_{MP}:……current at the maximum power
I_{SC}:……short circuit current
LTC:……load tap changer
LVR:……line voltage regulator
MI:……module integrated
MO:……module oriented
MPP:……maximum power point
P:……phosphor
P_{IN}:……power input
P_{MAX}:……maximum output power
PO:……plant oriented
P_{OUT}:……power output
PV:……photovoltaic
PVG:……PV generator
R_S:……sizing ratio
$R_{S\ OPT}$:……optimal value of the sizing ratio
SAS:……solar array simulator
Si:……silicon
SiO_2:……silicon dioxide
SPV:……solar photovoltaic system
STC:……standard test conditions
T:……temperature
V_{MP}:……voltage at the maximum power
V_{OC}:……open circuit voltage
W_P:……watt peak

Chapter 1

Introduction

Today more than ever, the energy crisis is a theme that regards us all. Last year, and especially this very one, have showed us how this world is in continuously changing and how its safety is in our hands. The crisis has already had wide-ranging impacts on economics, environment and security.

The pandemic of these last years brought about a historic drop in energy demand and prices, but recovering demand is now straining fossil fuel markets for oil and gas, and even coal. As a result, prices were never been so high and it's difficult to find a solution. Rebalancing energy systems to prioritize energy security could further both economic and environmental goals [1].

First of all, it is important to understand how our actions can affect the climatic situation we're actually facing and what we can effectively do to effort this problem.

People all over the world are trying to do their best and basing on that, on 25 September 2015, 193 UN member countries have subscribed the new Agenda 2030 containing 17 goals regarding the sustainability, to achieve in 2030.

"The new agenda is a promise by leaders to all people everywhere. It is an agenda for people, to end poverty in all its forms – an agenda for the planet, our common home."[1]

It is an Agenda which proposes different changes in different life aspects, but it also includes elements connected to a sustainable management and the improvement of the energetic devices which can generate energy from natural sources [2].

Nowadays, in fact, there is more consideration towards renewable energy generation, especially due to the greenhouse gas emissions (GHGs). In particular, there's an emerging interest in solar and wind power generations. We also often hear about nuclear energy but it has time of installation way bigger than the others, so it can be for sure a solution and an improvement for the future, but right now we have to accelerate resolution times with cutting-edge techniques on the existing systems trying to contain costs and times.

So, coming back to the renewable energy generation, the interest is in particular in sources like sun and wind. It has emerged that these two together accounted for more than two third of the 265 GW of new electrical power installed worldwide in 2019, compared to less than a quarter in 2010 [3].

In particular in this project just the solar systems are considered and all their principle aspects are analyzed in the following discussion.

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[1] Ban Ki-moon. He is a South Korean politician who served as the eighth Secretary-General of the United Nations between 2007 and 2016.

An overview of the present research project steps follows.

In Chapter 2 the PV system itself is explained. At the beginning it is discussed the basic functioning of it, analyzing the structure, how it is composed and the photovoltaic effect who guarantees the generation of the current. The function of the inverter is also presented and at the end of the chapter it is given some information about a new type of reconfigurable photovoltaic system which is called Team system.

Chapter 3 contains instead all the methods, the tools and the procedures used to connect all the instruments considered. Each of them will be briefly explained, giving instructions on the languages used for the communication between one to another.
At the end of it, it will be shown the procedures adopted in doing the simulations which lead to the power generated by this new reconfigurable system.

In Chapter 4 the results of the simulations are illustrated and analyzed comparing at the same time the results obtained in terms of energy with the one coming from a conventional system.

In Chapter 5 the results are better analyzed and the conclusions of the project is presented with the considerations on the usefulness of the Team system.

Chapter 2

Photovoltaic systems

2.1 Conventional PV systems

Before studying the new cutting-edge technologies that can improve a normal photovoltaic system, it is important to better understand its basic functioning just to have a global overview and to have the possibilities to get more into the heart of the discussion.
Starting by its basic aim, a photovoltaic (PV) system is created to use energy from the sun to generate electricity.
It is mainly composed of one or more solar panels and another crucial element which is essential to the correct generation and the correct use of power in the utilities: the inverter. Since the electricity produced from a solar panel is in the form of direct current (DC) and the utilities can mostly receive an alternating current (AC), the presence of the inverter starts to be really important in doing this change.
The principle functioning is that when the photons, which composed the light of the Sun, reach the panel, this creates an electric current thanks to the photovoltaic effect [4].
A scheme of a solar system can help before going deeper in the argument.

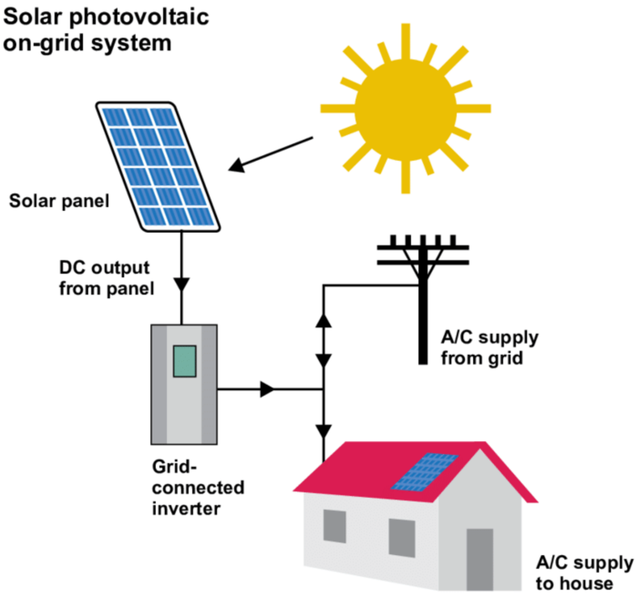

Figure 2.1. PV system scheme of a panel connected to households and to the grid [5].

2.1.1 Solar cell

The solar panel is made up by several solar cells with semiconductor properties and it is all encapsulated within a material whose function is to protect it from the environment. These solar cells are typically combined into modules that hold up to 72 cells; a number of these modules are mounted in PV arrays that can measure up to several meters on a side.

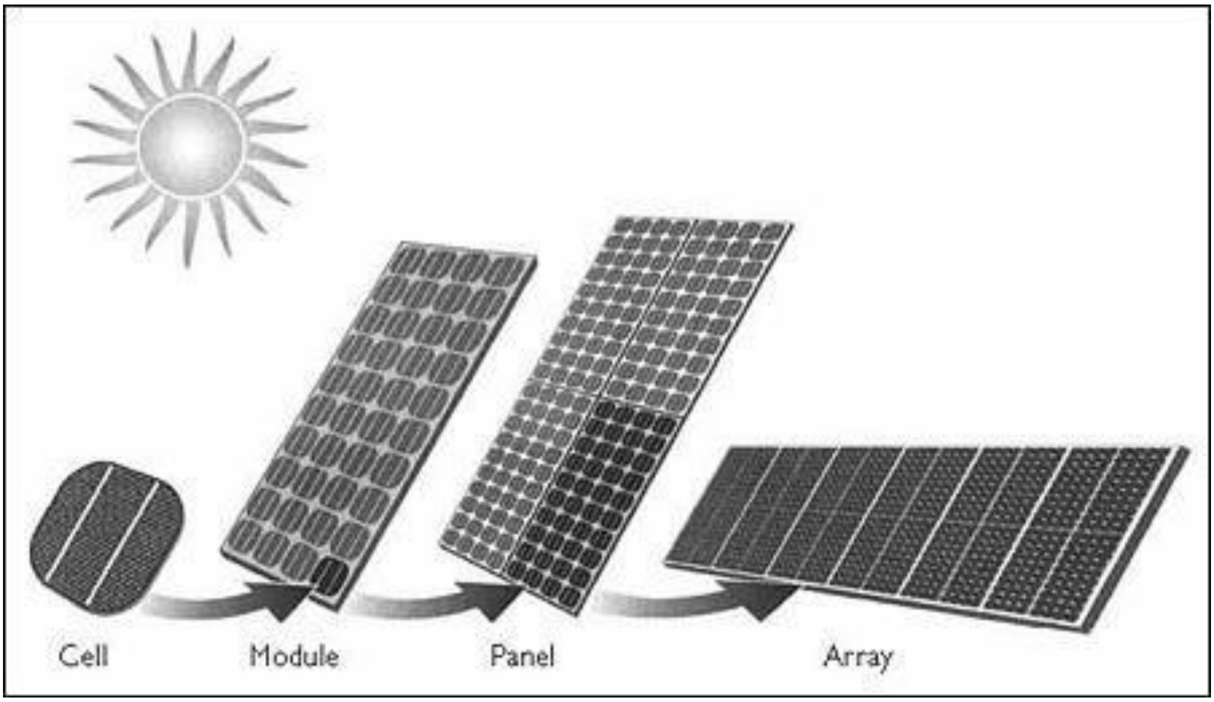

Figure 2.2. Relationship among cell, module and array [6].

As we can see from the figure 2.2, photovoltaic cells are connected electrically in series and/or parallel circuits to produce higher voltages, currents and power levels. Photovoltaic modules consist of PV cell circuits and they are the fundamental building blocks of PV systems. Keeping going, photovoltaic panels include one or more PV modules assembled as a pre-wired, field-installable unit. At the end, the photovoltaic array is the complete power-generating unit, consisting of any number of PV modules and panels.

Returning to the smallest component part of the system, the majority of solar panel is realized with crystalline silicon [7].

These kind of panels belong to the first generation solar cells [8] and they still dominate the market with their low cost.

The energy conversion efficiency is around 20% for multicrystalline silicon and around 15% for monocrystalline silicon modules. Silicon is produced from silica (SiO_2) which is mined as quartz sand. Moreover, both the electronics industry and the PV industry use silicon in a monocrystalline form. Therefore, the silicon is molten and subsequently crystallized under carefully controlled conditions so that large blocks or ingots of crystalline material are obtained. After removal of the outer edges, the ingots are cut into smaller blocks and then into thin layers, called wafers. Typical wafers are 0.3 mm thick and 100 cm^2 in area.

Most of the solar panels on the market today for residential solar energy systems can fit into three categories: monocrystalline solar panels, polycrystalline solar panels, and thin film solar panels. Every different type has its own characteristics so, basing on the different situation, there's a panel that fits the most with that.

Figure 2.3. Types of PV panel [6].

As already mentioned, monocrystalline solar panels are the most used, especially in the rooftop solar installation and even in this same category there are different types like for example the bifacial ones which guarantee the generation of the electricity on both the front and the back of the module. The reason why it is the most used lies in the fact its efficiency is the highest obtainable from a solar panel (around 17-22%) because being made by a single crystal of silicon allows electrons flowing easily throughout the cell and this parameter is important in the consideration of the surface needed to produce a certain amount of energy: in a roof with a limited surface, a monocrystalline panel gives the possibility to produce the same energy of an another panel with a lower efficiency.

The polycrystalline panel, or multicrystalline one, has been mentioned but in general, it is used by homeowners. So they are mostly used in residential applications and the main difference with the other is in the realization of those, in particular in the cooling process. Their efficiency is in a range of 15% to 17%: as explained before, the composition of the panel can facilitate the electron flow and in this case it decreases the efficiency.

The latest type is the thin film panel, which is made by deposing a thin layer of a photovoltaic substance onto a solid surface like glass. These substances can include for example amorphous silicon (aSi), copper indium gallium selenide (CIGS) and cadmium telluride (CdTe). In some cases, the film they create can be flexible. Since their efficiency are around 10-13%, it makes no sense to use them in residential applications where the available surface is limited. Despite their low efficiency, they have the best temperature coefficient: they can handle the heat better than the other panel types.

How regards the cost of these different elements, obviously is higher in the panel which has the highest efficiency and so on until the thin film which is the cheapest.

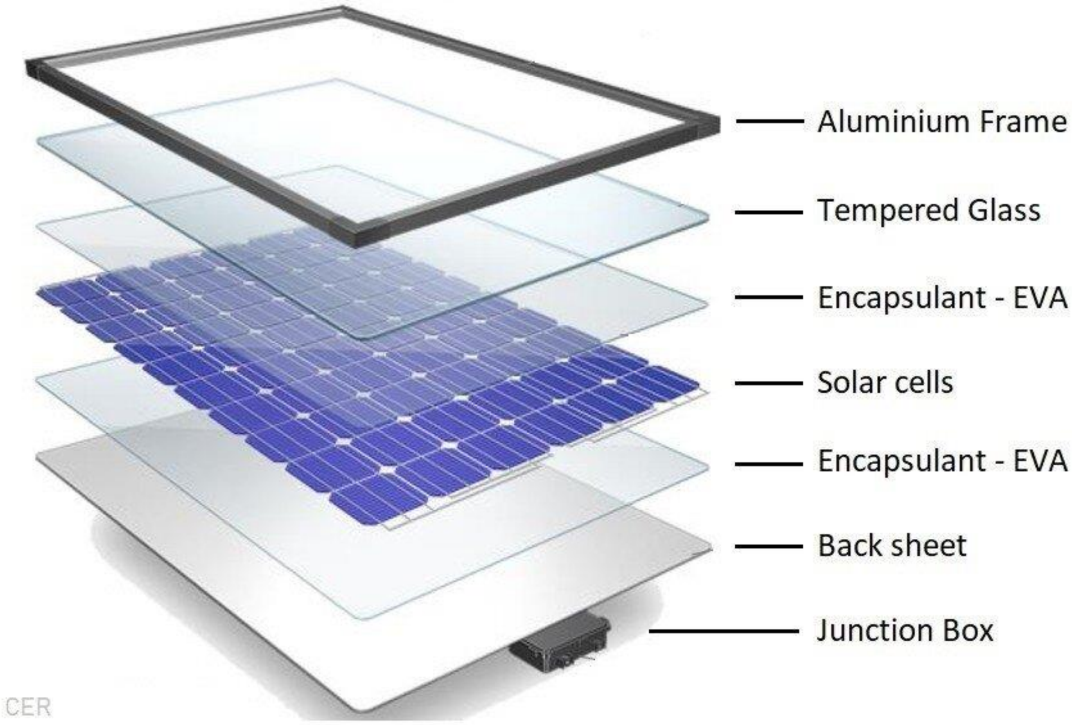

Figure 2.4. PV cell structure [9].

The figure 2.4 presents the structure of a PV cell where all the elements are well defined:

- EVA, ethylene vinyl acetate, it is simply an element inserted as a sort of glue with the adjacent layer given its malleability. In fact, it softens every time the panel is hit by the sun's rays;
- photovoltaic cell itself;
- tempered glass, whose function is fundamental in order to prevent the absorption of the sun’s rays and increase the efficiency of the cell. It is practically the same function and the same material in which the back sheet is realized;
- aluminum frame, which simply represents a way to connect all these elements together;
- junction box. It is put outside the structure described before and this box performs monitoring, safety and optimization functions of the photovoltaic cells installed in the module.

2.1.2 Doping

As we said, at the base of this photovoltaic cells there’s a semiconductor element which is silicon (Si), but it presents, like the other semiconductors, defects and impurities. To make it fits for the purpose, it often goes through a practice called *doping*.
First of all it’s important to introduce the valence band E_v, which is the most external band that contains electrons, and the conductor one E_c, that represents the electronic band with the lowest energy among the ones which are not completely occupied. For a conductor these two bands overlap, while for an insulator the difference potential is high as shown in figure 2.5.

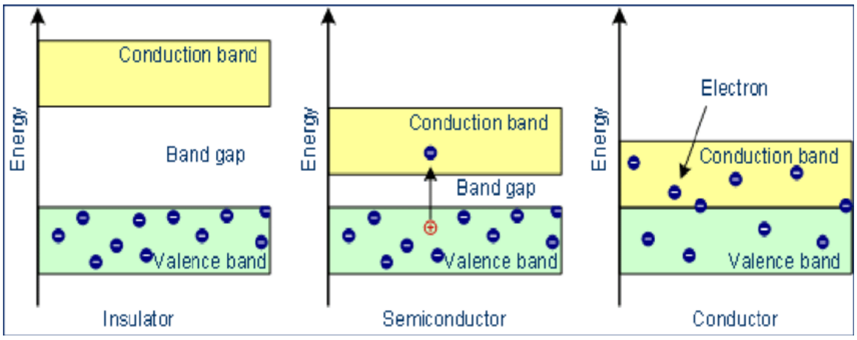

Figure 2.5. The energy gap and the differences among conductor, semiconductor and insulator [10].

So, in a semiconductor like silicon there's an energetic gap which is low and consequently the conduction can be possible only giving an external potential (in particular for a silicon atom this gap is 1.1 eV, it means it will be necessary a 1.1 eV to break the covalent bond). In fact, according to the theory of semi-conductors given by Wilson[2], there exist in these substances lattice imperfections at which an electron can exist in a bound stationary state below the conduction band, electrons being raised from these levels into the conduction band by the thermal agitation of the surrounding atoms [11].

For energetic reasons it's important having a configuration in which each atom complete its external orbital with all the eight electrons it can contain. Since silicon is a tetravalent element, which means it has four valence electrons, to make its configuration complete, it needs to share each of these four electrons with four other silicon atoms in a covalent bond.

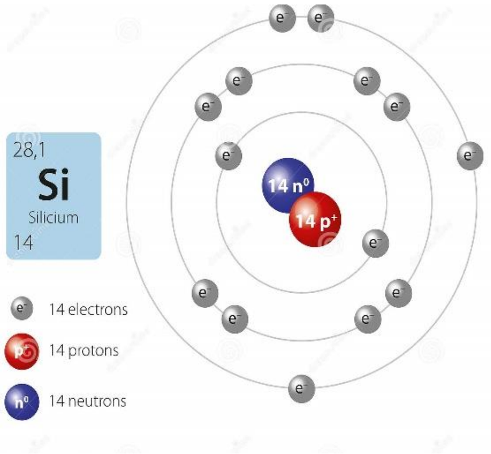

Figure 2.6. Silicon atom.

When the electrons "jumps" in the conduction band, it leaves the so called hole, so that there will be always a couple electron-hole. A new electron can occupy the hole formed and so on: that's how the conductivity in a semiconductor element works.

As already said at the beginning of the paragraph, a semiconductor present impurities and these ones can introduce new groups of energetic levels in the system. If these levels go in

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[2] Alan Herries Wilson (1906-1995) was a British mathematician who studied with Heisenberg on the application of quantum mechanics to electrical conduction in metals and semiconductors.

the forbidden region, a new band will be created so that the conductivity increase.

To improve this conductivity it is also possible to do the so called doping. It consists of adding a different element that generally can be atoms whose external orbital have one more or one less electron than the one in the silicon atom.

Basing on the number of electrons in the external orbital, there are two types of dopants: n and p type [12].

Energy levels of n-type dopants are in the semiconductor band gap near the lower edge of the conduction band, and they easily give electrons to the conduction band, but the dopants itself are charged positively. Analogously, p-type dopants have energy levels near the upper edge of the valence band, and they easily accept electrons from the valence band, and in particular they generate holes.

It means that, if it is used a n-type dopants, the element has five electrons on its last level, like for example phosphor (P), and so, being necessary just four of them for the bond, the other one is unused and free. So it's like each atom donates an electron which contributes to the conductivity of the negative parts.

On the second hand, if a silicon element is substituted by an element which has three electrons on the external orbital, like boron (B), there will be an electron missing which gives the possibility to create a hole and to accept an electron. This is the situation for a p-type dopants.

Generally, the both types of dopants are contained in organic semiconductors but in a different percentage: obviously a type dominates on the other. Free electrons from n-type dopants recombine with holes from p-type dopants leaving the one type of charge carriers and a lot of compensated dopants.

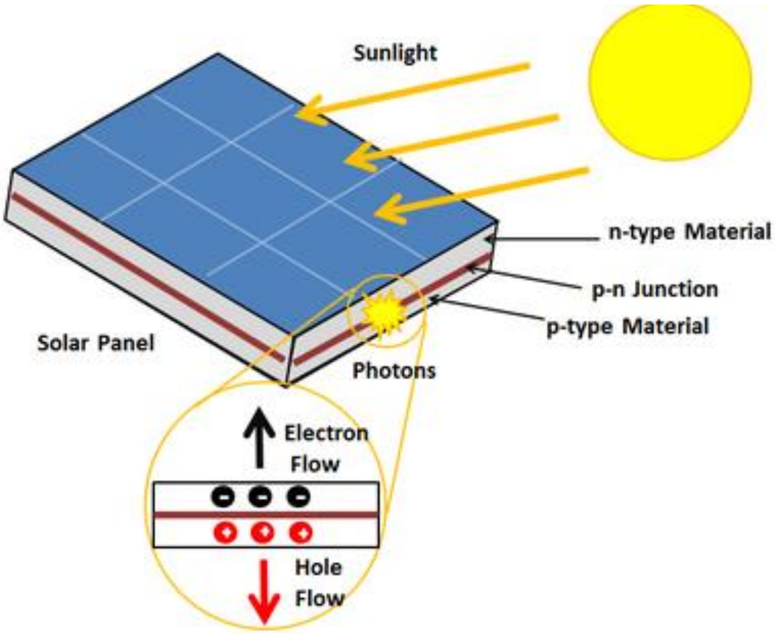

Figure 2.7. PV cells structure with p-type and n-type material [13].

Applying an electric field E on a semiconductor with these characteristics, it means generating a drift current, consequence of the movements of the electrons and holes and their respective velocities.

2.1.3 Photovoltaic effect

After having analyzed the structure of the photovoltaic system and the characteristics of the single cell constituted by silicon and, more precisely, by silicon and dopant elements, it is possible to talk about the effect itself: the photovoltaic effect, the one that makes possible the energy conversion. The figure 2.7 can help in the understanding of the phenomenon.

The photovoltaic effect is defined also as Becquerel effect[3], in honor of its discoverer. In 1839 he observed that an electric current was generated when he illuminated one of two electrodes immersed in a dilute acid [14]. In particular he noted that the voltage of the cell increased when its silver plates were exposed to the sunlight. After his discovery, there would be numerous investigations of workers with different types of "wet" cells and "dry" cells.

And so, photovoltaic effect is basically the production or change of potential between two electrodes separated by a suitable electrolyte or other substance when the electrodes are unsymmetrically illuminated. So, more precisely in this case, there's a production of voltage or of an electric current in a photovoltaic cell when it is exposed to the sunlight.

As already described, a solar cell is composed of p-type and n-type that are joined together to create the p-n junction. Joining these two types of semiconductor, there's an electric field which is formed in the region of junction as electrons move to the positive p-side and the holes move to the negative n-side.

Let's see what happens when the sunlight reaches this electric field E.

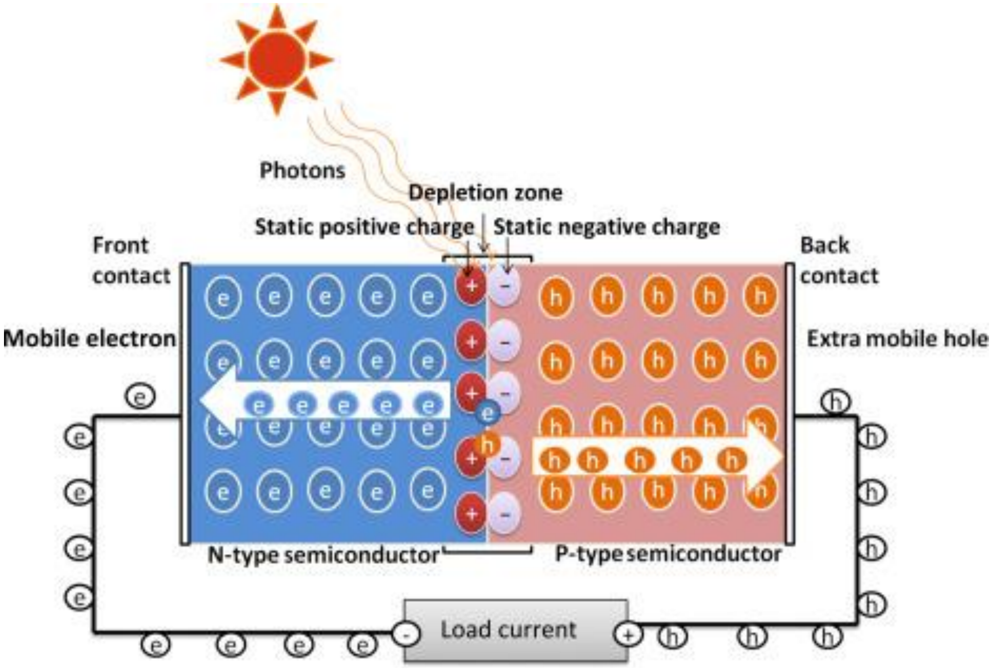

Figure 2.8. Particular of the solar cell for the current generation [15].

Light is composed by photons, which are simply small bundles of electromagnetic radiation or energy. All these photons can be absorbed by the solar cell itself and in particular, when the light reaches the panel with a suitable wavelength, the energy of the photon is

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[3] Alexandre-Edmond Becquerel (1820-1891) was a French physicist who studied the solar spectrum, magnetism, electricity and optics. His fame is due to the discovery of the photovoltaic effect in 1839.

transferred to an atom of semiconducting material of p-n junction. All this energy is carried by electrons so that they jump to the higher energy state, the conduction band. This leaves behind a hole in the valence band that the electron jumped up from. In their excited state in the conduction band, these electrons are free to move through the material and their movement generate a direct current.

2.1.4 Inverter

This device is an electrical one whose function is to convert the direct current generated by the solar panel into an alternating one. This conversion is necessary to operate most electric devices or interface with the electrical grid and today most of solar inverters are grid connected. They are important for almost all solar energy systems and they're typically the most expensive component after the solar panels themselves [16].
Beside conversion from DC to AC power modern inverters include additional functions like controlling the solar generator, measurements of DC or AC parameters, monitoring and protection of the complete solar system, communication to user or grid and others.
The configuration of the solar plants is different and depends on the produced power and so the position of the inverter with respect to the solar panel may vary.
Basically the heart of the inverter is constituted by the power semiconductors. There are also an equipment for measuring electrical parameters on DC and AC sides, and drivers which interact between hardware component and controller units. The controller is a sort of protection element and in the same time it can be considered a controlling, monitoring and interfacing unit.

2.1.5 Research of the V-I characteristics

Another important aspect in the study of the photovoltaic panel is the obtainment of the V-I characteristic.
The basic element of the cell is the p-n junction diode which governs the generation of the direct current when it is hit by the sunlight. For better understanding, it is possible to represent the equivalent circuit.

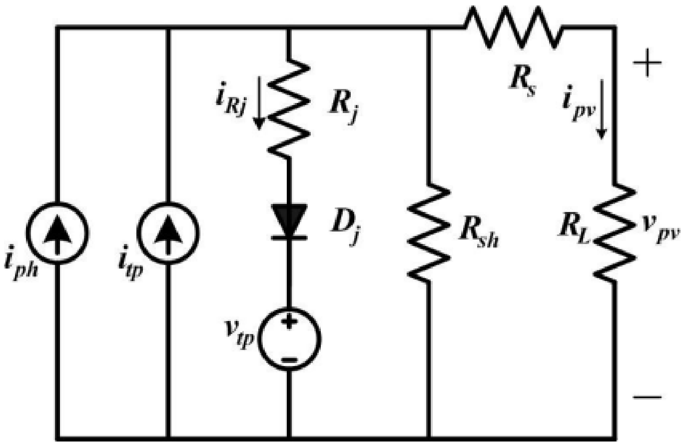

Figure 2.9. Equivalent circuit of solar panel [17].

D_j is a P-N junction diode; R_j is the nonlinear resistance of the P-N junction diode; R_s stands for the effect caused by contact resistance and a lead, which is generally called series resistance; R_{sh} stands for the effect caused by leakage current, which is generally called parallel resistance; i_{Rj} is the reverse saturation current of diode; i_{ph} is a current source converted from solar illumination; i_{tp} refers to the equivalent current source corrected and output under various temperature changes; v_{tp} is the corrected voltage generated by barrier potential of the diode upon changes of temperature; v_{pv} and i_{pv} are the output voltage and current of a solar panel [17].
All these elements and their values depend on the material and the techniques used in the production, but at the end the shape of the I-V curve is something like the one shown in the figure 2.10.

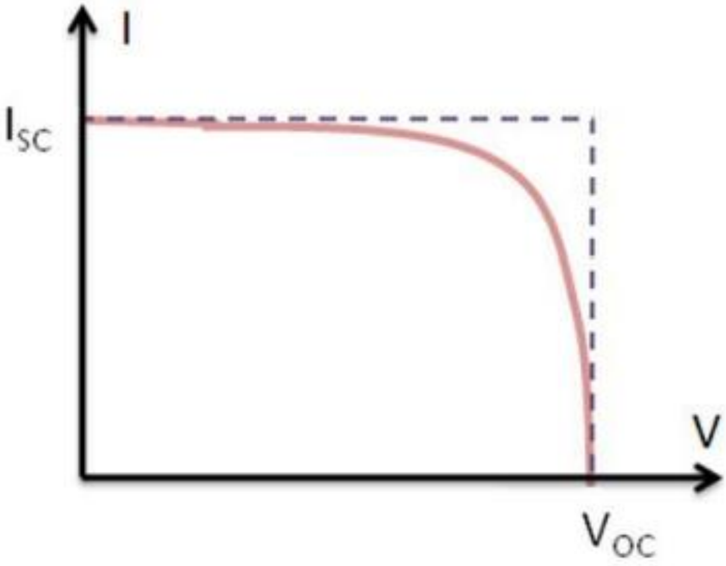

Figure 2.10. I-V curve [18].

The short circuit current I_{SC} corresponds to the short circuit condition when the impedance is low and is calculated when the voltage equals 0 [18]. For an ideal cell, this maximum current value is the total current produced in the solar cell by photon excitation. The open circuit voltage V_{OC} occurs when there is no current passing through the cell. The power produced by the cell in Watts can be easily calculated along the I-V sweep by the equation P=IV. At the I_{SC} and V_{OC} points, the power will be zero and the maximum value for power will occur between the two.
The study of this characteristic is essential in getting the value of the solar panel efficiency [19]. It is essentially the ratio of the electrical power output P_{out}, compared to the solar power input P_{in}, where this last parameter is taken as the product of the irradiance of the incident light, measured in W/m^2 with the surface area of the solar cell hit by the photons. The maximum efficiency can be affected by the ambient conditions like all the other parameters already presented.

$$\eta = \frac{Pout}{Pin}$$

Equation 2.1. Efficiency.

An important aspect that governs the change of the parameter is temperature. In fact, the crystal used in the realization of the PV panels is sensitive to temperature: when it increases, the I_{SC} increases too even though slightly, while V_{OC} decreases more significantly. In general, having fixed ambient conditions, higher temperatures result in a decrease in the maximum output power P_{MAX}.

2.2 Improvements to the photovoltaic systems

As already mentioned, the power generated by a solar panel is dependent on different conditions like temperature and insolation. The conventional power tracking algorithms fail to track the global maximum power point and in general there's no real-time calculation because of the delay due to a slow convergence process [20].

The critical problems related to grid-connected systems are voltage variations and harmonic problems [21]. The first one is connected to the rapid variation of solar irradiation and cloud passing but it is also minimized by implementing controllable, switched capacitors instead of fixed ones and lowering the voltage reference of existing load tap changers and line voltage regulators (LTCs and LVRs). Although the help of these two precautions, rapid voltage fluctuations may appear and result in the functioning of these elements with the consequence of reducing their life expectancy and of requiring frequent maintenance.

For how regards the second problem, it is a critical power quality issue that appears due to the involvement of a power electronic inverter. As already said its presence is fundamental in a SPV system but at the same time, it generates harmonics during the DC/AC power conversion process. Significant harmonic injection to the utility grid may result in parallel and series resonances, overheating of capacitor banks and transformers and false operation of protection devices. To solve this problem, it is possible to implement other devices like harmonic filters or multilevel inverters.

Before proceeding in the discussion, another aspect has to be taken into account: the fact that a solar photovoltaic system can generate power with the limitation of sun and so its power generation is limited in the daytime. So the maximum benefits of an SPVs system cannot be achieved without energy storage devices or peak shifting methods at the load side.

Anyway, SPV system has become the most attractive renewable source due to its high life span together with low maintenance requirements and costs. Plus, due to its modular nature and lightweight, transportation and installation are much easier than the other technologies. So, even though the problems listed before, it started to be important trying to solve them and at the same time, trying to find a better solution, a sort of improvement of the conventional photovoltaic system.

The aim of this project is, in fact, to demonstrate a new kind of application, the reconfigurable solar photovoltaic system which is expected to play a major role in the future.

2.3 Reconfigurable solar photovoltaic system

As already mentioned, the non-uniform irradiance significantly decreases the power delivered by solar photovoltaic arrays. And as a consequence, it is needed a technique for compensating this power losses.

A reconfigurable system is a system which gives the possibility to change its configurations depending on the operational conditions. Moving towards reconfigurable power system components is the solution to fulfil future requirements, in fact there are many different solutions available for different sections of SPV system.

The one that will be analyzed here is the kind of reconfiguration which involves a number of panels connected to one or more inverters. This type of reconfiguration gives birth to a new kind of system, called Team system, whose function is to modify the nominal power of the PVG, PV generator, connected to a central inverter and, in doing so, to modify the sizing ratio R_S [22].

Before continuing, let's have a look at the sizing ratio itself.

2.3.1 Sizing ratio

The sizing ratio R_S is defined as the ratio of peak power of the PVG, given in W_P, and the power of the inverter measured in W.

$$\mathrm{Rs} = \frac{P(PVG)}{\mathrm{P(INV)}}$$

Equation 2.2. Sizing ratio.

For how regards the power of the PVG, it is calculated at the standard test conditions, STC[4]. The other one is the power of the inverter calculated at the AC side.

The optimal PV/inverter sizing depends on local climate, PV surface orientation and inclination and inverter performance [23]. Under low insolation, a PV array generates power at only a part of its rated capacity and the inverter thus operates under part load conditions with lower system efficiency. PV efficiency is also affected adversely as when an inverter's rated capacity is much lower than the PV rated capacity, the inverter would be operating at overload conditions. Under overloading condition, excess PV output greater than the inverter rated capacity is lost. An oversized or undersized inverter thus increases PV energy cost.

In order to maximize the energy delivered, it is important to better design the system so that it is possible to reach the optimal value of this sizing ratio.

Of course R_S depends on the interval of time considered during the analysis and the irradiance G and temperature, both of which vary during the day and also during the period considered. This fact leads to the necessity of introducing a new type of configuration: with an adjustable R_S which is modified in real time, the system can be more efficient respect to the one with a constant value of sizing ratio. It gives the possibility to increase the power the

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[4] The standard test conditions are 1000 W/m^2, a temperature of 25 °C and a AM1.5 solar spectrum.

energy which is delivered to the grid.
There are different models used to better calculate this optimal R_S, in particular let's have a look at the one adopted in this project.

2.3.2 The central inverter model

This model is applicable for input power ranges lower than the inverter rated power.

$$\eta_{\mathrm{INV}} = \frac{\mathrm{P}_{\mathrm{dc}}\,(t)}{k_0 + k_1 \cdot \mathrm{P}_{\mathrm{dc}}(t) + k_2 \cdot {\mathrm{P}_{\mathrm{dc}}}^2(t)}$$

Equation 2.3. Inverter efficiency.

being $\mathrm{P}_{\mathrm{dc}}(\mathrm{t}) = \frac{\mathrm{P}_{\mathrm{dc}}(\mathrm{t})}{\mathrm{P}_{\mathrm{INV}}}$.

In the equation 2.3, P_{dc} is the inverter input normalized to the inverter rated power. For how regard the other three coefficients: k_0 is the one which represents the losses at no load, while k_1 and k_2 stand also for the losses but the first one represents the losses that vary linearly with the inverter current and the second coefficient the ones which vary quadratically with the same current previously considered. As already mentioned, this model can be used only if the input power is lower than the inverted rated power so, in case of an input higher than that, the model presents a limitation and the power assume this value:

$$\mathrm{P}_{\mathrm{DC}}(\mathrm{t}) = \mathrm{P}_{\mathrm{INV}}$$

Equation 2.4. Condition of the model when the input power is higher than the inverted rated one.

In a situation where this equation is verified, it means that the control unit of the inverter gives power to the output with no interruption because of its input power which is set to its rated value. It happens that the operating point of the PVG is shifted from its MPP, which is the maximum power point, until the overload condition is over.
In the body of work it'll be presented the simulation procedure used to obtain the $R_{S\ OPT}$ value. Before of that, let's continue with the explanation of the type of system which works at a constant sizing ratio.

2.3.4 PV system with constant sizing ratio

For this kind of system, it is considered a single location over a year where G and T are depending on time. Independently on the sample used and the interval of time Δt considered, the path of the R_S is practically the same and it is possible to individuate three different zones.

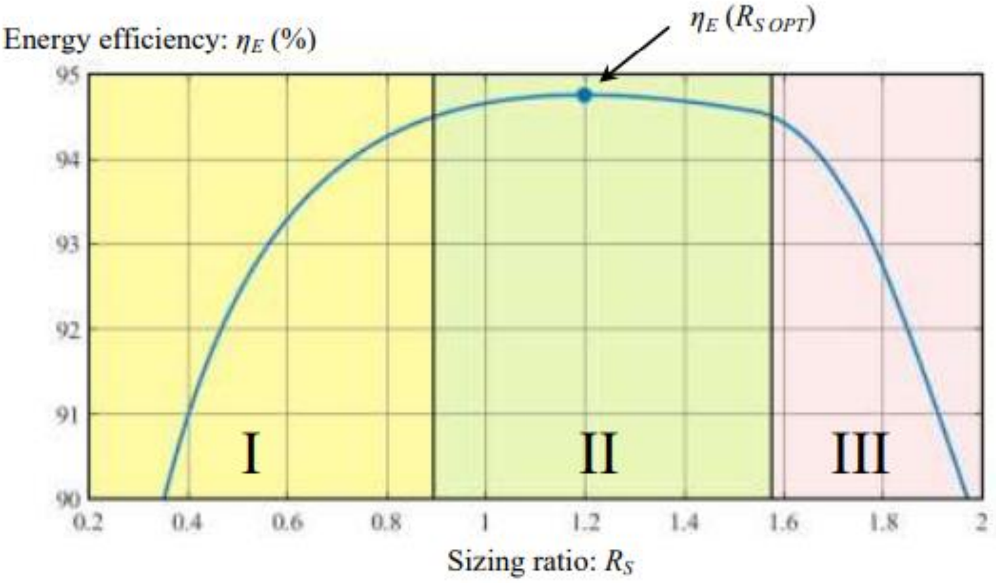


Figure 2.11. Annual energy efficiency depending on the sizing ratio value [22].

As it shown in the figure 2.11, the three regions are better distinguishable:

- the first zone is the region where R_S has a positive slope, where the inverter is oversized respect to the PVG. So here, the fact that the central inverter is operating at low conditions is predominant;
- the second one is a sort of low sensitive zone, where the efficiency in the year remains almost constant even if the value of R_S varies. This is the region where the optimal value of the sizing ratio is located;
- at least, the third zone is characterized by a negative slope: contrary to what happens in the first one, the inverter is undersized respect to the PVG and as a consequence, here the predominant effect is the limitation of the inverter output power as mentioned in the equation 2.4.

Obviously, considering a Δt shorter gives the possibility to reach a more precise value of the optimal sizing ratio. Let’s treat for example two different case: the first one with a time interval of one year, and the other with a time interval of one month repeated for all the twelve months of the year. In the first case it is taken into account a number of value lower than the second and at the end there’s one single value of the optimal sizing ratio. In the second one each month has its particular $R_{S\,OPT}$ and it makes the study more accurate than the first one. It is clear that decreasing the time interval considered, while on the one hand leads to a greater accuracy, on the other one complicates the study.

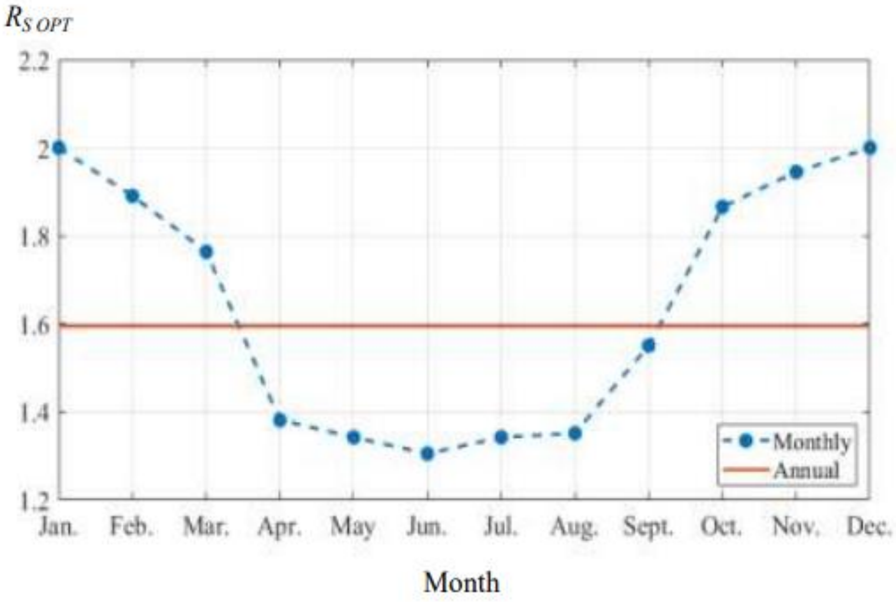


Figure 2.12. Rs value variations during the different months compared to the one obtained in a single year [22].

Seeing how the Rs changes even in a single day makes realize the importance of systems with a dynamical adaptation of the sizing ratio. It is absolutely an interest alternative solution with respect to the conventional one with a fixed value.

Next paragraph shows a new kind of technology called team system, whose basic principle is to work with a variable Rs value.

2.4 Team systems

In these systems the adjustment of the sizing ratio is due to the modification of the numerator, and therefore by modifying the nominal power of the PVG connected to the central inverter whose maximum power is fixed.

As it is known a PVG is formed by different PV array and it is important taking into account this particularity in the kind of study effort in this project. In fact, the main idea is to use every time a different number of PV array connected to the inverter, starting with *n* ones. They can be grouped or divided to respectively increase or decrease the nominal power of the resulting PVG and finally be connected to one or more inverters [22]. The action of grouping or dividing the PV array is dependent on the available power at the output of each single array and on the rated power of the existing inverter.

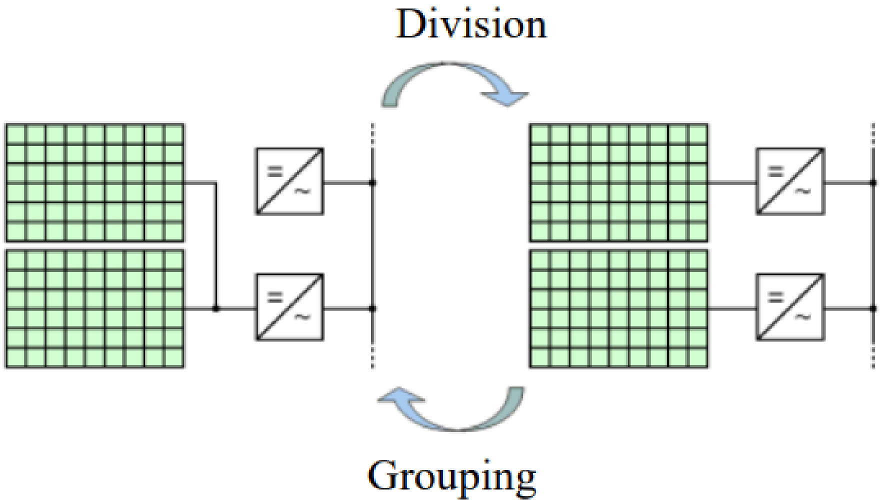


Figure 2.13. The different possible actions adopted in the Team system [22].

In particular, in the study conducted some hypothesis are taken into account in order to simplify the discussion:

- the number of PV array *n* is equal to the one of the available inverters;
- each PV array has the same nominal power which is named as P_{PVG}, the one already mentioned before in the project;
- since it is important to have a single $R_{S\ OPT}$ in a static association with one PVG and one inverter, it is also necessary to have the same rated power in the different inverters.

In this project it has been considered *n* = 2, and so with two PVG and at most two inverters used. The configuration of two PVG grouped and connected to a single inverter is the one considered in those days with low insolation which corresponds to the lower energy production. In this situation this is the configuration that better fit and gives the highest RS value. At the contrary, when the power production is increased, exceeding a particular threshold, the configuration changes to the one where the single PVG is linked to its own inverter. So it's like having two equal sizing ratio but half the value obtained previously and this one is the configuration which is generally used in the day characterized by periods of highest insolation that are the same of the highest energy production.
The mechanism behind this team system can be basically presented with two different actions the system can face and this is shown in figure 2.13:

- grouping action: the power produced is lower than a certain threshold so that it is necessary changing the configuration to the one where the PVG are grouped to a sort of single array and connected to a single inverter. Meanwhile the other inverter which is not used, it is turned off;
- division action: the generated power is higher than a fixed threshold and the system switches to a new configuration where the PV arrays are divided and each of them is linked to its own inverter. It involves the turning on of a inverter previously turned off.

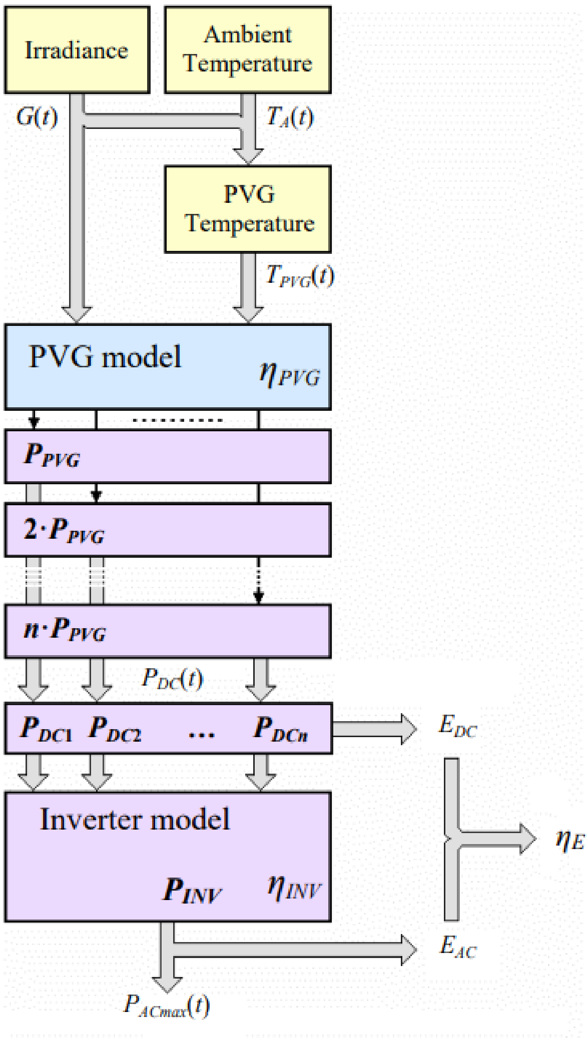


Figure 2.14. Procedures of the model in order to obtain the optimal value of the sizing ratio [22].

As it previously mentioned in the discussion, there are two different thresholds to be taken into account in order to know what is the action the system has to do. Let's see what these values are.

$$P_{UG} = P_{INV} \cdot \sqrt{\frac{k_0}{2 \cdot k_2}}$$

Equation 2.5. Value of the threshold power for the grouping action: once this value is crossed the two panel have to be grouped.

$$P_{UD} = P_{INV} \cdot \sqrt{\frac{2 \cdot k_0}{k_2}}$$

Equation 2.6. Threshold of the power, if crossed both the inverters need to be divided.

When the output power of two PV generators reaches the value P_{UG}, they must be grouped. In addition, when the output power of one PV generator reaches the value P_{UD}, it must be divided in two PV generators with the same nominal power.
In these equations, the two coefficients k_0 and k_2 are the ones considered in the equation 2.3. Next in the discussion it is shown how these parameters are obtained.
Obviously there's a relationship between the energy efficiency and the number of the PVG considered in the study. But, even though the increase in the number of the PVG cause an increase of the energy efficiency, at a certain point this behavior is not so more efficient.

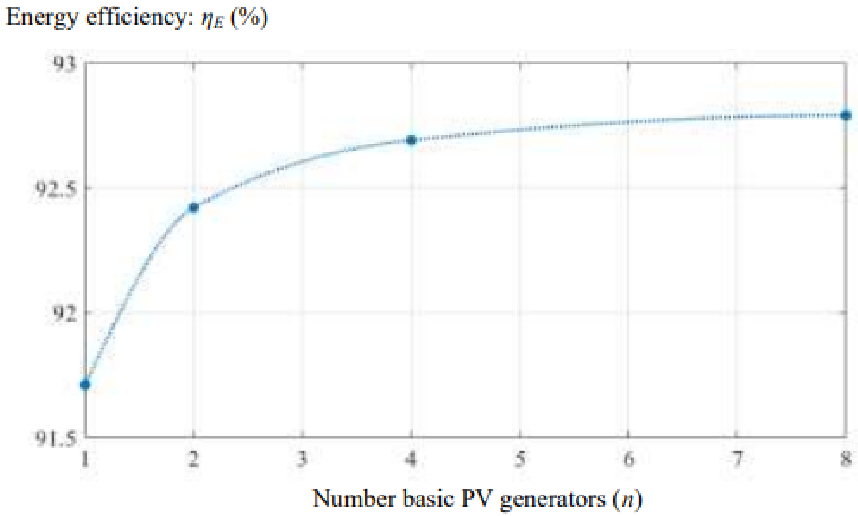


Figure 2.15. The dependence of the energy efficiency to the number of PV generators involved in the examination [22].

As observed in the figure 2.15, after a certain number of PV array, the increase of the efficiency η is not so evident and it reaches a sort of saturation. That's why in this project it has been analyzed a system with $n = 2$.
Finally, once the power of the PVG is determined as well as the $R_{S\ OPT}$ has been calculated, it is possible to use the equation 2.2 and, reversing it, obtain the value of the rated power of each inverter used.

$$P_{INV} = \frac{n \cdot P_{PVG(STC)}}{R_{S\ OPT}}$$

Equation 2.7. Evaluation of the inverter rated power.

So, what has been analyzed in this paragraph is a new tendence of the photovoltaic system which involves the adjustment of the sizing ratio in the measure to find its optimal value, which is the one who guarantees the maximum value of the yearly efficiency.

Chapter 3

Tools and methods used

The basic principle of the project itself is to use the concept of the team system and after doing some simulations, evaluate the data obtained and eventually trying to confirm if this method is really useful and gives an improvement in the generation of the output power.
In doing that it has been necessary several instruments in the lab and different software to elaborate correct results.
First of all, let's analyzed the different possibilities of the PV modules and the one taken into account in this treatment [24].

- module integrated (MI), where each PV panel is connected to one DC/AC power processor;
- module oriented (MO), where a series-string of PV modules is connected to a DC/AC power processor;
- plant-oriented (PO), where all the modules are connected in a parallel-series string to a unique DC/AC processor, usually referred as central inverter.

In this discussion it will be considered the PO configuration which is the most predominant architecture of GCPV systems due to its simplicity and low cost per kW_P.

3.1.1 Solar array simulator

Since these simulations are not conducted through a real solar panel, it has been used a model of it which aim is to simulate the work done by a solar array. In particular, the model of SAS used in this discussion is a SAS Keysight E4362A. Solar panels consisting of multiple solar cells provide power to satellites. Since the output power varies with environmental conditions and operational conditions, a specialized power supply such as the solar array simulator must be used for making accurate tests and verifying the satellite power system. First of all, is a current source with very low output capacitance and this kind of simulator offers the possibility to change rapidly the I-V curve so it can better simulate changes in environmental condition (temperature, eclipse, spin) [25].
It is important to give as input the four key operational parameters needed to internally create an I-V curve of solar array. Or, alternatively, it is possible to download a user defined table. There's an internal algorithm which is used to approximate this curve, which can be done via the I/O interfaces or from the front panel where a PC is not needed. Since it results much easier, in this simulation a PC has been used and it helps in the programming of the SAS trough the help of the software Matlab.

As already mentioned, four parameters are needed to determine the curve profile:

- V_{oc}, open circuit voltage;
- I_{sc}, short circuit current;
- I_{mp}, current at the peak power point on the curve;
- V_{mp}, voltage at the peak power point on the curve.

For the generation curve, it is also important the time of the generation: less point of I given, less time necessary.

Figure 3.1. An overview of the SAS in operation during a simulation in the laboratory

3.1.2 Inverter

The inverter plays an important role in the functioning of the solar system. In this case, connected to the SAS which simulates the solar array, there's an inverter of this typology: Sunny Boy 700 (or SB700) [26]. Its efficiency depends mainly on the input voltage of the connected PV strings. So, the lower the input voltage, the higher is the efficiency of the SB700.

This model is the smallest among the other of the same manufacturer and it is generally used for little PV plants.

The signal transmission between the PC and the single inverter is normally done by Powerline communication. For the communication with the PC is necessary to install the visualization software Sunny Data. The current fed to the grid is perfectly sinus shaped and has a very low harmonic distortion due to the fact that a one-chip computer manages the control. Of course it has to be considered that any kind of measurements can be affected by the accuracy of the instrument.

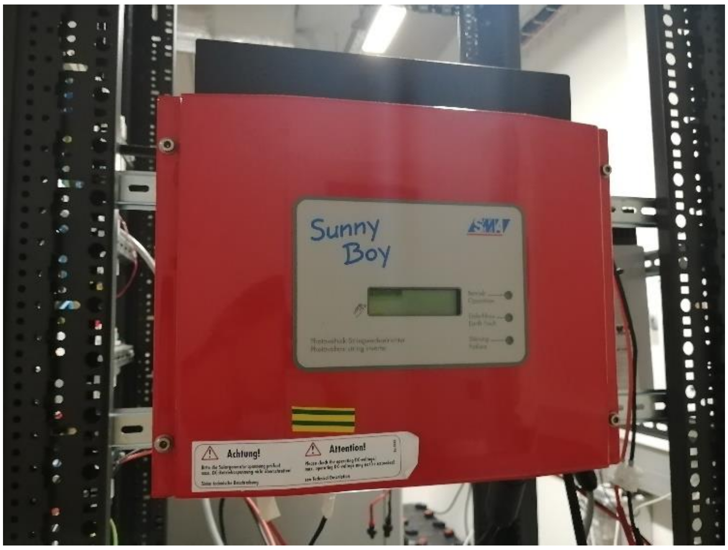


Figure 3.2. An image of the SB700 used in the simulations for the project.

3.1.3 Power meter

The power meter is one of the most useful and simple instruments to measure electrical power: it measures the voltage in V and the current in A and it gives back the power result. A power meter is easy to use, accurate and is the preferred instrument for cost effective power measurement solutions for a wide range of applications.

The analyzer measures active and reactive energy, summing or separating imported energy from exported energy. It can be equipped with an optional output to communicate measurements: pulse output, RS485 Modbus port or M-Bus port [27].

Figure 3.3. An image of both the power meter EM111 adopted in the calculation of the power.

3.1.4 Matlab

After having analyzed these instruments used for the simulation of a solar panel and having understood the characteristics of each of them, it remains to introduce the software which make possible the connection between them and the PC where the results are sent.

The first and the main one is Matlab, a programming platform to study and design systems and products. The heart of this software is its language which is an high performance one for technical computing. It integrates computation, visualization, and programming in an easy-to-use environment where problems and solutions are expressed in familiar mathematical notation.

It is provided with a working environment which is a set of tools and facilities that can be taken into consideration to manage the variables introduced and to import or export data.

In this particular case Matlab is used to program the instruments used like the SAS and sent the correct information about the four parameters necessary to create the I-V curve and also, thanks to a new tool, receiving the output power generated after having sent the temperature and the irradiance values which change during the day. It'll be better explained later in the discussion in the paragraph 3.2.

3.1.5 Arduino

The one considered in this project is Arduino UNO, a microcontroller board based on a hardware which is easy to use. It has 14 digital input/output pins, 6 analog inputs, 16 MHz ceramic resonator, a USB connection and a power jack. In fact, it can be simply connected to a PC with a USB cable as it has been done in this project. Arduino platform is able to read an input and turn it into an output and this communication is possible thanks to the link with the instruments previously listed from which it receives information. Even in this case with this software it is necessary to use a particular programming language. After having elaborated the inputs received, through the code set the output is sent to a relay which is connected to it and simply close or open the circuit, which means connect or not the two SAS to a single or to both the inverters available.

3.1.6 Languages adopted

All this instruments and software used communicate among them through particular languages.

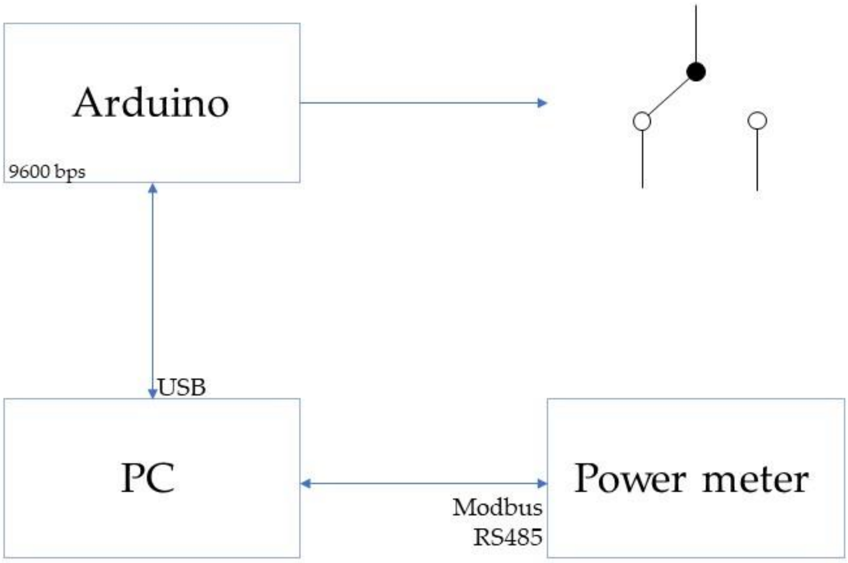


Figure 3.4. Scheme of the connection between the software and instruments used in the simulation.

The scheme of the system presented is fundamentally like this one: the Arduino UNO platform is connected to the relay which governs the opening or the closure of the switch, and so the connection to one inverter or both the ones; the same board that is also linked to the PC through an USB port; the PC is connected to the power meter and their interaction is due to this particular language which is regulated by Modbus.

This one is a serial communication protocol developed by Modicon in 1979 and it is a method used for transmitting information over serial lines between electronic devices. It has become a standard communications protocol in industry, and is now the most commonly available means of connecting industrial electronic devices.

The data are sent as series of ones and zeroes called bits. Each bit is sent as a voltage. Zeroes are sent as positive voltages and a ones as negative. The bits are sent very quickly and a typical transmission speed is 9600 baud (bits per second).

For doing so, it is also necessary a serial hardware, a form for serial communication and this role is occupied by RS485 which is a standard defining the electrical characteristics of serial lines for use in serial communications systems. As already stated, a serial communication is a way to send data and this type used in this project is just one of them like USB can be. RS485 is known for being able to be used effectively over long distances and in electrically noisy environments [28]. So at the end, RS485 is the standard that defines the electrical characteristics of the drivers and receivers for the communication protocol.

3.2 Procedures

In this project there are been already discussed all the principles that are at the base of a PV system functioning. The methods that can improve the conventional systems have been analyzed as well as all the instruments and the tools used are presented. Now, let's go deeper in the discussion and see the steps that lead to the experimental results before commenting them.

First of all, it is now important to clarify the aim of the project and the way it is reached: the purpose is to obtain results in terms of output power from a SAS, as it was a normal PV panel linked to an inverter. Through Matlab has been sent the irradiance and temperature values minute by minute to realize a real time simulation. In particular, it has been adopted this strategy: all the data of irradiance and temperature about Barcelona in the year 2006 has been analyzed. It's important to notice how irrelevant the year is in this simulation: it could be a year or another but the matter is to collect data over a year where the climatic situations can vary and select among them three days, each of them with a particularity:

- sunny day, it is the one characterized by high temperatures and, mostly, high irradiance values. In this day it is possible to reach the threshold P_{UD} in the first hours of the day and so switch to the configuration where the two SAS are connected to two different inverters. At the end of the day, what it is expected is to reach the value P_{UG}, and so, a value of power that brings back to the old configuration with the two solar array grouped and only one inverter working. All this behavior until the end of the day where the value of irradiance is so low that no power generation exists;
- cloudy day. In this case is completely the reverse of the day of the previous point. Here's what it is expected to the system which received low value of irradiance is to obtain no possibility to switch in the other configuration. So, for all day long, it will be a group of two SAS linked to one inverter and, in practice, it will be the conventional configuration;
- a day with variations in the irradiance. This third day considered is the day of the year which mostly presents variations in the values of irradiance received maybe because of the climatic conditions that vary a lot during the day going from a cloudy hour to another one of sunshine and high irradiance. This is the day of most interest for the study conducted because it's the one which gives more results in terms of usefulness of the reconfigurable PV system.

At the end, the results will be compared to the ones of a conventional system and it will be understood if a reconfiguration like the one of a team system is useful or not. It is recalled the meaning of a team system analyzed in the previous paragraph: it is a PV system where there's the possibility to have a reconfiguration, which means switching the configuration of a group of arrays connected to a single inverter to the one with each array is linked to its own inverter. This switching is due to a power threshold fixed and calculated by a model. So, basing on the results of power obtained, the Arduino UNO platform elaborates through a code if the configuration needs to be switched or not.

In this project all these instruments are used:

- a PC;
- two SAS E4362A;
- two inverter SB700;
- two power meter EM111;
- arduino UNO;
- arduino breadboard;
- relay shield;
- three cables for the connection of the arduino UNO platform to the relay shield used.

First of all, since everything starts from the functioning of the PV panels and for this reason, in this case from the SAS, it is the main step to program the SAS and it is done by the PC through the matlab software.

3.2.1 Programming of a SAS and of a power meter

To program a solar array simulator via PC there are some sentences that is important to know because there's a particular language used to make these two elements communicating between them. For all these one see the Appendix A.
All these sentences have to be implemented into a Matlab code whose function is to program the solar array simulator. It starts with giving it the four parameters useful for the elaboration of the I-V curve, also lower ones. Then they are rearranged thanks to the code basing on the values of irradiance and temperature received minute by minute through Matlab.
Basically, the concept is to implemented the values of irradiance, temperature and the voltage of the panel and to obtain as a result, the current of the panel itself, depending on the three parameters previously listed.

$$\mathrm{I_a = msx60(V_a, Irr_a, T_{ac})}$$

Equation 3.1. Dependence of the panel current on the values of voltage, irradiance and temperature.

where the msx60 is simply the name given to the function.
In this code it has been used a series of constant value like:
$\mathrm{k} = 1.38\mathrm{e}^{-23}$
$\mathrm{q} = 1.60\mathrm{e}^{-19}$
A = 1.2 (depending on the type panel)
$\mathrm{V_g} = 1.12$ eV
$\mathrm{N_s} = 213$ (n° of cells connected in series).

For how regards this last parameter Ns, it basically indicates the number of diodes. A diode has the function to become activated in the moment when the panel results shadowed because of the buildings near to it for example and basing on the different day moments where the inclination of the sun changes. Every panel has its diodes to protect against overheating and minimize the efficiency losses due to the shading. They're practically semiconductors which act like switches of unidirectional current: they avoid that a current coming from a panel no shading can flow into a shading one. This flowing can lead to some undesirable effects like power losses and panel damaging since the shading is felt as a short circuit whose effect is to decrease the possible power generable.
Another equation to take into account is the one for the conversion from Suns to Irr considering another unit of measure, Sol. Since 1 Sol = 1000 W/m^2:

$$\mathrm{Suns} = \frac{\mathrm{Irr_a}}{\mathrm{Sol}} = \frac{\mathrm{Irr_a}}{1000}$$

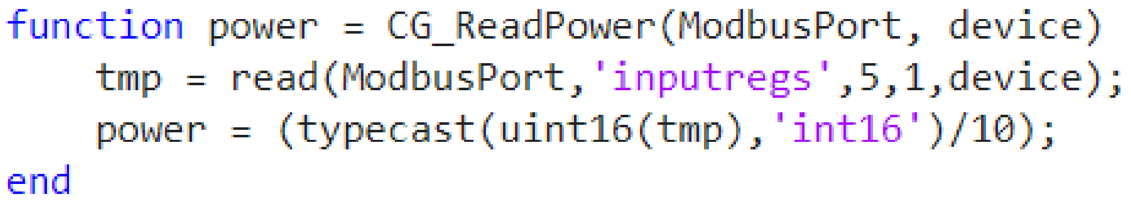
Equation 3.2. Conversion from Suns to Irr.

Then, in figure 3.5 is shown the Matlab code for the programming of the SAS.

```
function [Vmpp, Impp, Voc, Isc] = SAS_Param(Irra, Temp)
```

Figure 3.5. Matlab code to program the SAS.

Another code is necessary to connect all the instruments used, and it is the one which gives the possibility to communicate with the power meters thanks to the sentence available in Matlab that fit with the EM111.



```
function power = CG_ReadPower(ModbusPort, device)
    tmp = read(ModbusPort,'inputregs',5,1,device);
    power = (typecast(uint16(tmp),'int16')/10);
end
```

Figure 3.6. Matlab code used to read the power from the EM111 power meter.

It is a simply reader of the value of power calculated by the power meter connected to the SAS via cable. Of course, as all the other codes, even this one is built using the Modbus language.

3.2.2 Arduino UNO connection

For how regards the connection of the Arduino UNO platform, this procedure has been simply realized with the connection with the PC via USB and three cables adopted to connect it to the relay by means of the breadboard.

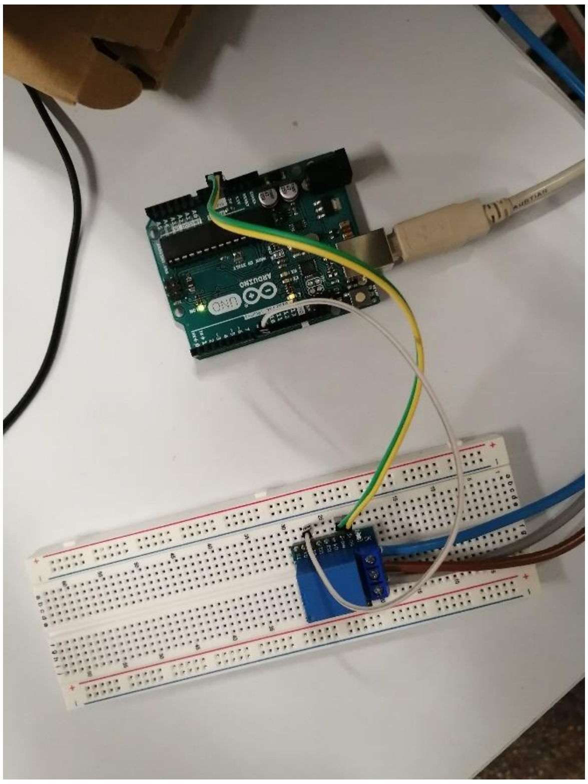
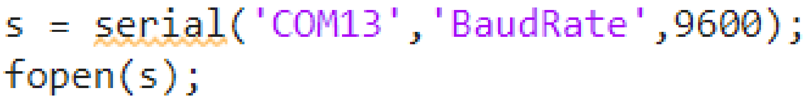


Figure 3.7. An image of the connection between Arduino UNO and the relay through three cables and the breadboard.

First, let's talk about the connection between Matlab and Arduino UNO. This happens thanks to the PC which makes the communication possible and so through the USB cable. Of course in the Matlab code it is necessary to implement a sentence that send the information to the Arduino platform.



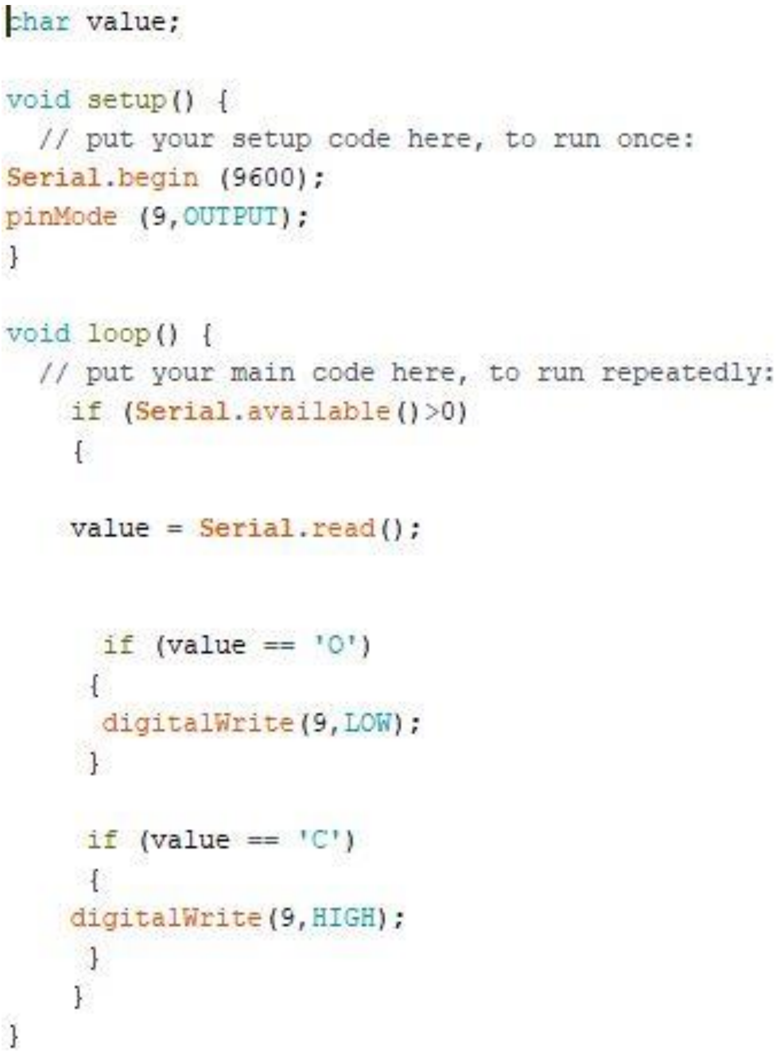
```
s = serial('COM13','BaudRate',9600);
fopen(s);
```

Figure 3.8. Matlab code for opening the communication with Arduino UNO.

Obviously, in the Matlab code it is necessary to indicate the baud rate[5], which is the rate used to transfer information in a communication channel and it has to be equal for both the platforms considered. So, in the Arduino UNO system it has to be added the same number used before.

---

[5] The values of the baud rate are generally fixed, so it is possible to choose between a selection of preset values and in this project, since the volume of the information is low, it's not so important what this number is. Choosing for example 9600 means that the serial port is capable of transferring a maximum of 9600 bits per second.



```
char value;

void setup() {
  // put your setup code here, to run once:
Serial.begin (9600);
pinMode (9,OUTPUT);
}

void loop() {
  // put your main code here, to run repeatedly:
    if (Serial.available()>0)
    {

    value = Serial.read();


      if (value == 'O')
     {
      digitalWrite(9,LOW);
     }

     if (value == 'C')
     {
    digitalWrite(9,HIGH);
     }
    }
}
```

Figure 3.9. Arduino UNO code used to receive information from Matlab and send the command to the relay.

In the figure 3.9 it is shown, not only the baud rate considered, but also the complete code which gives the possibility to send the information to the relay connected to it. In particular, since the cable connection it is put in the number 9, that's the reason why in the void setup, this number appeared[6].

While in the void setup there are listed the general characteristics of the Arduino system adopted, in the void loop is presented the real code, the one which is repeated endlessly. So, imposing the serial available major than 0, it has simply imposed that the bytes it has to read are the ones greater than one; in this particular case there is just one byte because the signal sent from Matlab is summarized just in one letter:

- O, if Arduino has to send the signal to open the circuit;
- C, in the opposite case.

---

[6] The choice of one pin with respect to another is completely random, there's no reason to choose one instead of another. The important thing is to connect with two different cables the pin of the 5 V and the GND (stands for ground and so 0 V) of both the relay and the Arduino UNO platform.

In fact Arduino has just to send the information through the relay, but the real evaluation of data, the reading of the power value and its comparison with the thresholds as well as the decision to close or open the circuit is done by Matlab.
After evaluating the receipt of the character and therefore of the byte, the code goes on with the reading of the letter itself: it is "O" it proceedes in one direction opening the circuit, while in the other case, it closes and sends the opposite signal.

The success or failure of the relay operation can be ascertained from the sound it makes when it changes configuration and from the red light emitted in the case of a closed circuit. With these two elements it is possible to know that the relay is properly working.

3.2.3 Power threshold

After having connected all the instruments and stabilized how they're linked together considering the language and the codes used, it is now important proceeding with the explanation of the steps adopted in doing the project.
First of all, it has been already said that all the considerations regarding the choice of the configuration have been done on the output power generated. The thresholds of the power have been presented in the equations 2.5 and 2.6.
There are two coefficients, k_0 ad k_2, that have to be evaluated. These ones are the same presented in the equation 2.3 about the efficiency and here's where they are extrapolated. It's like having an expression like that:

$$y = \frac{x}{a + b \cdot x + c \cdot x^2}$$

Equation 3.3. A simple x-y dependance function expressing the relation between the power and the efficiency, used to calculate the coefficients a,b and c.

Using this equation and the function *curve fitting* of Matlab it is possible to obtain these coefficients from this curve.

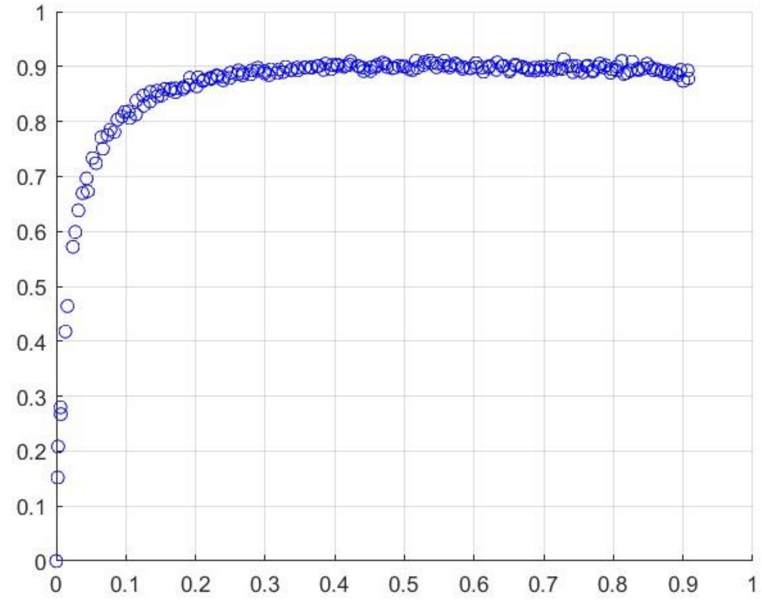


Figure 3.10. Correlation between x and y which makes possible the evaluation of the coefficients a, b and c.

Here the results:
$\mathrm{k_0} = 0.01634;$
$\mathrm{k_2} = 0.05454;$
where k_0 stands for the *a* of the previous equation 3.3 and k_2 for the *c*.

Actually, they're not fixed values but obtained as an average from a range of values that this curve proposes.
Another parameter considered in the calculation of the thresholds of the power is the inverter rated power which is the nominal one. In this case, considered the model of the inverter used in the laboratory, is:
$\mathrm{P_{INV}} = 460$ W.

Collecting all these values, it is possible to evaluate the power thresholds:

$$\mathrm{P_{UD}} = \mathrm{P_{INV}} \cdot \sqrt{\frac{\mathrm{k_0}}{2 \cdot \mathrm{k_2}}} = 363\ \mathrm{W}; \qquad P_{UG} = \mathrm{P}_{INV} \cdot \sqrt{\frac{k_2}{2 \cdot k_0}} = 181.5\ \mathrm{W}.$$

Having just a value as threshold can be a problem for the inverters used. In case the $\mathrm{P_{UD}}$ value was exceeded, the relay would give the order to close the circuit and divide the two SAS each on its own inverter. But little variations in temperature and irradiance from minute to minute could lead to continuous oscillations between one configuration and another making the reconfigurable system useless.
For this reason, in this project, an interval of 5% with respect to the value previously found was considered rather than a single value and in particular:
$\mathrm{P_{UDll}} = 344.8$ W; $\mathrm{P_{UDul}} = 381.1$ W.
$\mathrm{P_{UGll}} = 172.4$ W; $\mathrm{P_{UGul}} = 190.6$ W.[7]

---

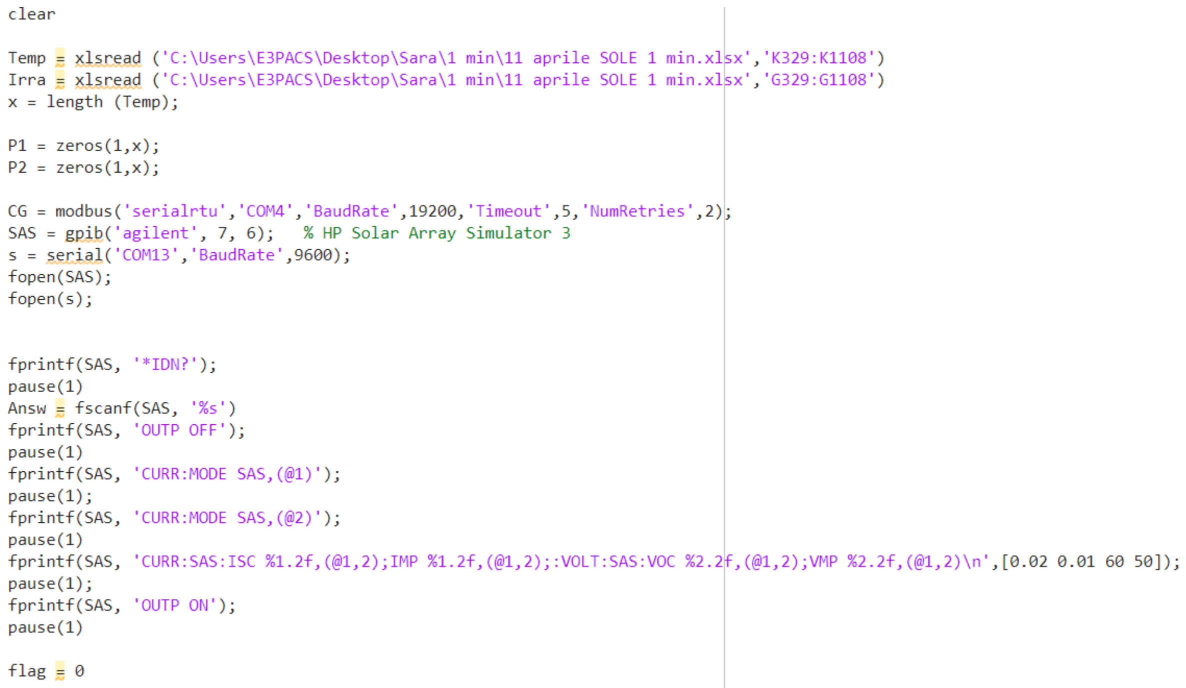
[7] The subscripts "ll" and "ul" stand respectively for the *lower limit* and the *upper limit* of the range

These values are respectively +/- 5% of the P_{UD} and the P_{UG} ones calculated before. At this point, all the evaluations will be done not considering just one value but an entire range. It means that if for example the configuration is the open one with the two SAS connected to one inverter, when the upper limit of the P_{UD} is exceeded the configuration switches to the other one and the second inverter starts working. Passing to the new configuration, the new range to be taken into account is the P_{UG} one and since there are two inverters working, an amount in the production of power is expected. So in this case it's like having great values of irradiance and temperature and a production of power which exceeds the upper limit. But when the generated power starts to be lower and goes below the threshold value, it changes again its configuration.

The advantage is that the system is configured not to change in the range: if the switch is closed, remains in that configuration, if it's open remains in the other one without oscillations.

All power limits in changing the configuration have been set as well as the instructions to switch from one to the other have been set on Arduino. So it remains to see how to realize the Matlab code to give the information and conclude the project.

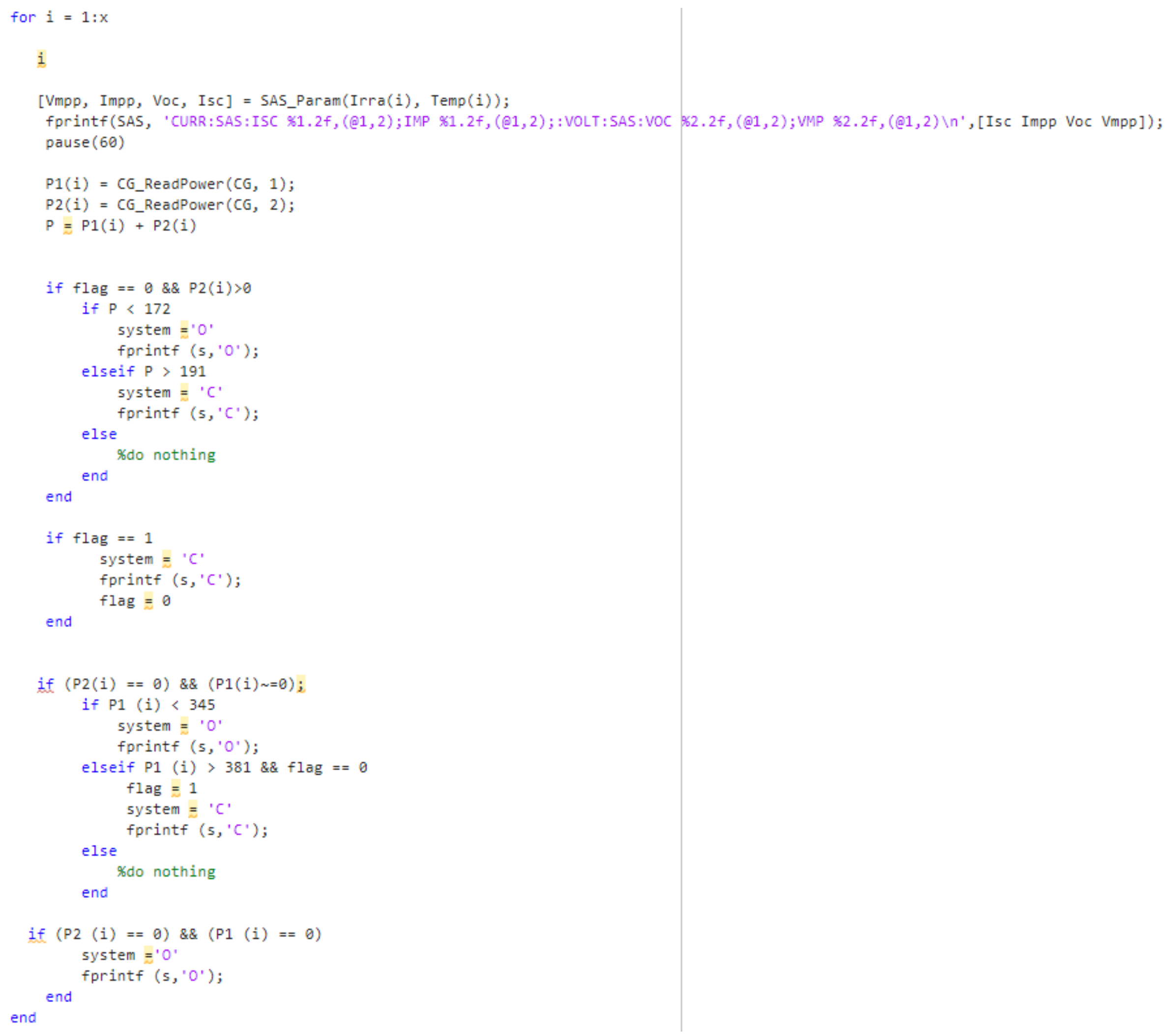
3.2.4 Matlab code



```
clear

Temp = xlsread ('C:\Users\E3PACS\Desktop\Sara\1 min\11 aprile SOLE 1 min.xlsx','K329:K1108')
Irra = xlsread ('C:\Users\E3PACS\Desktop\Sara\1 min\11 aprile SOLE 1 min.xlsx','G329:G1108')
x = length (Temp);

P1 = zeros(1,x);
P2 = zeros(1,x);

CG = modbus('serialrtu','COM4','BaudRate',19200,'Timeout',5,'NumRetries',2);
SAS = gpib('agilent', 7, 6);    % HP Solar Array Simulator 3
s = serial('COM13','BaudRate',9600);
fopen(SAS);
fopen(s);


fprintf(SAS, '*IDN?');
pause(1)
Answ = fscanf(SAS, '%s')
fprintf(SAS, 'OUTP OFF');
pause(1)
fprintf(SAS, 'CURR:MODE SAS,(@1)');
pause(1);
fprintf(SAS, 'CURR:MODE SAS,(@2)');
pause(1)
fprintf(SAS, 'CURR:SAS:ISC %1.2f,(@1,2);IMP %1.2f,(@1,2);:VOLT:SAS:VOC %2.2f,(@1,2);VMP %2.2f,(@1,2)\n',[0.02 0.01 60 50]);
pause(1);
fprintf(SAS, 'OUTP ON');
pause(1)

flag = 0
```

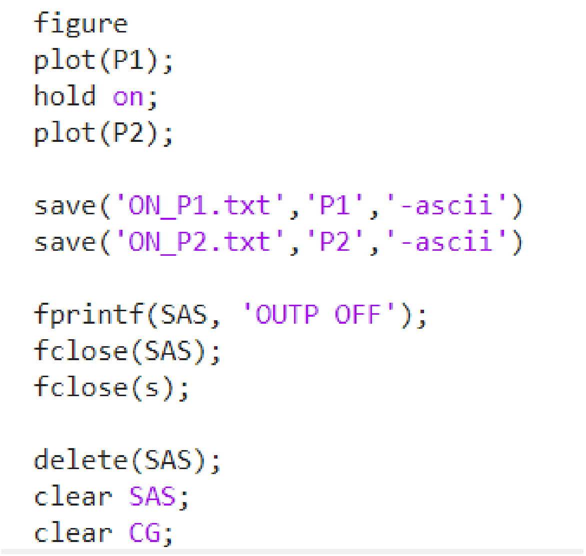
Figure 3.11. First part of the code where all the data are collected.

created.



```
for i = 1:x

   i

   [Vmpp, Impp, Voc, Isc] = SAS_Param(Irra(i), Temp(i));
    fprintf(SAS, 'CURR:SAS:ISC %1.2f,(@1,2);IMP %1.2f,(@1,2);:VOLT:SAS:VOC %2.2f,(@1,2);VMP %2.2f,(@1,2)\n',[Isc Impp Voc Vmpp]);
    pause(60)

    P1(i) = CG_ReadPower(CG, 1);
    P2(i) = CG_ReadPower(CG, 2);
    P = P1(i) + P2(i)


    if flag == 0 && P2(i)>0
        if P < 172
            system ='O'
            fprintf (s,'O');
        elseif P > 191
            system = 'C'
            fprintf (s,'C');
        else
            %do nothing
        end
    end

    if flag == 1
          system = 'C'
          fprintf (s,'C');
          flag = 0
    end


   if (P2(i) == 0) && (P1(i)~=0);
        if P1 (i) < 345
            system = 'O'
            fprintf (s,'O');
        elseif P1 (i) > 381 && flag == 0
             flag = 1
             system = 'C'
             fprintf (s,'C');
        else
            %do nothing
        end

  if (P2 (i) == 0) && (P1 (i) == 0)
        system ='O'
        fprintf (s,'O');
    end
end
```

Figure 3.12. Second part of the code with the for-loop where the decisions about the configuration are taken.



```
figure
plot(P1);
hold on;
plot(P2);

save('ON_P1.txt','P1','-ascii')
save('ON_P2.txt','P2','-ascii')

fprintf(SAS, 'OUTP OFF');
fclose(SAS);
fclose(s);

delete(SAS);
clear SAS;
clear CG;
```

Figure 3.13. Third and last part of the code which shows how the variable are plotted.

Let's explain how this code works.

The figure 3.11 shows the characteristics of the panel and the conditions considered for example about temperature and irradiance while the second one, the 3.12, presents the real code. It is the main part of the Matlab code where the decisions are made basing on the results of the power sent. At the end, in the figure 3.13 it is simply shown how to plot with Matlab the results expected.

First of all it's necessary to introduce the parameters considered: Temp and Irra stand respectively for the temperature and irradiance given by the sun, both calculated in a precise minute of the day. These values are extrapolated from SoDa website[8] and registered in an excel file and since in this discussion it has dealt with a real time simulation, the values collected are minute by minute. This explains why in the for-cycle of the Matlab code the index *i* goes from 1 to x, where x represents the length of the vector Temp (which is equal to the length of the vector Irra) and therefore all the minutes of the day considered in the simulation.

For each *i* the code extrapolates both the values from the correct excel file and cell which are specified in the code and then it starts with the configuration of the SAS. The fixed pause of 60 second is necessary to let the instruments elaborate the results and give time for the elaboration and the calculation of the generated power as it is a real time. Once the minute has passed the for-cycle ends and starts again with the following *i* value until the end of the vector length and so after passing 24 hours.

After configuring the SAS, the power obtained by the two power meters is read and it is summed. Then it begins the moment in which Matlab has to make the decision and send the signal to Arduino: based on the generated power value, it has to choose whether to change configuration or leave it unchanged. Before dealing with the different possibilities that the system is faced with, a problem arose during the simulations: as already said, being a real-time simulation, each *i* step is held for only 60 seconds but it has been noticed that the inverter takes about 80-90 seconds for its activation. It means that, in case the configuration has to be switched to the close one whit both the two inverters working, the new inverter switches on but it has no time for its activation in only 60 seconds: it gives zero power but since the code reads configuration C, the output power coming from a single inverter is too low and returns in the following cycle to the configuration O by switching off the second inverter and so on in the next step, creating a situation of this type.

---

[8] SoDa stands for Solar Radiation Data and it is a website where the data regarding the irradiance and temperature are collected. It's possible to receive average values of them if considered month by month or the real-time considered minute by minute.

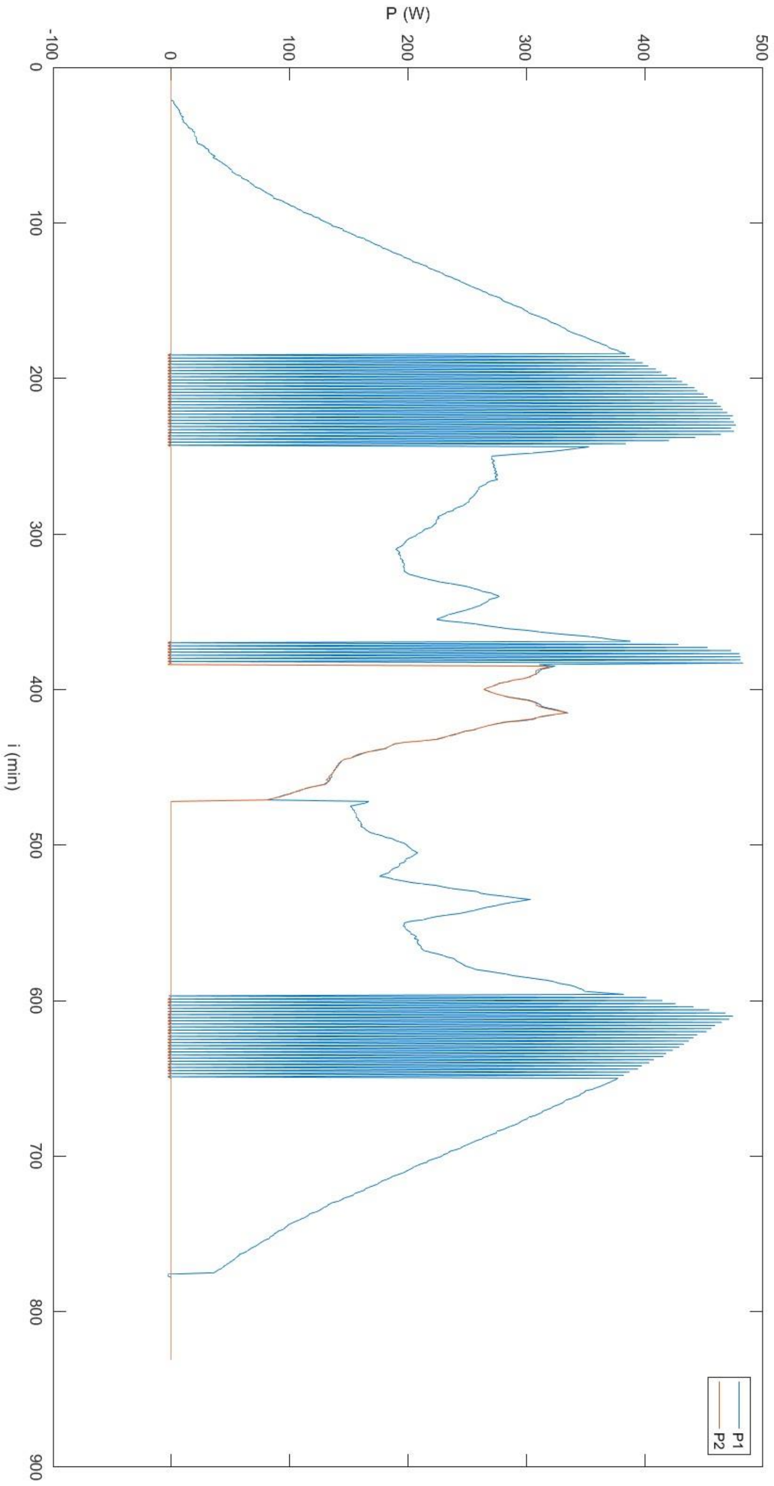
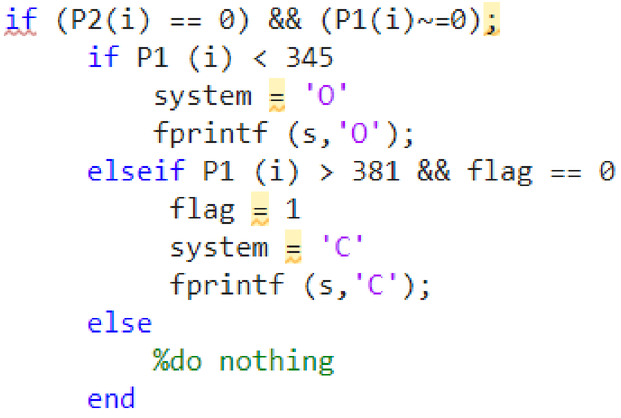


Figure 3.14. Results obtained in the simulation without *flag* and with evident errors in an oscillating behavior between the two configurations.

This is for example the situation of the day with more variations of temperature and irradiance values. The system continuously oscillates between one configuration and another until the second inverter is able to activate.
In order to avoid it, in the final code presented in the figure 3.11, the term *flag* is also present. At the beginning it is set to 0 and it is switched to 1 only when the change of configuration is needed. It is a sort of redundancy in such a way that when the system switches to configuration C, in the next step the state C is maintained regardless of the power generated. In this way the second inverter has twice the previous time, 120 seconds, more than enough for its activation.

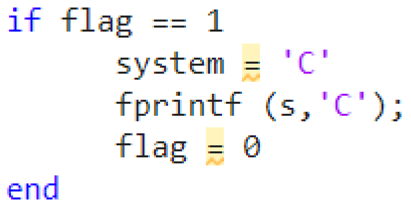
The several *if* in the code show all the possible situations and the different decisions the code can make:

- 

```
if (P2(i) == 0) && (P1(i)~=0);
     if P1 (i) < 345
         system = 'O'
         fprintf (s,'O');
     elseif P1 (i) > 381 && flag == 0
          flag = 1
          system = 'C'
          fprintf (s,'C');
     else
         %do nothing
     end
```

Figure 3.15. Third *if* in the for-cycle which show the decisions to make in case of there's only one inverter functioning.

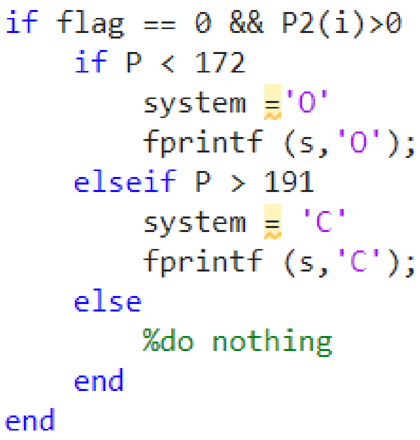
In this part of the code Matlab enters at the beginning of the simulation when the irradiance value is still too low and there's only one inverter working. So the generated power of the second inverter is zero because it is not activated. At this point a decision has to be made basing on the value of the P_1: if it is still too low it remains to the O configuration, while when it reaches the P_{UDul} threshold it switches to the other and change the value of the flag to 1.
The sentence "fprintf" is just the communication between Matlab and Arduino: it's the way the information of what the system has to do has been sent;

- 

```
if flag == 1
      system = 'C'
      fprintf (s,'C');
      flag = 0
end
```

Figure 3.16. Second *if* in the for-cycle which represents the redundance of the system.

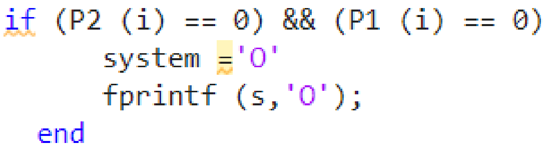
It is the continuum of the previous point and represents the redundancy mentioned above. The flag is 1 and this is the only *if* the system can read: so it maintains the C status and returns the flag value to 0. The result is that 60 seconds have been gained and that in the next step, having returned the flag to its original value, the evaluation will be made on the power. In particular, being in a C configuration, the system will enters in the *if* showed in the following point;

- 

```
if flag == 0 && P2(i)>0
    if P < 172
        system ='O'
        fprintf (s,'O');
    elseif P > 191
        system = 'C'
        fprintf (s,'C');
    else
        %do nothing
    end
end
```

Figure 3.17. First *if* of the code which works when both the inverters are activated.

Here it's when, after the redundance, the second inverter has been activated and so the flag is returned to the value 0 and the power of the second inverter is greater than 0. The configuration is the C one and as long as the irradiance is high, this will be maintained. When it starts to be low and the output of the generated power gives a value lower than P_{UGII} the system has to switch to the O configuration.

- 

```
if (P2 (i) == 0) && (P1 (i) == 0)
      system ='O'
      fprintf (s,'O');
  end
```

Figure 3.18. Fourth *if* of the code used as the starter condition.

This last one is simply inserted to set the initial condition where, considering that the first value is that of the beginning of the day at midnight with low irradiance, the configuration will be for sure the O one.

At the end, all the instructions to plot the P_1 and P_2 basing on time, and so *i* are listed, as already shown in the figure 3.13.

3.3 Simulations

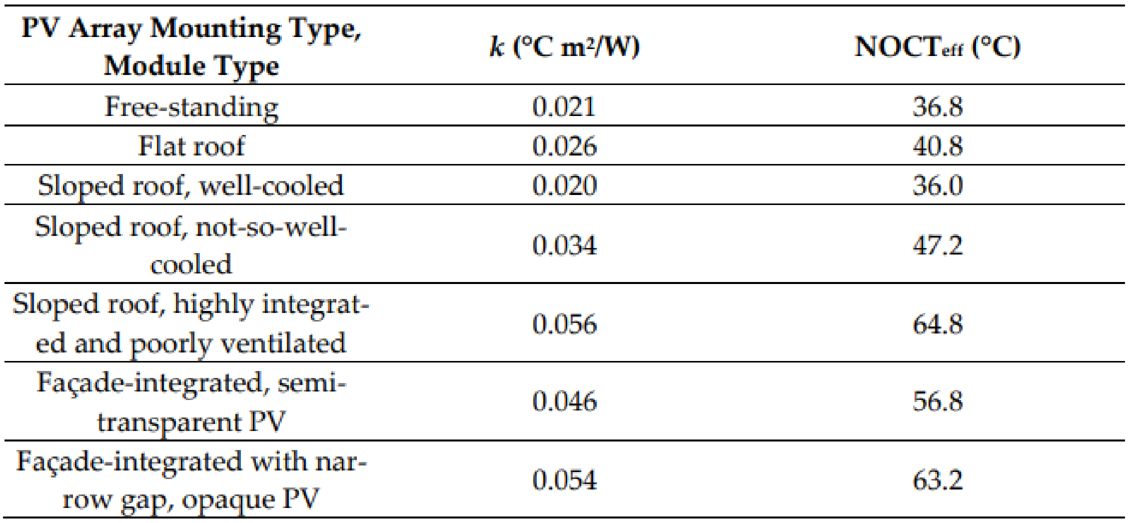
Having defined all the codes used it is possible to proceed with the simulation itself. It has already been said that the simulations considered in this discussion are three: the one on a sunny day, on a cloudy one and the last one characterized by variations in the irradiance and temperature values.

All the data are collected minute by minute from the website SoDa which asks for a city and a year before giving the data. In this project Barcelona was chosen as the city and 2006 as the year, the last one available on the site. In reality, the place and even the reference year are not so important as the parameters that matter are Irra and Temp which vary according to the random climatic conditions. As regards the latter, the temperature supplied by SoDa is the ambient temperature while for a more precise treatment, that of the panel itself must be taken into account. So the Ross coefficient is introduced, which is a parameter that depends on the characteristics of the panel and changes the ambient temperature in this way:

$$\mathrm{Temp} = \mathrm{T_A} + \alpha \cdot \mathrm{Irra}$$

Equation 3.4. Evaluation of the panel temperature considering Ross coefficient and the ambient temperature.

Irra and T_A are the values extrapolated from the website, α is the Ross coefficient and Temp is the effective temperature of the panel to be considered in the simulation. For this reason, the value of the coefficient which depends on the type of panel is missing. In this discussion it has been considered a panel on a sloped roof with a good ventilation.



PV Array Mounting Type, Module Type	*k* (°C m²/W)	NOCT$_{eff}$ (°C)
Free-standing	0.021	36.8
Flat roof	0.026	40.8
Sloped roof, well-cooled	0.020	36.0
Sloped roof, not-so-well-cooled	0.034	47.2
Sloped roof, highly integrated and poorly ventilated	0.056	64.8
Façade-integrated, semi-transparent PV	0.046	56.8
Façade-integrated with narrow gap, opaque PV	0.054	63.2

Figure 3.19. Representation of the Ross coefficient value basing on the different types of panel [29].

So, seeing the figure 3.19 and the *sloped roof, well-cooled* the value chosen in this project is 0.020.

Once all these parameters have been determined, it is possible to proceed with the simulation by varying the considered excel file from time to time, each containing the information of the three days analyzed. In particular, regarding the year 2006 it has been found that the sunniest day was April 11th, the cloudiest was January 5th while the day with more variations in the irradiance values was August 11th.

These are the three days considered for the simulations and they have to be done separately. The code in all the three of them is equal so there's no variation to be made from one to the other and at the same time also the considerations done are the same: instead of making real-time evaluations considering the time from midnight to midnight and employing 24 hours for each simulation, only the hours of sunshine in which there is an irradiance and so an output of power are taken into account. Naturally the hours of sunshine of April 11th are more than January 5th, so the simulation will last longer but for the purposes of the results obtained nothing changes except a time saving.

Chapter 4

Results

Then the results obtained from the three simulations performed are shown. It has already been said that they have been obtained considering only the hours in which the sun gives an irradiance value and not the total 24 hours but that in any case they have been obtained in real time by varying the corresponding values of Temp and Irra in every minute.

It must also be said that in output, Matlab will give the power values as time varies but, being interested in the energy supplied by this reconfigurable system it will be necessary to integrate the curve. Then, having the value of the energy it will be possible to compare it with that obtained from a conventional system.

In the following pages, the graphs of the power from each simulation.

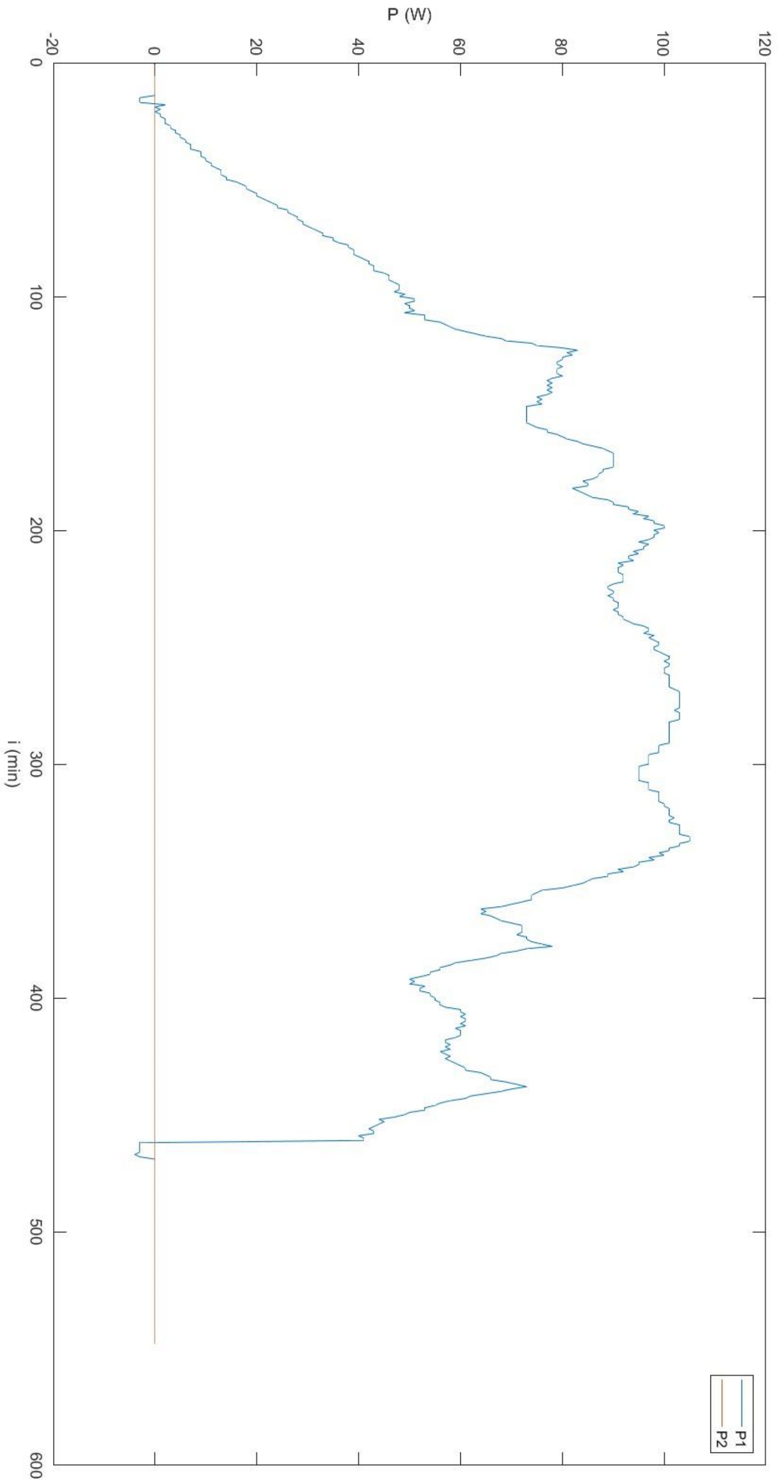


Figure 4.1. Results obtained in a reconfigurable way in a cloudy day.

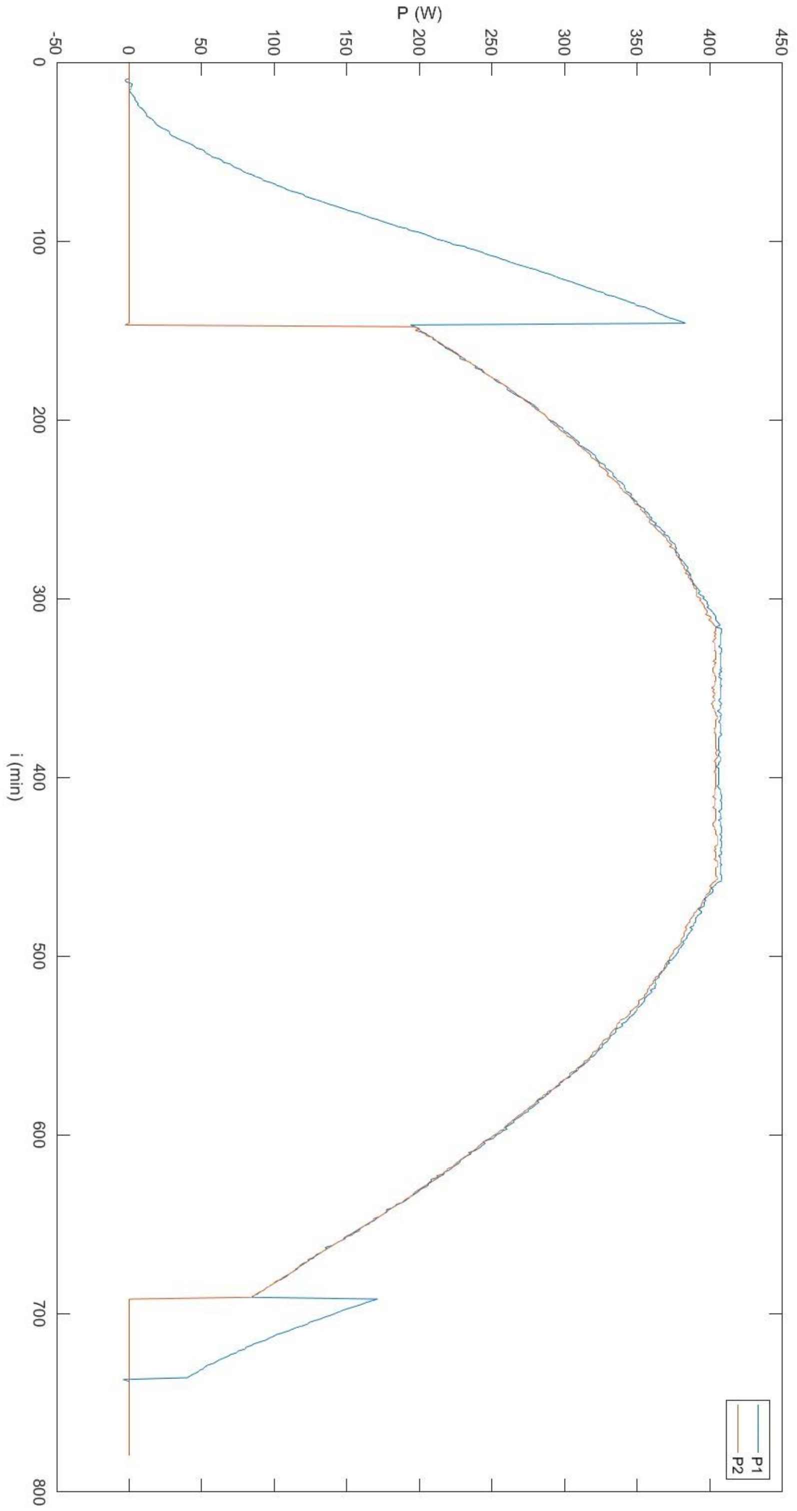


Figure 4.2. Results obtained from a Team system for a sunny day.

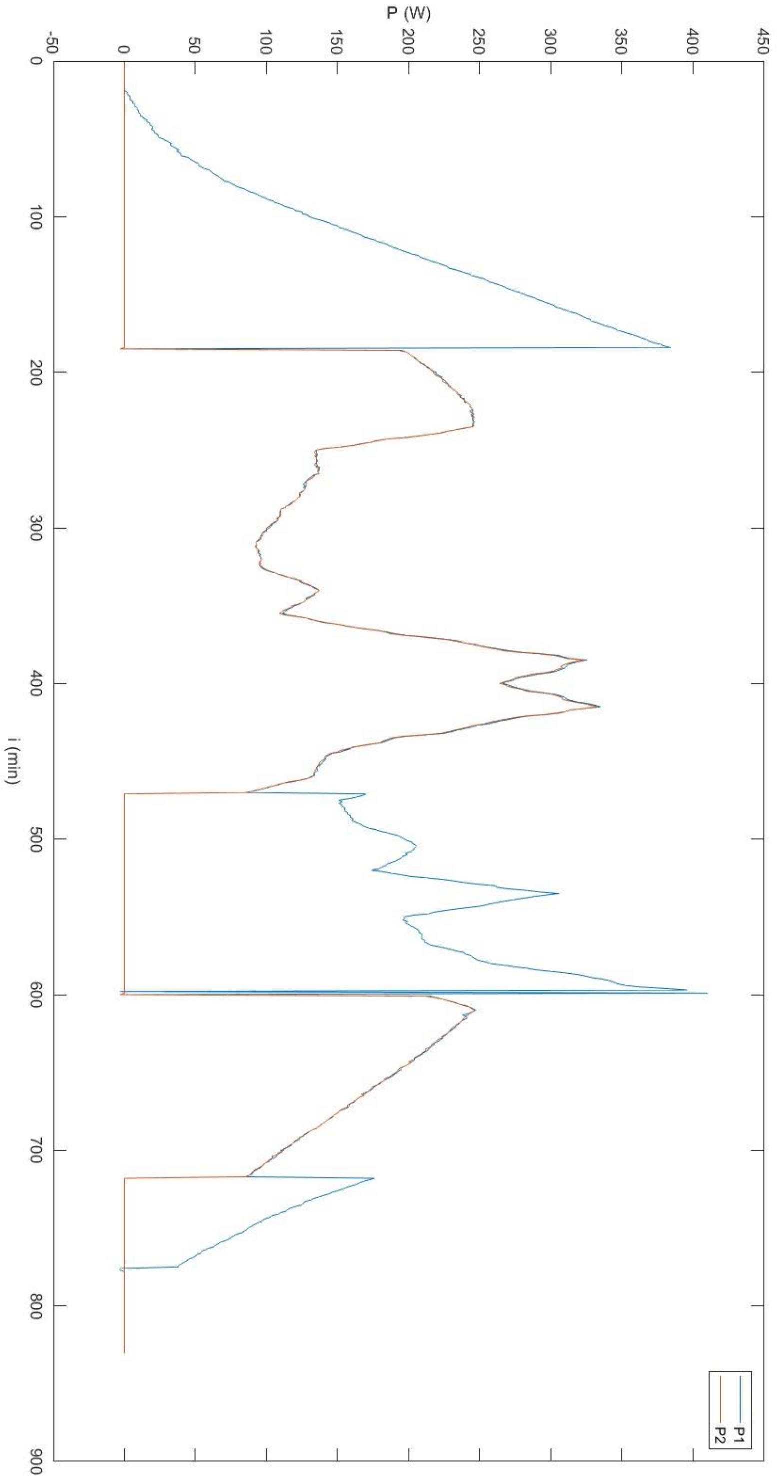


Figure 4.3. Results obtained from a reconfigurable system in a day characterized by variations in the irradiance values.

In each figure shown there are two curves: the blue one representing the power generated by the first inverter which is always in operation, and the red one due to that generated by the second inverter which, on the contrary, is activated only if a certain threshold value is exceeded.
Let's analyze the different results obtained.

- In the figure 4.1 it is shown the curve obtained in the simulation of a cloudy day, in particular the cloudiest one of the year 2006 in Barcelona. In this case the values of irradiance are low all day long so that in that 24 hours it never can possible to reach the threshold and change the configuration to the C one with both the inverters functioning. In fact the second one gives an output value of 0 W.
  For how regards the energy obtained from it, the curve has been integrated and it has found a value of 0.5 kWh.

- In the figure 4.2, a sunny day is instead presented, in particular the sunniest one which corresponds to Aprile 11th. In this case it is possible to individuate the moment in which, by increasing the power of the first inverter, the limit is exceeded and the configuration is changed: the second inverter starts working. When at the end of the day the irradiance becomes low again, only one inverter is used again.
  Also in this case the energy obtained from this type of configuration has been calculated and is equal to 6.3 kWh.

- The last case is the one representative of a day with more variations in the irradiance values which can cause an alternation in the using of the configuration. It is shown in the figure 4.3 where in fact the second inverter is switched on and off twice. This is due to the climatic conditions that vary depending on the clouds that can obscure the sun and not allow the impact on the panel.
  It is possible to notice how at the second activation an error occurs because even after 120 s the second inverter is not activated and the configuration changes again. At the second attempt, the inverter activation is successful and the configuration stabilizes on C. In fact, the inverter activation time is about 80-90 seconds but it may take longer, which is why the error occurs. However it is not so relevant to the results obtained.
  Also this time the integration of the two curves was carried out with the aim of obtaining the energy value and the sum of the two was made. In the end, a value of 3.4 kWh was obtained.

As can be seen in all the curves, when the inverter is switched on, a lowering of the power value occurs. This is due to an attempt to settle with the grid to which it is connected and once stabilized it starts with a positive generation of power.

4.1 Non-reconfigurable systems

This paragraph briefly shows the results obtained if the system was not reconfigurable, and therefore using only one inverter for the whole day regardless of the power generated.

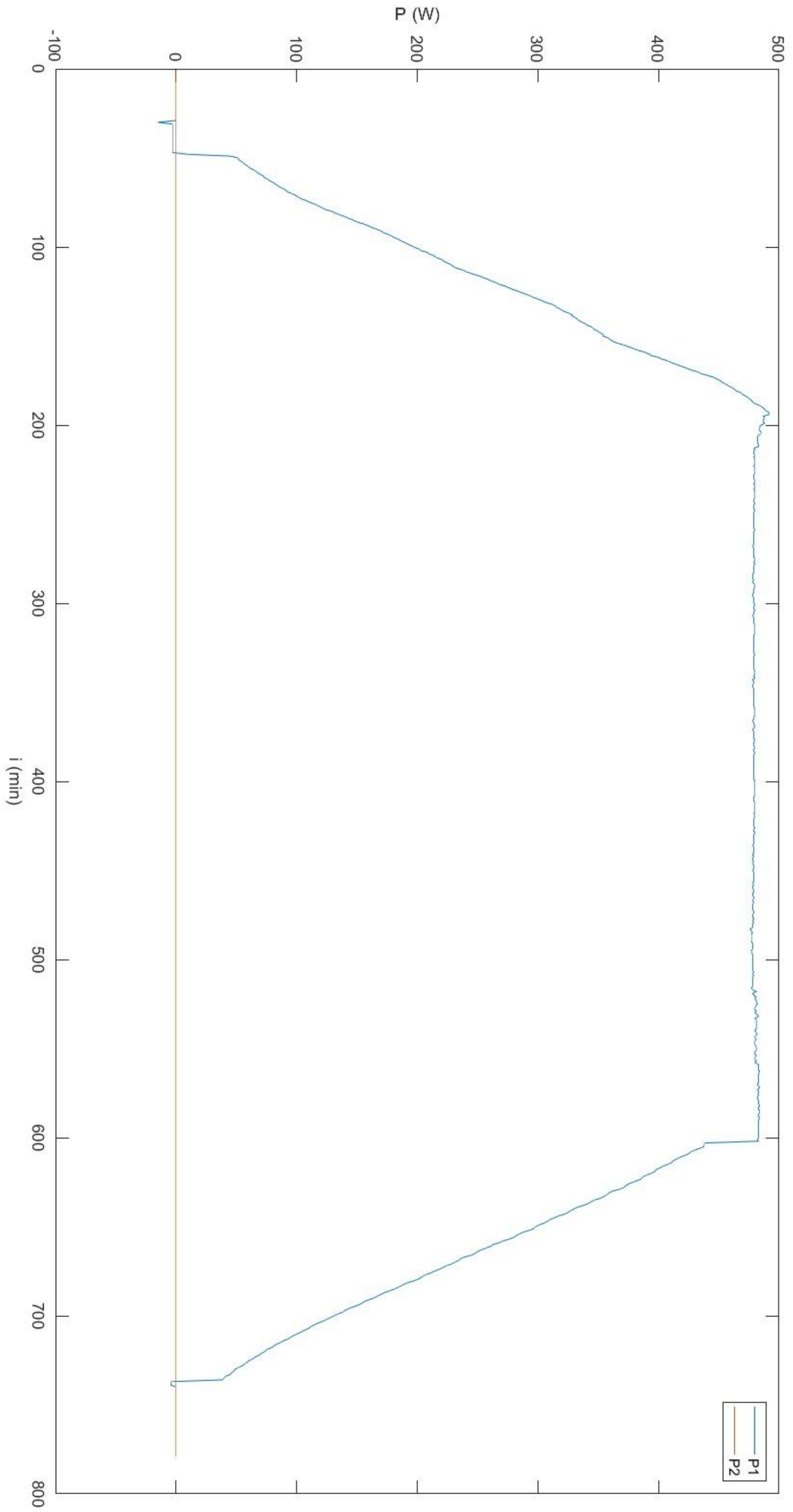


Figure 4.4. Results obtained from a non-reconfigurable system in a sunny day.

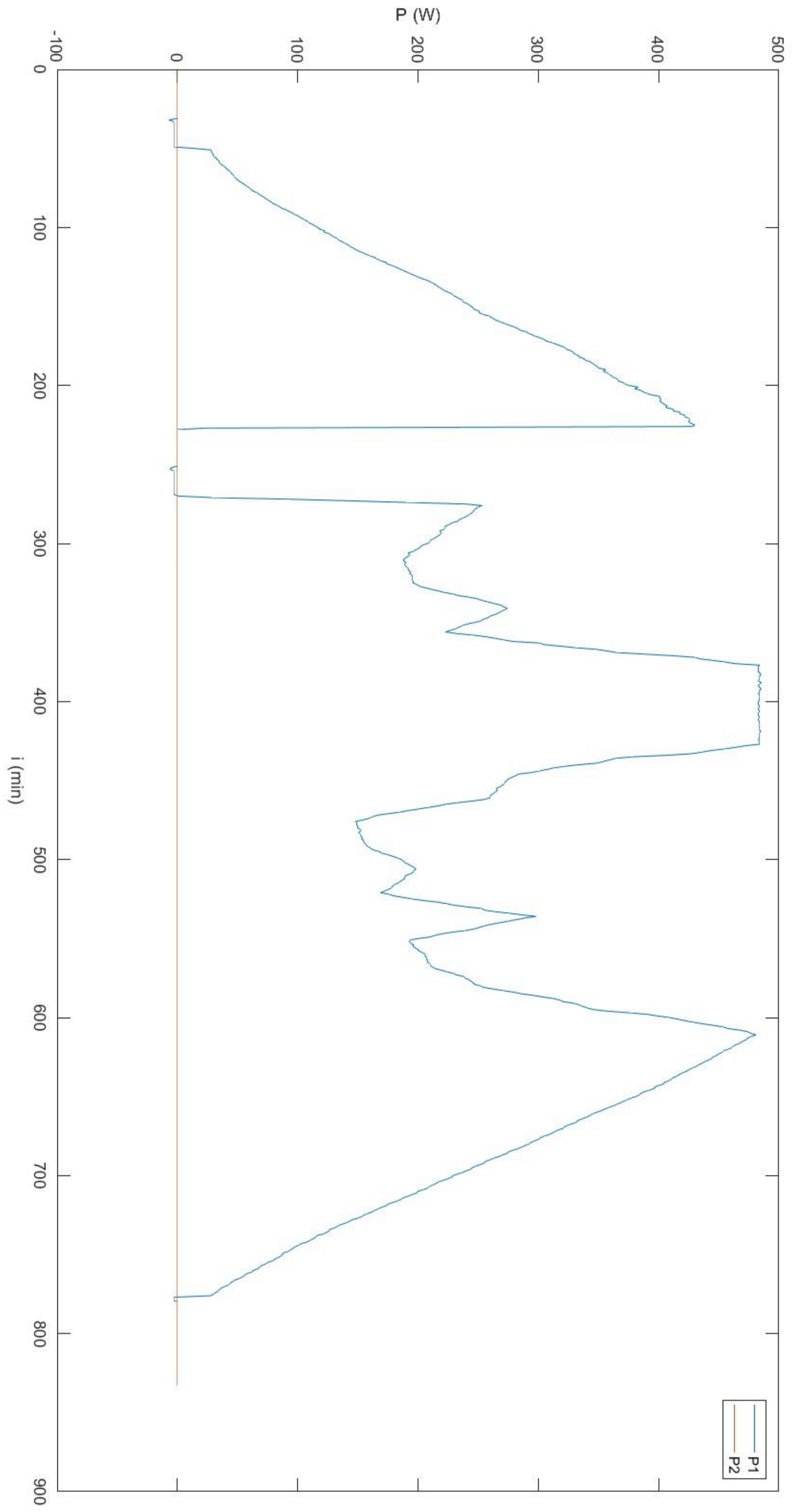


Figure 4.5. Results obtained in a day with irradiance values variations in a non-reconfigurable system.

For how regards the cloudy day nothing changes with respect to the reconfigurable system since, also in that case, the second inverter never activated. So, it is possible to see the results in the figure 4.1. By analyzing the figures it is possible to see how the second inverter is never activated (the red curve is always set to 0).
Also in in these cases the curves are integrated and these results are obtained: 4.4 kWh for the sunny day and 2.9 kWh for the other.

	Team system	**Conventional system**
Cloudy day	0.5 kWh	0.5 kWh
Day with irradiance value irradiance	3.4 kWh	2.9 kWh
Sunny day	6.3 kWh	4.4 kWh

Table 4.1. Comparisons in terms of energy between the conventional systems and the Team ones.

Chapter 5

Conclusions

As shown in table 4.1 the results give encouraging information on the use of the reconfigurable team system. The three days considered and therefore the three simulations conducted were carried out in three extreme cases of the year: the first where the clouds covering the sun entirely during the day ensure that there is no space for the use of the second inverter; the second where, in optimal conditions for the panel that receives the sun many hours of the day, the advantage of using this system is guaranteed; the latter, where even in the case of variations in irradiance the advantage, even if less conspicuous, is evident. It must also be considered that the reported values refer exclusively to one day and that over a year the weight of the advantage is more evident.

Of course it is not possible to consider the advantage of the sunniest day and multiply it for 365 because those represent only the optimal conditions that certainly do not occur often in the year. At the same time, however, we must recognize the amount of energy it is certainly interesting also considering that an average must be made between the three days taken into consideration.

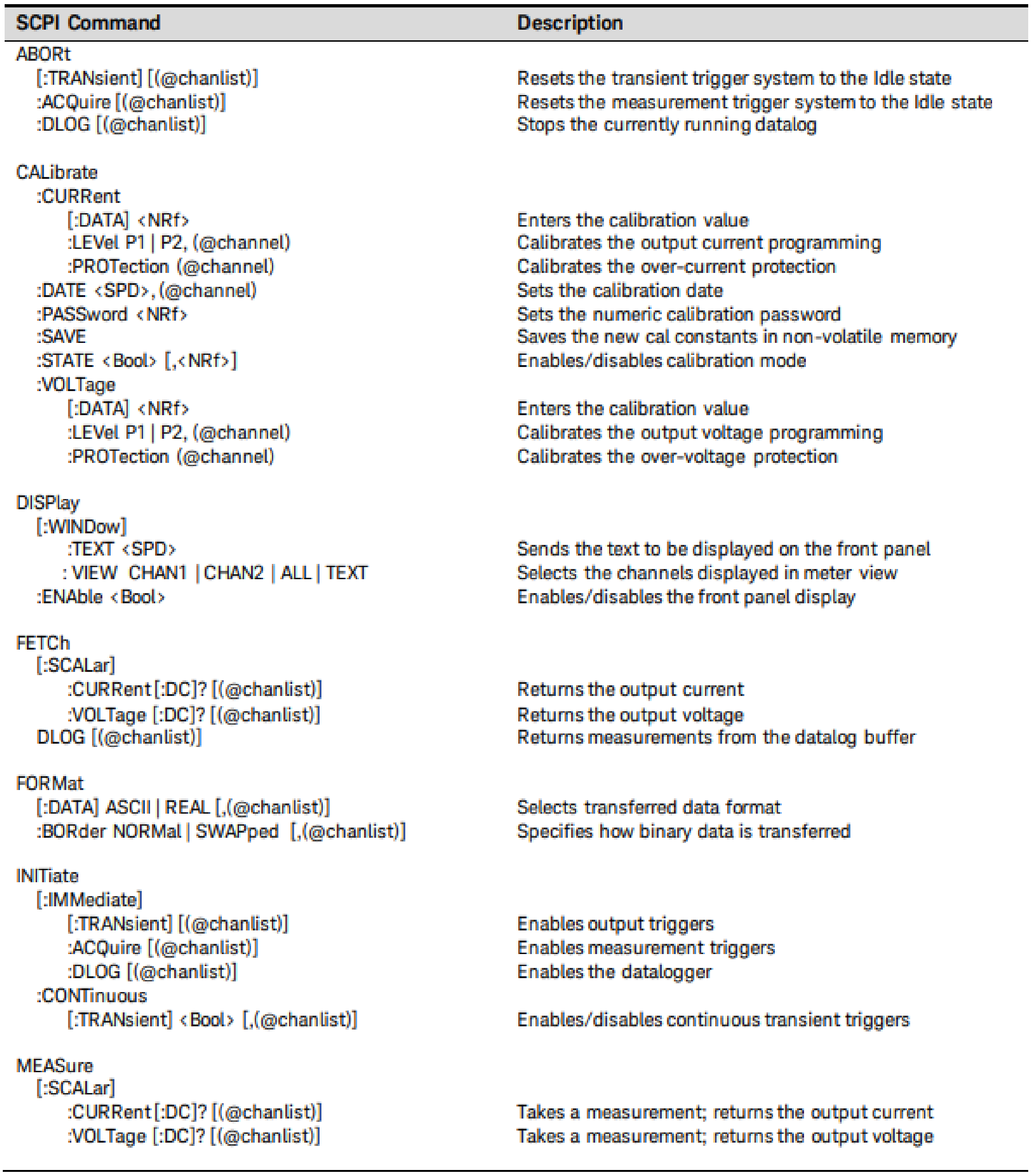
Certainly, the use of a reconfigurable system of this type does not involve any disadvantages in terms of energy, so its use is always well received. Even in terms of costs, its use does not greatly complicate the structure of a conventional system as the tools adopted are convenient and the only additional expense may be that of an additional inverter and generally its cost is around 1000-2000 €.

Therefore, globally it can be confirmed that the use of the *team* system is an advantage in terms of gain in energy produced and that the only expense can be considered negligible after all.

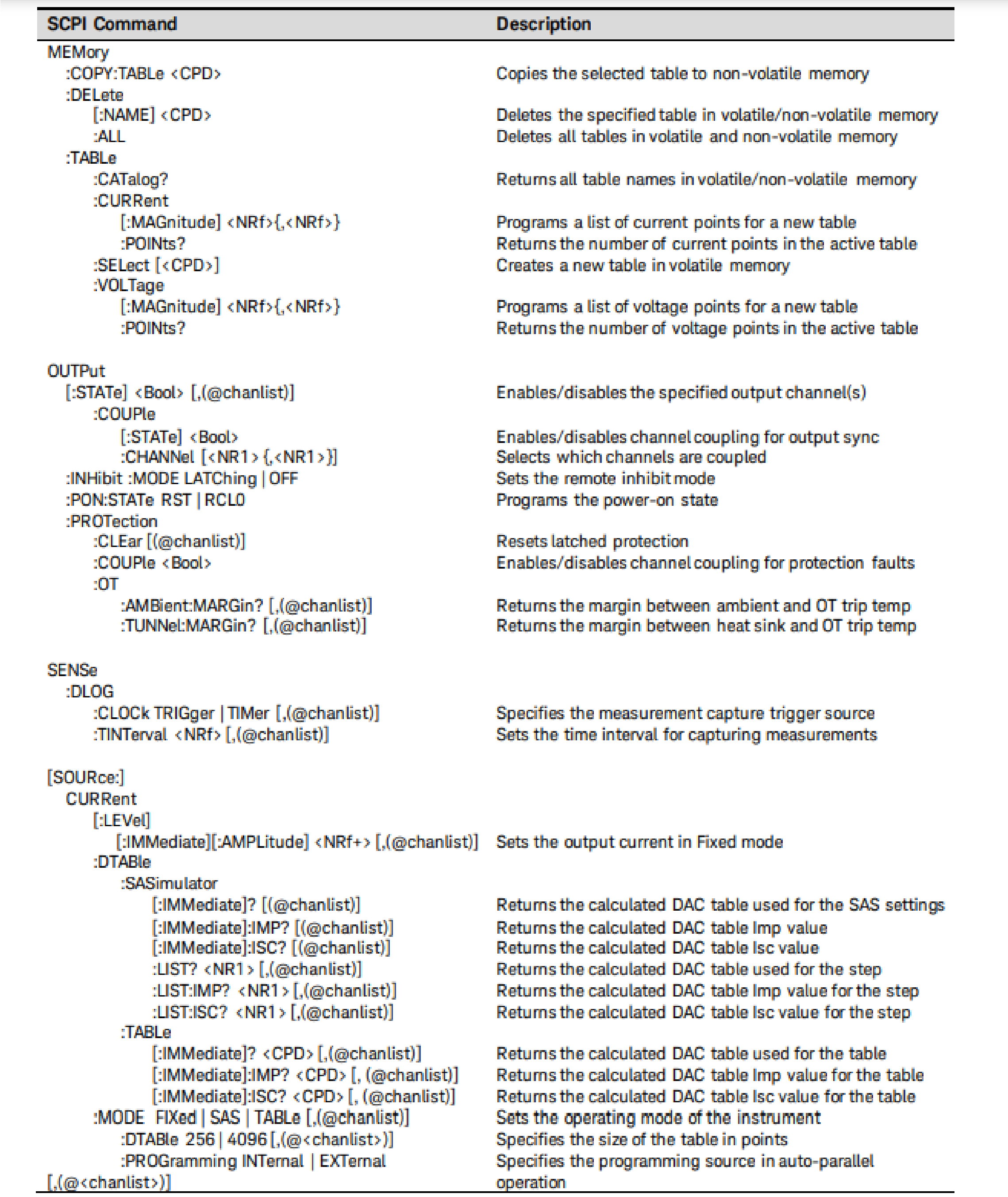
Appendix

A. SAS commands summary

In the following pages all the commands for the communication between the instrument SAS E4362A and Matlab are shown [25].

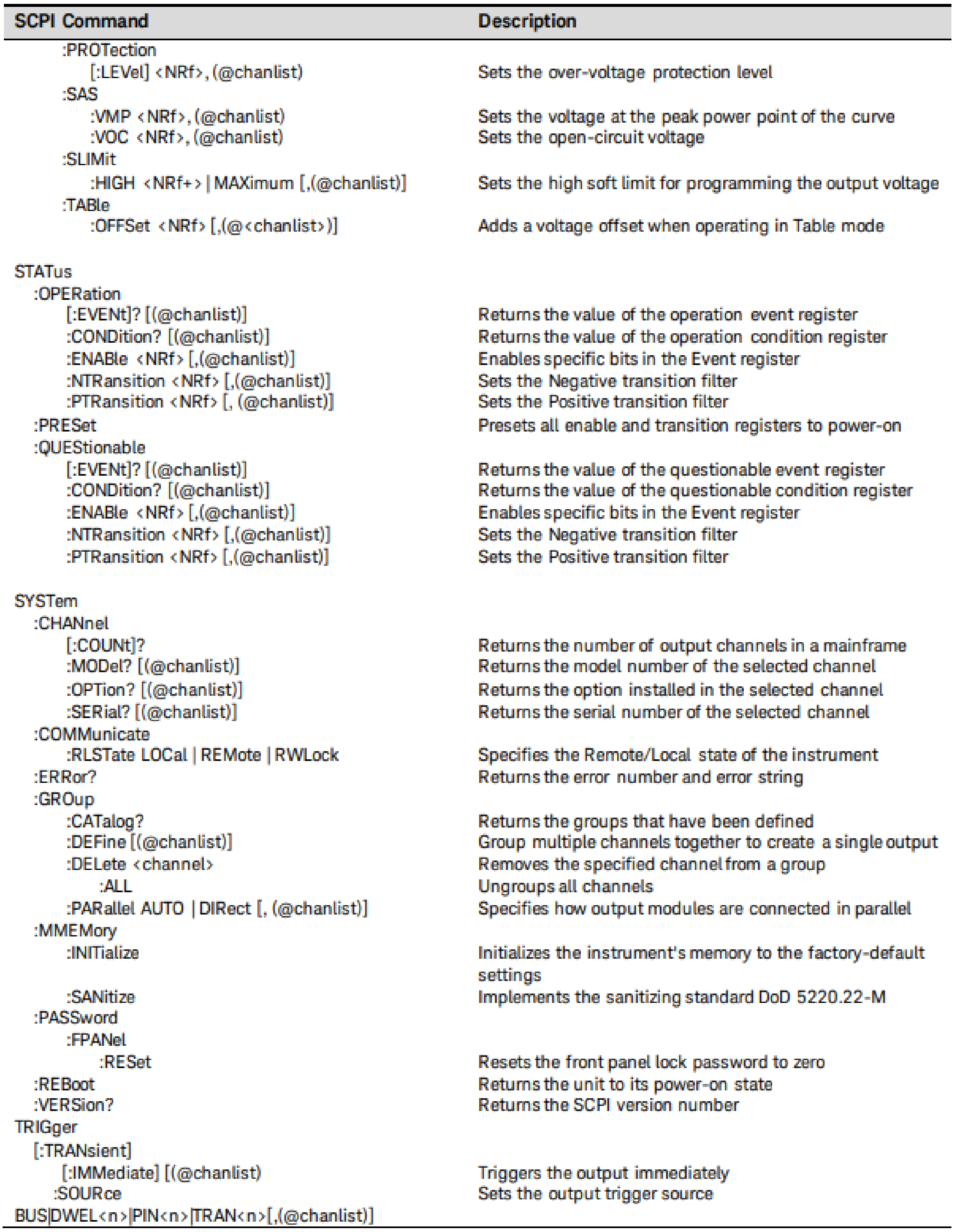


SCPI Command	Description
ABORt	
[:TRANsient] [(@chanlist)]	Resets the transient trigger system to the Idle state
:ACQuire [(@chanlist)]	Resets the measurement trigger system to the Idle state
:DLOG [(@chanlist)]	Stops the currently running datalog
CALibrate	
:CURRent	
[:DATA] <NRf>	Enters the calibration value
:LEVel P1 | P2, (@channel)	Calibrates the output current programming
:PROTection (@channel)	Calibrates the over-current protection
:DATE <SPD>, (@channel)	Sets the calibration date
:PASSword <NRf>	Sets the numeric calibration password
:SAVE	Saves the new cal constants in non-volatile memory
:STATE <Bool> [,<NRf>]	Enables/disables calibration mode
:VOLTage	
[:DATA] <NRf>	Enters the calibration value
:LEVel P1 | P2, (@channel)	Calibrates the output voltage programming
:PROTection (@channel)	Calibrates the over-voltage protection
DISPlay	
[:WINDow]	
:TEXT <SPD>	Sends the text to be displayed on the front panel
: VIEW CHAN1 | CHAN2 | ALL | TEXT	Selects the channels displayed in meter view
:ENAble <Bool>	Enables/disables the front panel display
FETCh	
[:SCALar]	
:CURRent [:DC]? [(@chanlist)]	Returns the output current
:VOLTage [:DC]? [(@chanlist)]	Returns the output voltage
DLOG [(@chanlist)]	Returns measurements from the datalog buffer
FORMat	
[:DATA] ASCII | REAL [,(@chanlist)]	Selects transferred data format
:BORder NORMal | SWAPped [,(@chanlist)]	Specifies how binary data is transferred
INITiate	
[:IMMediate]	
[:TRANsient] [(@chanlist)]	Enables output triggers
:ACQuire [(@chanlist)]	Enables measurement triggers
:DLOG [(@chanlist)]	Enables the datalogger
:CONTinuous	
[:TRANsient] <Bool> [,(@chanlist)]	Enables/disables continuous transient triggers
MEASure	
[:SCALar]	
:CURRent [:DC]? [(@chanlist)]	Takes a measurement; returns the output current
:VOLTage [:DC]? [(@chanlist)]	Takes a measurement; returns the output voltage

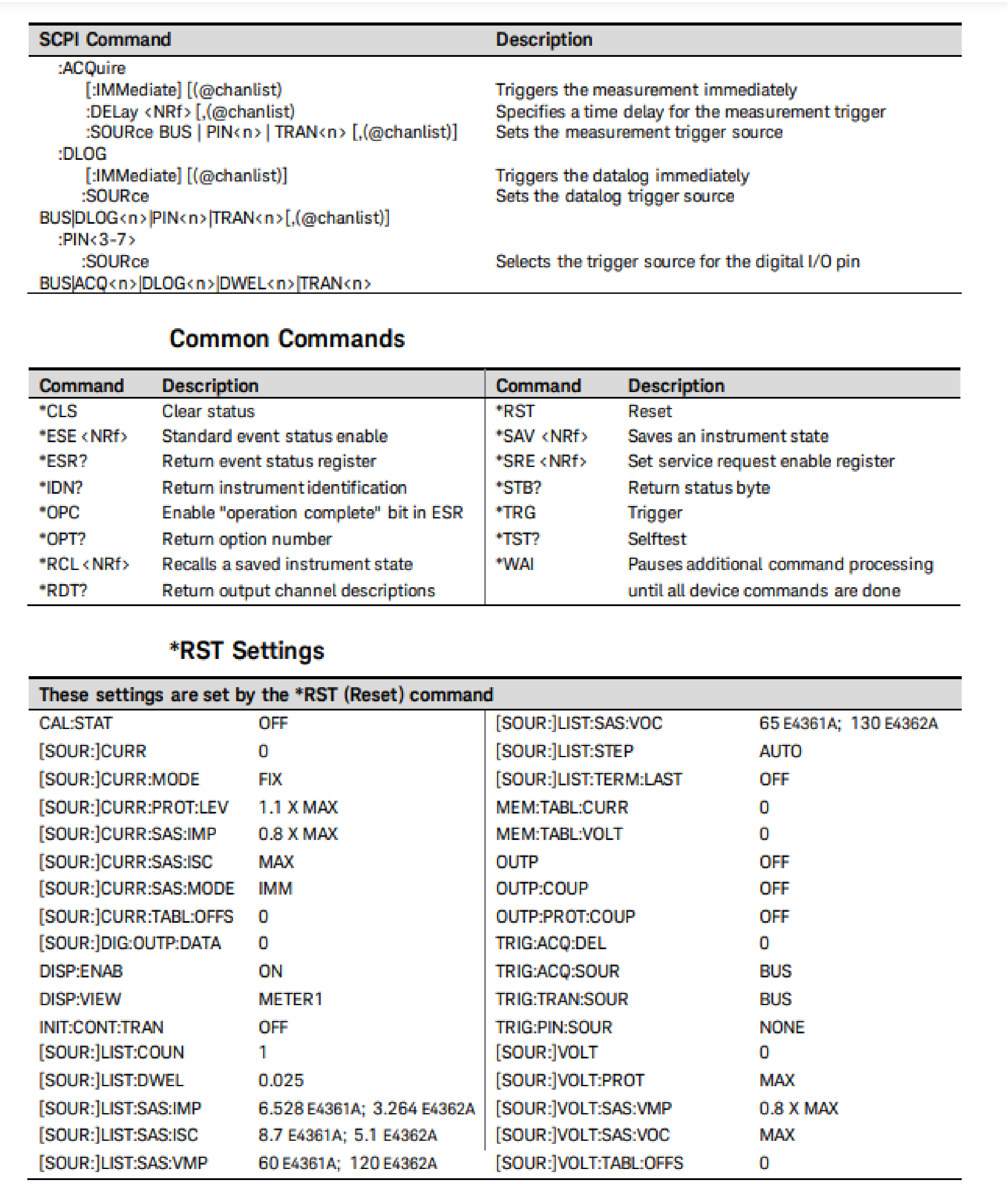


SCPI Command	Description
MEMory	
:COPY:TABLe <CPD>	Copies the selected table to non-volatile memory
:DELete	
[:NAME] <CPD>	Deletes the specified table in volatile/non-volatile memory
:ALL	Deletes all tables in volatile and non-volatile memory
:TABLe	
:CATalog?	Returns all table names in volatile/non-volatile memory
:CURRent	
[:MAGnitude] <NRf>{,<NRf>}	Programs a list of current points for a new table
:POINts?	Returns the number of current points in the active table
:SELect [<CPD>]	Creates a new table in volatile memory
:VOLTage	
[:MAGnitude] <NRf>{,<NRf>}	Programs a list of voltage points for a new table
:POINts?	Returns the number of voltage points in the active table
OUTPut	
[:STATe] <Bool> [,(@chanlist)]	Enables/disables the specified output channel(s)
:COUPle	
[:STATe] <Bool>	Enables/disables channel coupling for output sync
:CHANNel [<NR1>{,<NR1>}]	Selects which channels are coupled
:INHibit :MODE LATChing | OFF	Sets the remote inhibit mode
:PON:STATe RST | RCL0	Programs the power-on state
:PROTection	
:CLEar [(@chanlist)]	Resets latched protection
:COUPle <Bool>	Enables/disables channel coupling for protection faults
:OT	
:AMBient:MARGin? [,(@chanlist)]	Returns the margin between ambient and OT trip temp
:TUNNel:MARGin? [,(@chanlist)]	Returns the margin between heat sink and OT trip temp
SENSe	
:DLOG	
:CLOCk TRIGger | TIMer [,(@chanlist)]	Specifies the measurement capture trigger source
:TINTerval <NRf> [,(@chanlist)]	Sets the time interval for capturing measurements
[SOURce:]	
CURRent	
[:LEVel]	
[:IMMediate][:AMPLitude] <NRf+> [,(@chanlist)]	Sets the output current in Fixed mode
:DTABle	
:SASimulator	
[:IMMediate]? [(@chanlist)]	Returns the calculated DAC table used for the SAS settings
[:IMMediate]:IMP? [(@chanlist)]	Returns the calculated DAC table Imp value
[:IMMediate]:ISC? [(@chanlist)]	Returns the calculated DAC table Isc value
:LIST? <NR1> [,(@chanlist)]	Returns the calculated DAC table used for the step
:LIST:IMP? <NR1> [,(@chanlist)]	Returns the calculated DAC table Imp value for the step
:LIST:ISC? <NR1> [,(@chanlist)]	Returns the calculated DAC table Isc value for the step
:TABLe	
[:IMMediate]? <CPD> [,(@chanlist)]	Returns the calculated DAC table used for the table
[:IMMediate]:IMP? <CPD> [, (@chanlist)]	Returns the calculated DAC table Imp value for the table
[:IMMediate]:ISC? <CPD> [, (@chanlist)]	Returns the calculated DAC table Isc value for the table
:MODE FIXed | SAS | TABLe [,(@chanlist)]	Sets the operating mode of the instrument
:DTABle 256 | 4096 [,(@<chanlist>)]	Specifies the size of the table in points
:PROGramming INTernal | EXTernal [,(@<chanlist>)]	Specifies the programming source in auto-parallel operation

SCPI Command	Description
:PROTection	
[:LEVel] <NRf+> [,(@chanlist)]	Sets the over-current protection level
:SAS	
:IMP <NRf> [,(@chanlist)]	Sets the current at the peak power point of the curve
:ISC <NRf> [,(@chanlist)]	Sets the short-circuit current
:MODE IMMediate | LIST [,(@chanlist)]	Selects the source of the curve parameters
:SLIMit	
:HIGH <NRf+> | MAXimum [,(@chanlist)]	Sets the high soft limit for programming the output current
:TABle	
:NAME <CPD> [,(@<chanlist>)]	Activates a user-defined table in Table mode
:OFFSet <NRf> [,(@<chanlist>)]	Adds a current offset when operating in Table mode
DIGital	
:INPut:DATA?	Reads the state of the digital port pins
:OUTPut:DATA <NRf>	Sets the digital port
:PIN<1-7>	
:FUNCtion DIO| DINPut| TOUTput| TINPut| FAULt| INHibit| ONCouple| OFFCouple	Sets the selected pin's function
:POLarity POSitive | NEGative	Sets the selected pin's polarity
LIST	
:COUNt <NRf+> | INFinity [,(@chanlist)]	Sets the list repeat count
:DWELl <NRf> {,<NRf>}[,(@chanlist)]	Sets the list of dwell times
:POINts? [(@chanlist)]	Returns the number of dwell list points
:SAS	
:IMP	
[:LEVel] <NRf>{,<NRf>}[,(@chanlist)]	Sets the list of peak power current points
:POINts? (@chanlist)	Returns the number of peak power current points
:ISC	
[:LEVel] <NRf>{,<NRf>}[,(@chanlist)]	Sets the list of short-circuit current points
:POINts? (@chanlist)	Returns the number of short-circuit points
:VMP	
[:LEVel] <NRf>{,<NRf>}[,(@chanlist)]	Sets the list of peak power voltage points
:POINts? (@chanlist)	Returns the number of peak power voltage points
:VOC	
[:LEVel] <NRf>{,<NRf>}[,(@chanlist)]	Sets the list of open-circuit voltage points
:POINts? (@chanlist)	Returns the number of open-circuit points
:STEP ONCE | AUTO [,(@chanlist)]	Specifies how the list responds to triggers
:ACTive? [(@chanlist)]	Returns the present list step
:TERMinate	
:LAST <Bool> [,(@chanlist)]	Sets the list termination mode
POWer	
:LIMit? [,(@chanlist)]	Returns the power limit of the module
VOLTage	
[:LEVel]	
[:IMMediate][:AMPLitude] <NRf+> [,(@chanlist)]	Sets the output voltage in Fixed mode
:DTABle	
:SASimulator	
[:IMMediate]? [(@chanlist)]	Returns the calculated DAC table used for the SAS settings
[:IMMediate]:VMP? [(@chanlist)]	Returns the calculated DAC table Vmp value
[:IMMediate]:VOC? [(@chanlist)]	Returns the calculated DAC table Voc value
:LIST? <NR1> [,(@chanlist)]	Returns the calculated DAC table used for the step
:LIST:VMP? <NR1> [,(@chanlist)]	Returns the calculated DAC table Vmp value for the step
:LIST:VOC? <NR1> [,(@chanlist)]	Returns the calculated DAC table Voc value for the step
:TABLe	
[:IMMediate]? <CPD> [,(@chanlist)]	Returns the calculated DAC table used for the table
[:IMMediate]:IMP? <CPD> [, (@chanlist)]	Returns the calculated DAC table Imp value for the table
[:IMMediate]:ISC? <CPD> [, (@chanlist)]	Returns the calculated DAC table Isc value for the table



SCPI Command	Description
:PROTection	
[:LEVel] <NRf>, (@chanlist)	Sets the over-voltage protection level
:SAS	
:VMP <NRf>, (@chanlist)	Sets the voltage at the peak power point of the curve
:VOC <NRf>, (@chanlist)	Sets the open-circuit voltage
:SLIMit	
:HIGH <NRf+> | MAXimum [,(@chanlist)]	Sets the high soft limit for programming the output voltage
:TABle	
:OFFSet <NRf> [,(@<chanlist>)]	Adds a voltage offset when operating in Table mode
STATus	
:OPERation	
[:EVENt]? [(@chanlist)]	Returns the value of the operation event register
:CONDition? [(@chanlist)]	Returns the value of the operation condition register
:ENABle <NRf> [,(@chanlist)]	Enables specific bits in the Event register
:NTRansition <NRf> [,(@chanlist)]	Sets the Negative transition filter
:PTRansition <NRf> [, (@chanlist)]	Sets the Positive transition filter
:PRESet	Presets all enable and transition registers to power-on
:QUEStionable	
[:EVENt]? [(@chanlist)]	Returns the value of the questionable event register
:CONDition? [(@chanlist)]	Returns the value of the questionable condition register
:ENABle <NRf> [,(@chanlist)]	Enables specific bits in the Event register
:NTRansition <NRf> [,(@chanlist)]	Sets the Negative transition filter
:PTRansition <NRf> [,(@chanlist)]	Sets the Positive transition filter
SYSTem	
:CHANnel	
[:COUNt]?	Returns the number of output channels in a mainframe
:MODel? [(@chanlist)]	Returns the model number of the selected channel
:OPTion? [(@chanlist)]	Returns the option installed in the selected channel
:SERial? [(@chanlist)]	Returns the serial number of the selected channel
:COMMunicate	
:RLSTate LOCal | REMote | RWLock	Specifies the Remote/Local state of the instrument
:ERRor?	Returns the error number and error string
:GROup	
:CATalog?	Returns the groups that have been defined
:DEFine [(@chanlist)]	Group multiple channels together to create a single output
:DELete <channel>	Removes the specified channel from a group
:ALL	Ungroups all channels
:PARallel AUTO | DIRect [, (@chanlist)]	Specifies how output modules are connected in parallel
:MMEMory	
:INITialize	Initializes the instrument's memory to the factory-default settings
:SANitize	Implements the sanitizing standard DoD 5220.22-M
:PASSword	
:FPANel	
:RESet	Resets the front panel lock password to zero
:REBoot	Returns the unit to its power-on state
:VERSion?	Returns the SCPI version number
TRIGger	
[:TRANsient]	
[:IMMediate] [(@chanlist)	Triggers the output immediately
:SOURce BUS|DWEL<n>|PIN<n>|TRAN<n>[,(@chanlist)]	Sets the output trigger source



SCPI Command	Description
:ACQuire	
[:IMMediate] [(@chanlist)	Triggers the measurement immediately
:DELay <NRf> [,(@chanlist)	Specifies a time delay for the measurement trigger
:SOURce BUS | PIN<n> | TRAN<n> [,(@chanlist)]	Sets the measurement trigger source
:DLOG	
[:IMMediate] [(@chanlist)]	Triggers the datalog immediately
:SOURce BUS|DLOG<n>|PIN<n>|TRAN<n>[,(@chanlist)]	Sets the datalog trigger source
:PIN<3-7>	
:SOURce BUS|ACQ<n>|DLOG<n>|DWEL<n>|TRAN<n>	Selects the trigger source for the digital I/O pin

Common Commands

Command	Description	Command	Description
*CLS	Clear status	*RST	Reset
*ESE <NRf>	Standard event status enable	*SAV <NRf>	Saves an instrument state
*ESR?	Return event status register	*SRE <NRf>	Set service request enable register
*IDN?	Return instrument identification	*STB?	Return status byte
*OPC	Enable "operation complete" bit in ESR	*TRG	Trigger
*OPT?	Return option number	*TST?	Selftest
*RCL <NRf>	Recalls a saved instrument state	*WAI	Pauses additional command processing until all device commands are done
*RDT?	Return output channel descriptions		

*RST Settings

These settings are set by the *RST (Reset) command			
CAL:STAT	OFF	[SOUR:]LIST:SAS:VOC	65 E4361A; 130 E4362A
[SOUR:]CURR	0	[SOUR:]LIST:STEP	AUTO
[SOUR:]CURR:MODE	FIX	[SOUR:]LIST:TERM:LAST	OFF
[SOUR:]CURR:PROT:LEV	1.1 X MAX	MEM:TABL:CURR	0
[SOUR:]CURR:SAS:IMP	0.8 X MAX	MEM:TABL:VOLT	0
[SOUR:]CURR:SAS:ISC	MAX	OUTP	OFF
[SOUR:]CURR:SAS:MODE	IMM	OUTP:COUP	OFF
[SOUR:]CURR:TABL:OFFS	0	OUTP:PROT:COUP	OFF
[SOUR:]DIG:OUTP:DATA	0	TRIG:ACQ:DEL	0
DISP:ENAB	ON	TRIG:ACQ:SOUR	BUS
DISP:VIEW	METER1	TRIG:TRAN:SOUR	BUS
INIT:CONT:TRAN	OFF	TRIG:PIN:SOUR	NONE
[SOUR:]LIST:COUN	1	[SOUR:]VOLT	0
[SOUR:]LIST:DWEL	0.025	[SOUR:]VOLT:PROT	MAX
[SOUR:]LIST:SAS:IMP	6.528 E4361A; 3.264 E4362A	[SOUR:]VOLT:SAS:VMP	0.8 X MAX
[SOUR:]LIST:SAS:ISC	8.7 E4361A; 5.1 E4362A	[SOUR:]VOLT:SAS:VOC	MAX
[SOUR:]LIST:SAS:VMP	60 E4361A; 120 E4362A	[SOUR:]VOLT:TABL:OFFS	0

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