Control for Reliability of Photovoltaic Inverters

Master's Thesis

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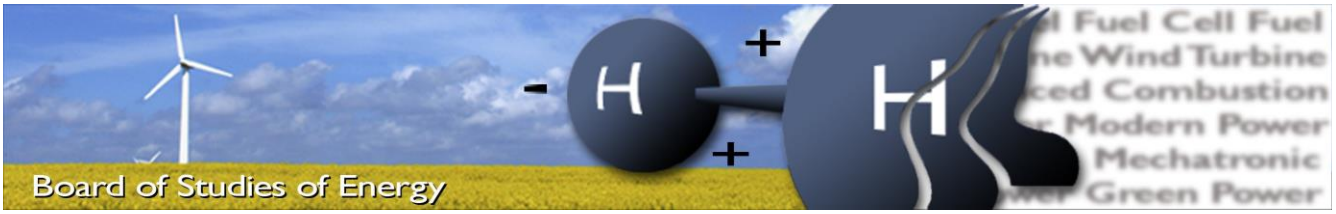

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SYNOPSIS:
With an increase of the investments on grid-connected PV systems, a pursue for solutions to assure the stability and reliability of the technologies applied is under way. In order to limit or even control the thermal damage caused by overheat on PV Inverters, different approaches to their control have been tested and implemented, using different parameters to guide Constant Power Generation (CPG). This project presents a comparative approach between three major strategies to implement it, using as a measure the energy cost of different setups in selected scenarios, and then checked with their Lifetime Consumption (LC) reduction.

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Contents

Preface

This Master's Thesis *Control for Reliability of Photovoltaic Inverters* was conducted at the Department of Energy Technology, Aalborg University during the 9th-10th semester of the Master program entitled "Power Electronics and Drives".

Instruction for reading

The references are made according to the Institute of Electrical and Electronics Engineers (IEEE) citation style and can be found at the end of the report. Figures, tables and equations are referred to as Fig., Table, and Eq., respectively (e.g., Fig. X.Y refers to a figure Y in a chapter X). All the units used in this report are based on the SI units.

Acknowledgments

The author would like to thank his supervisors Yongheng Yang, professor at Aalborg University, and Ariya Sangwongwanich, a postdoctoral fellow at Aalborg University, for their patience, true dedication and valuable guidance during the study. In addition, the author would also like to thank his colleagues in the department for their enlightening discussions. Finally, the author would like to express his eternal gratitude to all his familiars for their unlimited kindness and support during this long journey.

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Abstract

Photovoltaics (PV) have shown a constant growth rate for several years and have the potential to be a major energy source in the world power production. For making the investment on the source more reliable, improvements on the technologies applied and operational techniques are a must, and the increment and addition of different capacities are making the PV systems smarter and more flexible.

Together with new materials and supervision systems, new strategies to amplify the stability of the entire system, especially the power converters. One of the main challenges on the reliability improvements are the thermal cycles faced by the Insulated Gate Bipolar Transistors (IGBTs), that cause a decrement on their lifetime thus also depleting the entire system reliability. Therefore, this thesis studies the different impact of different strategies applied to minimize this impact at an Inverter level, through the application of Constant Power Generation (CPG) strategies. These options are realized by limiting the power generated by the system according to different reference parameters.

Despite the difference between hardware demands required for the implementation of each strategy, each one presents apparent advantages that may or may not be translated on significant Lifetime Consumption (LC). Their attractiveness may also demand a high cost in energy production, bringing negative aspects capable of overpass any reliability improvement. After all comparisons, a simplified general parameter to rank different scenarios and different control strategies is applied to all the simulated results in order to make explicit the different impact that can be achieved with each control selected.

Chapter 1

Introduction

The modern economy demands more energy consumption, where the electrical energy demand increases 4% last year. While the significant portion of 70% of the global energy increment is represented by the consumption of fossil fuels, Solar and wind generation are growing at a fast pace, with solar alone increasing by 31%. [1]

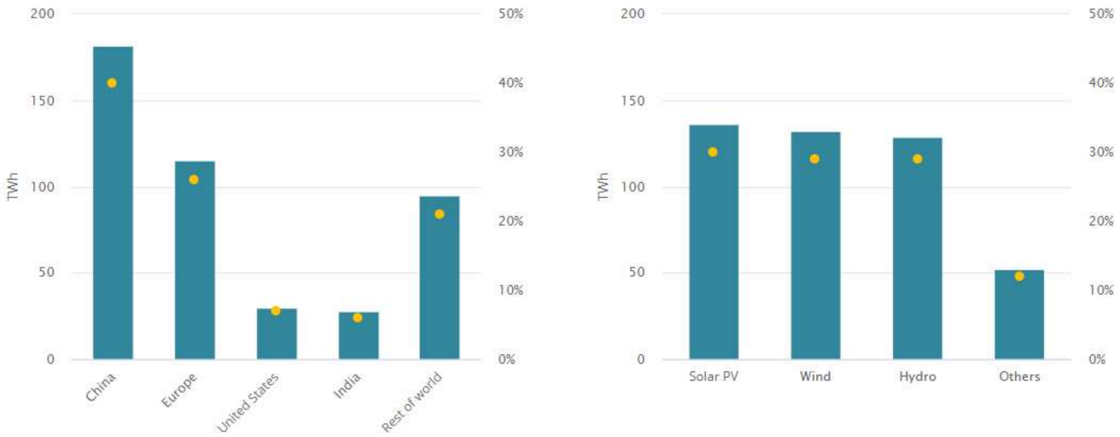

Figure 1.1: *Growth in renewable electricity generation by region and technology, 2017-18 [1]*

In that regards, large investments in renewable energy can be observed globally. The development of an energy matrix also supported by resources such as solar energy or wind power is can reduce the dependency from foreign resources, which is a very attractive scenario.

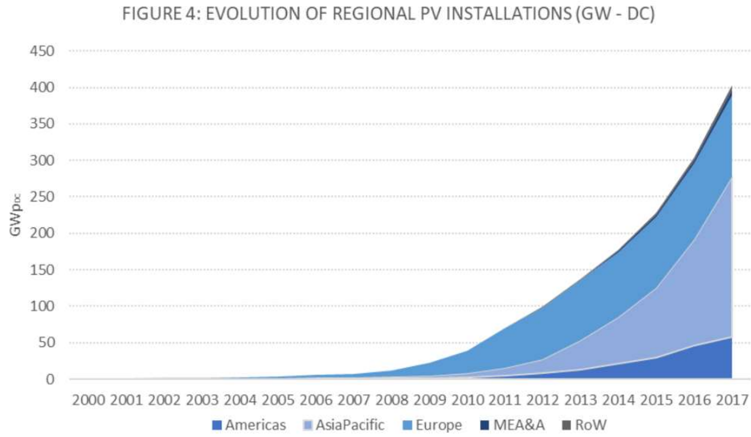

Figure 1.2: *The estimated evolution of regional PV installations in operation by region [2]*

While the implementation of different types of photovoltaic (PV) inverters intensifies, special attention has been dedicated to studying the parameters involved in the reliability and maintenance of grid-connected inverters. On that subject the reliability perspective has been highlighted [3], driving studies on all the possible failures causes for photovoltaic inverters such as manufacturing and quality control problems, inadequate design, and electrical component failure.

Undoubtedly, PV systems have as key price drivers of inverter costs their reliability [4]. Therefore, the designer's capacity to control and to measure it can make investments in photovoltaic technologies easily more attractive, making this subject to several studies. On that challenge, researchers are thriving to present solutions aiming to hold degradation of the devices while operating in relatively harsh, changing conditions such as broad temperature variation, absence of high humidity, high salinity, etc.

1.1 Background

1.1.1 Overall PV Installation and energy conversion process

In the PV system, solar energy is harvested by converting it into a Direct Current (DC) electricity. However, in order to deliver the power from the PV system into the electricity grid, the DC power needs to be converted to an Alternating Current (AC) power through the inverter. Therefore, a general layout for PV systems is usually applied to systemic studies:

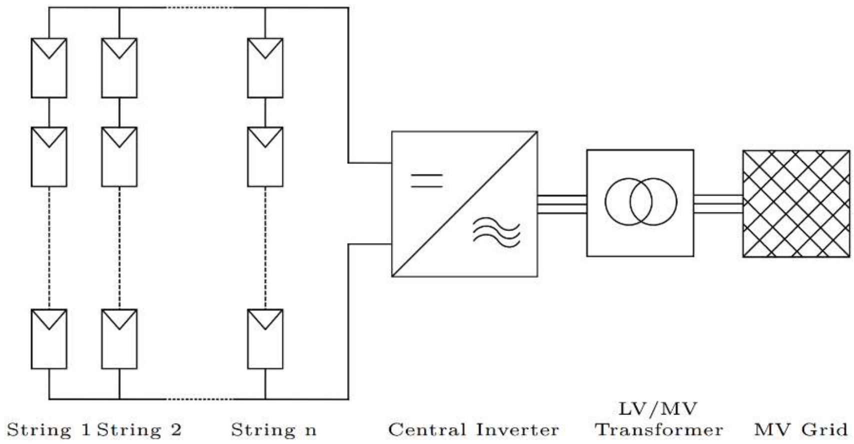

Figure 1.3: *Overview of a simplified PV System [5]*

In short terms, a PV Installation facility has three major sections:

- Energy harvesting – composed of PV panels and intermediary connections;
- Energy Control and transformation – include PV Inverters, transformers and charger controllers;
- Connections and protection – using switchboards and switch-breakers to export the energy to export to eventual storage systems.

Regarding Central Inverters for grid-connected facilities, they can still operate 2 different subprocesses: DCDC conversion and a subsequential DCAC conversion.

1.1.2 Reliability of the energy harvesting process

Usually, in the initial period of operation, the failure rate of a system is dominated by defects during manufacturing and transportation. This is known as early failures which will be decreased over time. After a certain period, the failure rate is expected to stabilize, when just random failures are observed and this period represents the system usefull life

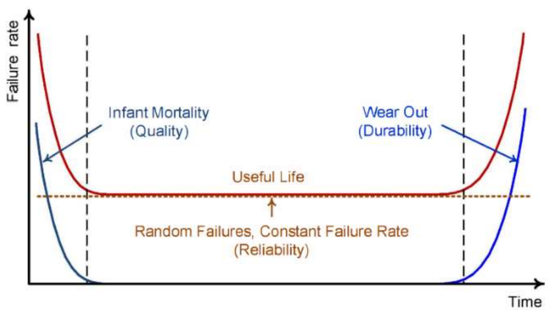

Figure 1.4: *Typical bathtub shape of a plot of the failure rate of a population of items over time [6].*

A new state starts only when the durability of the system or component is exhausted, and the wear out failures become regular. One could formally describe the reliability of an item is defined as the "ability to perform as required, without failure, for a given time interval, under given conditions"[7]. Thus, the reliability of a system always depends on the given operational conditions.

1.1.3 Reliability of PV systems and PV Inverters

PV systems are usually installed outdoor, where the installation sites can be isolated or difficult to be accessed. Thus, a quick replacement of its damaged parts is not an easy task. Therefore, the failure of components, e.g., inverter, may decrease significantly the overall economic investment of a PV plant, while the market expects the system to keep converting energy with minimum interruption for the typical 20-25 years duration of the contracts [8]. The subsequential pursue of maximum availability leads to strategies using hierarchical levels and by that, from the PV arrays to the grid or battery connections [13] both degradation aspects (eg. impairment) and catastrophic failures (eg. outage) can be discussed. On that matter, simplified block diagrams can express a general reliability approach of a PV system:

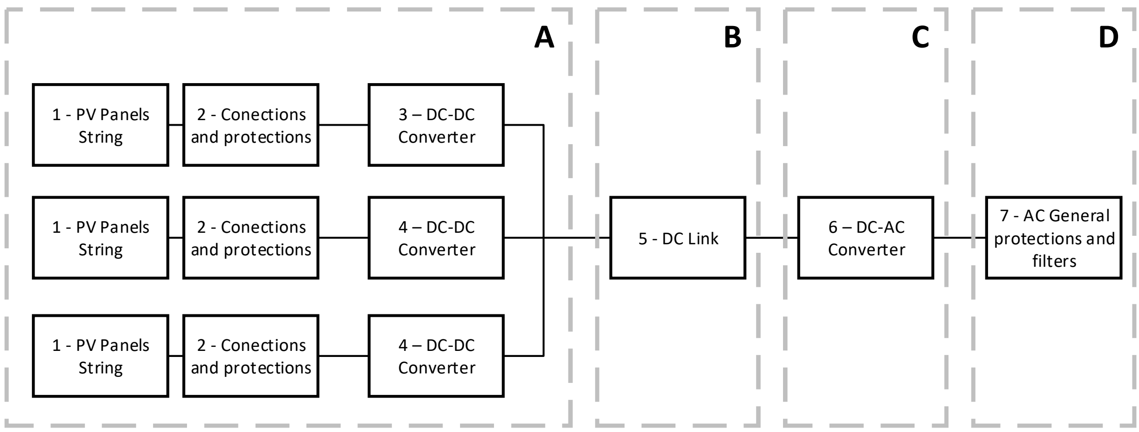

Figure 1.5: *A possible general approach to a PV system reliability analysis*

In this system, some component such as DC link capacitors and DC-AC inverters are more crucial to the overall system reliability, as their failure can lead to the entire malfunction of the system. On the other hand, the faults of PV panels will only lead to a fraction of power production loss while the remaining system can still be operated. Therefore, most outages on PV strings could only lead to limited power degradation.

In fact, outages of mission-critical subsystems comprise 69% of identified service issues and are responsible for 75% of the associated energy losses [8]. And Inverters are among the major causes:

General Failure Area	Pct of tickets	Pct of kWh lost
Inverter	43%	36%
AC Subsystem	14%	20%
DC Subsystem	6%	4%
Planned Outage	5%	8%
Others	32%	31%

Table 1: *Frequency of tickets and associated energy loss for each General Failure Area [8].*

While the tickets are indicative of outage events, the energy lost represent the sum of energy not produced due to the total time that lasts those events.

General root Cause	Pct of tickets	Pct of kWh lost
Parts/Materials	52%	48%
Software	9%	7%
Preventive Maintenance	1%	1%
Others	38%	43%

Table 2: *Tickets Frequency and Associated Energy Loss for each Root Cause [8]*

The role of parts and components on the reliability then becomes clear, and the switches play a major role on that.

1.1.4 Possible solutions for reliability improvement

There are several fronts to be researched when trying to control and improve the reliability of PV Inverters:

- **Facility and device structure**: improvements on the facilities and accessories such as coolers [9] or protections, used to control the influence of external parameters can bring stability to the system and its components [10], ;
- **Materials Applied**: Better alloys and efficient designs may improve heat dissipation and deplete the thermal stress [12];

- **Operational strategies**: Fitted strategies to predicted or monitored external variables can influence the behavior of internal components lifetime, thus their reliability expectancy [11].

The latter has a broad range of possibilities, and as a matter of the present studies is here shortly resumed to three main fronts:

- **Flexible MPPT** – Applies the choice to limit the power extraction of the Inverter by a referential value;
- **Smart Derating Control** – Characterized by a limitation to the power exported by the Inverter according to external parameters such as Ambient Temperature;
- **Active Junction Temperature Control** – Defined by the curtail of exported power in order to limit a junction temperature to a certain value.

1.2 Project motivation and objectives

As addressed before (see *1 - Introduction*), the outages on PV systems are a major cause to decrease in the investment return on these systems. On that matter, a clear indicator is a fact that the mean time between failure of inverters has been shown to be 300 to 500 times shorter than PV modules [16].

Still, on that matter, a variable profile of solar irradiation and ambient temperature (see 1.1.1) and the consequent unpredictable heat on components assumes a central paper on Inverters failure. Thus, trends in power electronics systems have placed increasing demands on the thermal management and control strategies to mitigate the effects of those unpredictable conditions.

This project aims to measure and point the impact of different strategies of PV inverter control in order to manage the thermal aspects of the most threatening components, thus analyzing how each impact the reliability of the device.

As an objective proposition, the study aims to propose and answer the major question:

- How does the control strategies affect the reliability and production performance of PV inverters?

1.3 Project Limitations

Considering the focus defined for the project as the effects on the Reliability from different design and operation conditions, the subject studied will be the control strategies applied on PV Inverters. During these studies, a limitation emerges especially on the effects expected on switches, being those part of a Monophasic inverter.

No special variation on the Pulse Width Modulation (PWM) technique is planned, and no variation on the grid parameters for the exported energy is considered.
The PV array production characteristics will be simulated using the mathematical relation described as:

- The PV inverter model used uses a single-phase full-bridge topology;
- A heat sink with a thermal resistance of 1K/W is considered;
- Two strings with 8 PV Panels each, with 200Wp in each module supporting the energy harvesting parameters;
- Solar irradiation data captured from public websites on the hourly sample and daily long will be used, limiting the mission profile to be accessed.
- Data from different sites can be used for testing specific theories and conclusions, but a common fit of environmental parameters should be applied to all scenarios;
- The study explored only three different strategies to improve the reliability of PV Inverters: Flexible MPPT, Smart Derating Control Active Junction Temperature Control.

1.4 Thesis Outline

The report is composed of five main chapters and one appendix. The following presents a summary of each chapter, with their main objectives.

Introduction

In chapter 1, the project background is presented. The role of PV inverters on the reliability of PV systems is explained, addressing the overall reliability challenge, leading to the problem objectives, applied solutions and project limitations.

Control and operation of PV converters

In the second chapter, the power electronics subsystems demanded a PV system operation have their operation and control explained, and additionally, their major parameters are pointed out.

Thermal effect on components reliability

In chapter 3, the thermal stress of the switches is discussed, together with their influence on the reliability of components. Also, a scheme to evaluate the reliability effects of control techniques is presented.

Reliability assessment and energy production

In chapter 4, the main predictions of the project are provided where the effects of different control strategies are tested regarding their effects on the reliability of switches and regarding their energy production.

Conclusion

The conclusions of the studied theme regarding reliability and energy production are explored in this chapter, together with future works.

Chapter 2

Control and Operation of PV Converters

2.1 Basic PV Systematic and energy harvesting

When the solar radiation reaches and illuminates a solar cell, electron-hole pairs (EHPs) are at the solar cell material. These phenomena convert fractions of the solar energy into electrical current if a load is connected to the electrodes.

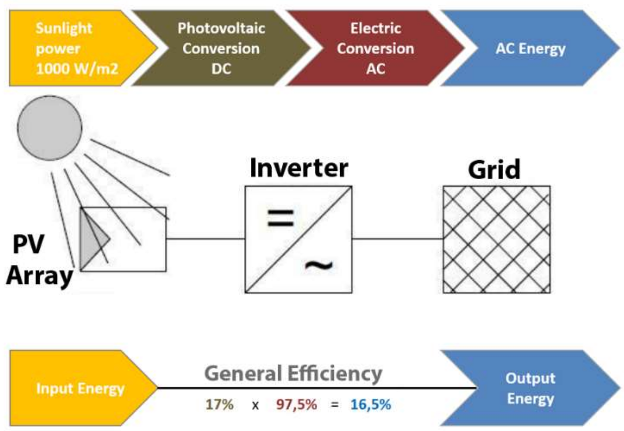

Figure 2.1: *The energy flow on a PV grid tie installation, supposing 17% efficiency for PV panels and 97.5% at the Inverter*

The transformation process can be described by several variables, but the list can be split into two very different groups:

- **Environmental variables** – Those heavily influenced by external systems or process and that are, in their nature, locationdependent. Examples are the amount of solar irradiation on a site or the local temperature.

- **Electrical and systemic variables** – These are a matter of design and control on PV devices. Examples consist of selected physical parameters on the semiconductors but also systemic levels such as voltage and current.

Limiting environmental variables

While studying and dimensioning photovoltaic systems, a first step is to define references for environmental variables. The standard option is to consider the AM1.5 global spectrum, designed for flat plate modules with an integrated power of 1000 W/m2.

For compatibility with the International Standard IEC 60904-3 the used Standard Test Conditions (STC) consider additional parameters such as a cell temperature of 25°C and the energy received by a flat surface exposed at 37° to the horizontal plane on a cloudless day.

Environmental variables influence on electrical and systemic variables

The influence of the environmental variables brings some challenges to the inverter design, though does not define directly the systemic limits of a PV system.

Those are a matter of design using PV cell basic parameters, and among them are the open circuit voltage (Voc) and the closed-circuit current (Icc). While the former corresponds to the cell output voltage without any load connected between the electrodes, the later is expressed by the maximal current possible to be measured in a short circuit condition.

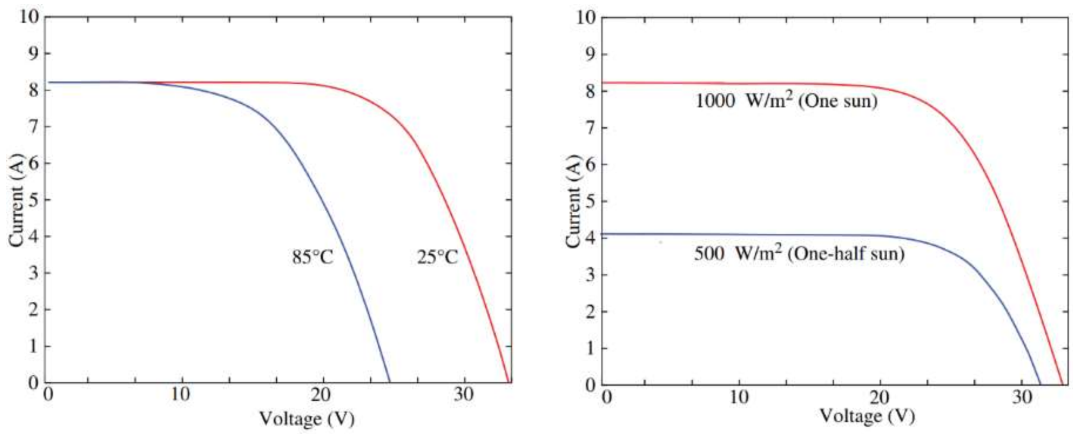

Figure 2.2: *(a) Effect of Temperature on PV module (b) I-V characteristics under different illumination levels*

2.2 Overall Control of PV Systems

The complete design of a PV system demands different studies around the environmental variables and a selection of a control strategy based on the desired characteristics of the entire facility.
For each scenario, a control system should be designed in order to control de harvested energy and shape it to standard and useful parameters.

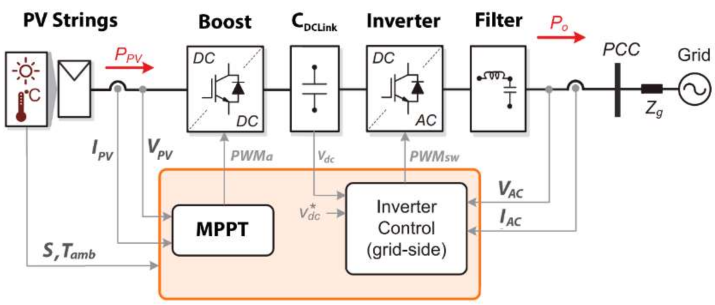

Figure 2.3: *Simplified control parts of a PV system*

In general terms, DC-DC conversion and a DC-AC conversion are required for PV systems. However, in some cases, the DC-DC conversion can be developed in independent smaller inverters – the so-called Multistring inverter scheme:

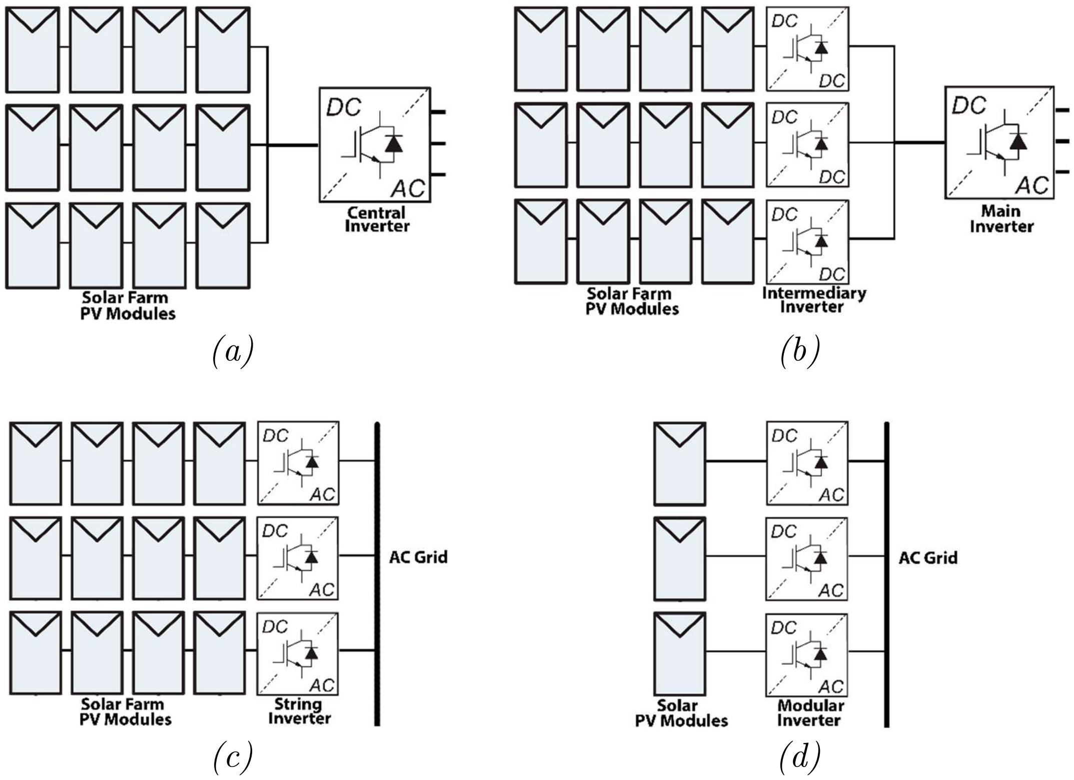

Figure 2.4: *Schemes with (a) a Central Inverter, (b) a Multi-string inverter, (c) String Inverters and (d) Modular Inverters*

2.3 DC-DC Control

The energy harvested from PV strings is a DC power. The vast range of possible combinations for the Environmental Parameters brings a certain variation to the Electrical and systemic variables (see 2.1).
For dealing with that, a boost or even buck-boost converter is used to stabilize the voltage produced, limiting the variation to the electrical current.

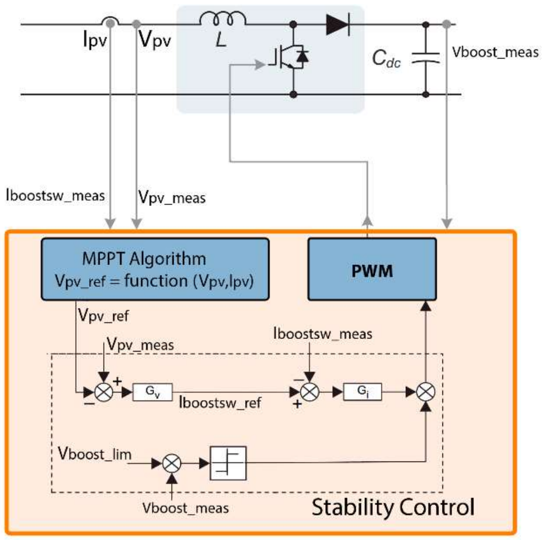

Figure 2.5: *Boost Converter Closed Loop Control scheme for a PV System*

It is important to notice that despite operating upstream on the energy production, this converter is designed to match not just the PV string parameters but also the rest of the system. In general terms, its main constrictions are:

- Voltage range expected from the PV string;
- Voltage bus level as a goal;
- Maximum current expected to output;
- Maximum ripple accepted at the current.

A closed loop has to be developed to constrain the control into a stable operation even while facing turbulences in the operating condition.

2.3.1 Maximum Power Point Tracking (MPPT)

The variable profile presented previously express the PV panel electrical characteristics (e.g., voltage and current) under different operating conditions.

This effect has roots on the fact that the electrical parameters (e.g. Voltage and Current) are a result of the photovoltaic effect on the PV panel material. On that matter, they are proportional to the number of electron pairs that the panel is capable of displacing per second under a specific set of conditions [17].

Under a certain environmental condition, there is a unique operating point that assures a maximum power supply and it is defined as Maximum Power Point (MPP). Different Maximum Point Tracking (MPPT) algorithms can be used to track the MPP. Normally, the MPPT algorithm is implemented on the DC-DC converter, interacting directly on the energy harvest section of the PV Plant.

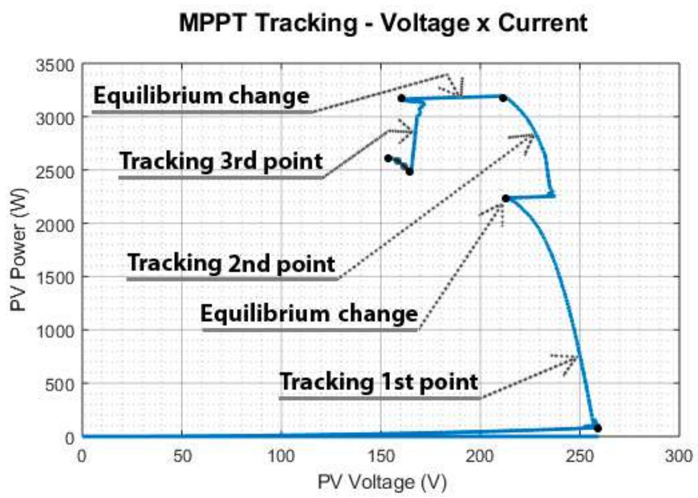

Figure 2.6: *MPPT tracking path through different punctual conditions*

Three of the most known tracking strategies are the IC (Incremental Conductance), P&O (Perturb and Observe) and the HC (Hill Climbing). While the first one use as parameter the Conductance and its derivative and (I/V and dI/dV) to track the power-voltage curve, the second and the third ones are guided by their Instant Power and its variation rate (P and dP/dV).

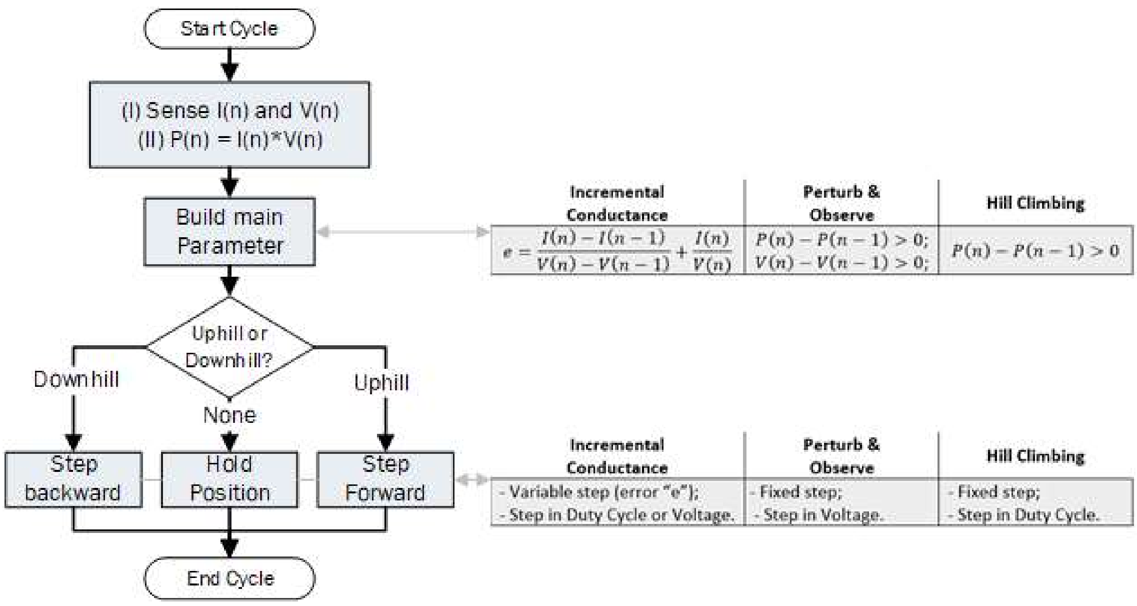

Figure 2.7: *Simplified view of the decisions taken under MPPT strategies*

2.3.2 Active Power Control

A typical requirement for PV Plants is to be able to align their power production to different constraints. One of the requirement is to be able to operate in the power curtailment mode, which is called *Constant Power Generation* (CPG) in the grid code.

The discussion around this last requirement emerges because while the MPPT technique assumes as a goal the search for the maximum energy harvested, these parameters are not always the best fit for every situation. Two distinct scenarios emerge in opposition to the MPPT premise:

- **External limitations**: Energy absorption limits at the storage system or grid stability criteria can be momentarily a boundary, or even be just a regulatory restriction;
- **Internal limitations**: Particular limits set for an inverter or specific components can justify the imposition of constraints to the generated power.

Unless a cost-effective energy storage system is introduced, in both cases the maximum power available on the connected PV string must be limited [18].

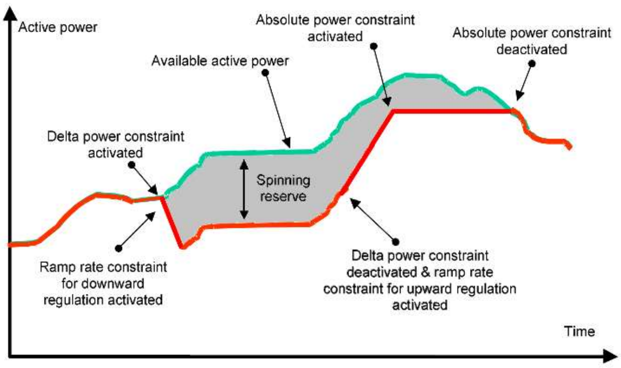

Figure 2.8: *General Grid constraint functions for active power control [19].*

On those situations is necessary to interact actively with the regular control system of the PV system in order to limit the harvested PV energy according to a different sort of parameters. That represents, by definition, the Active Power Control.

Demands for Implementing Active Power Control on PV Plants

The implementation of energy curtails production on PV plants always comes with the cost of the energy yield loss. On the other hand, in specific situations the electricity grid will experience less fluctuation of the power delivered from the PV systems, reducing the PV integration challenge [18].

If present, an intelligent central could shutdown different PV production units to balance grid parameters such as overvoltage, or just derate their productions to better manage the grid.

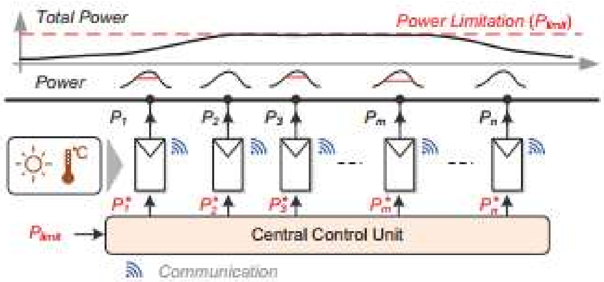

Figure 2.9: *Example of Power management control to achieve a total constant power production in an aggregated PV system [18].*

This scenario requires the Inverter not just to be able to be shut down by a distant command, but also to receive a numerical parameter to sustain the previously mentioned Constant Power Generation state (CPG). Additionally, possible physical limitations to the PV Inverter can be considered, and even managed if that is the case.

Realizing the Active power Control

Among other arrangements, different strategies can easily be implemented through the inclusion of subroutines on the MPPT logic. In comparison to a generic MPPT logic scheme (see *Fig. 2.7*), small subroutines can then be included such as exposed below:

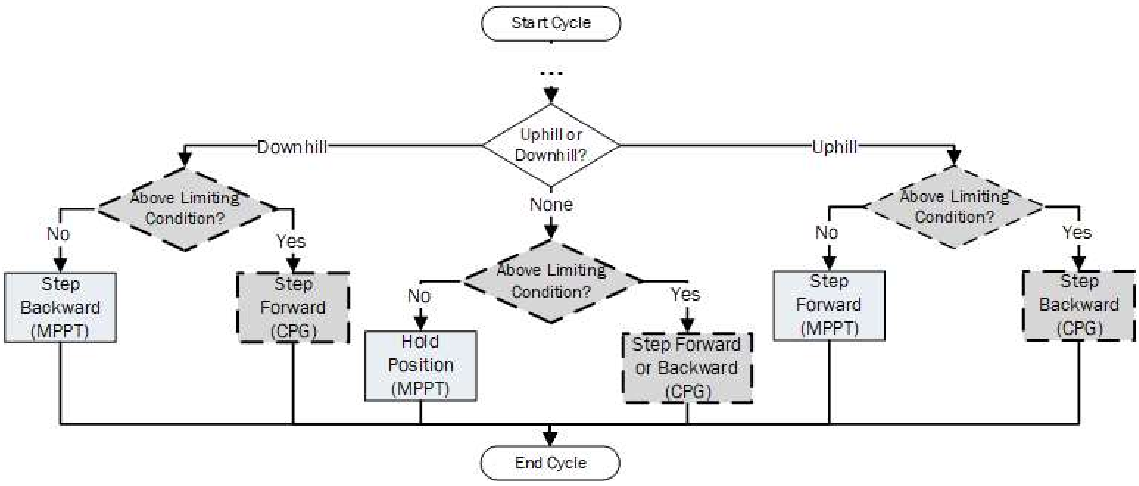

Figure 2.10: *Complement to allow the MPPT to receive an external limit*

As shown in the figure above, the CPG state is operated on the DC-DC conversion stage using the same logic structure applied to the MPPT control. Thus, there is no demand for additional devices for implementation.

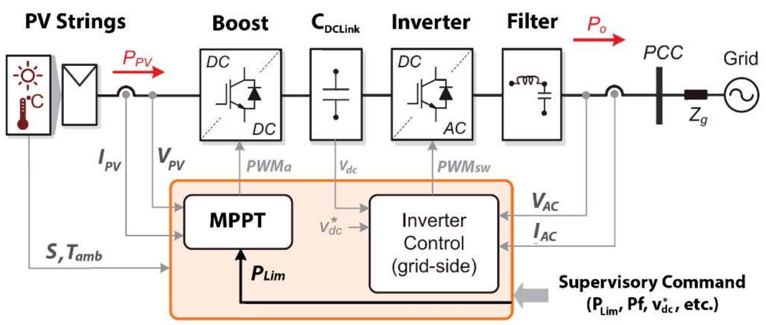

Figure 2.11: *Control diagram of a two-stage single-phase PV system with CPG ability by modifying the MPPT Control [18]*

Then, under normal operation an external condition can set a limit for the Power output for the PV system:

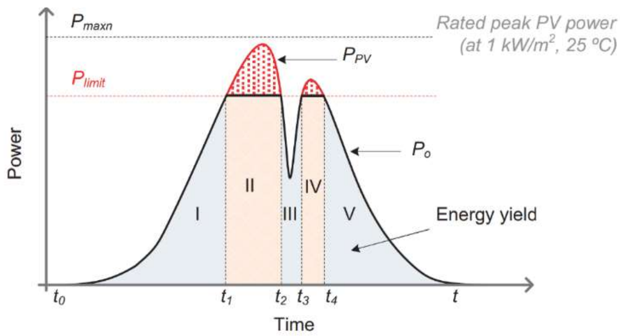

Figure 2.12: *Operation regions for a PV system during a day with MPPT and CPG operations [18]*

2.4 DC-AC Control

In comparison to a DC-DC converter applied on a PV system, the DC-AC main objective is to convert the available DC energy into the grid-friendly, in order to do that the DC-AC Inverter requires guidance for its production output to fit the grid parameters regarding:

- Voltage levels;
- Natural oscillation frequency;
- Phase oscillation.

Additional constraints such as Power Factor, limited harmonics distortion, and a resilient operation under disturbances [20] can also be applied.

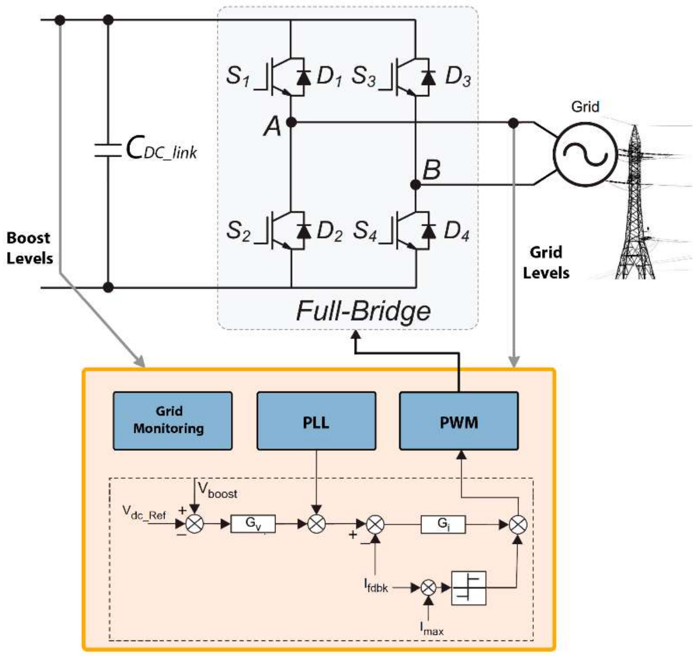

Figure 2.13: *Simplified scheme for DC-AC Control*

Complementary areas of study are set on the DCAC converter: the power switching structure and the control system. For the former, different strategies for modulation, bridge structure and frequency levels can be applied. For the latter, a few crucial subprocesses are indispensable, such as:

- Current control;
- Grid synchronization;
- Switches control.

The rule of the PLL

The aim of the PLL is to bring external information to the system, giving shape and time for the produced AC Output. The basic operation scheme of PLL consists of three block units as shown in Fig. 2.14.

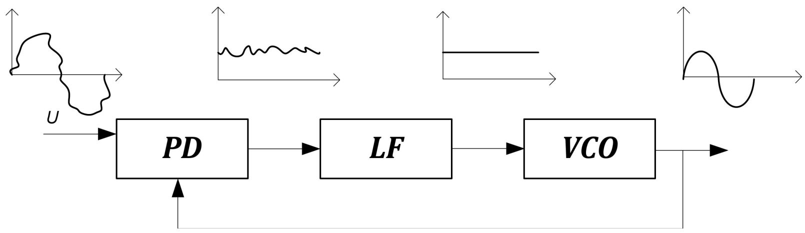

Figure 2.14: *The operation of the PLL*

In short terms, the operation of a PLL consists of the following events:

- The Phase Detector (PD), generates a signal proportional to the phase difference between grid voltage signal and internal oscillator called VCO;
- Using that PD signal, the task of Loop Filter (LF) attenuates the high-frequency components in order to generate trustable values for it;
- Using this reference, the Voltage Controlled Oscillator (VCO) generates a periodic signal, which frequency is guided by a pre-defined basic frequency.

2.4.1 Bridge Structure

In order to create the sinusoidal wave requested by the AC grid, the energy released by the switches while open is controlled using PWM techniques.

By this way, the actual conversion of DC Power input into AC Power output is operated through the semiconductors arranged on structures so-called bridges.

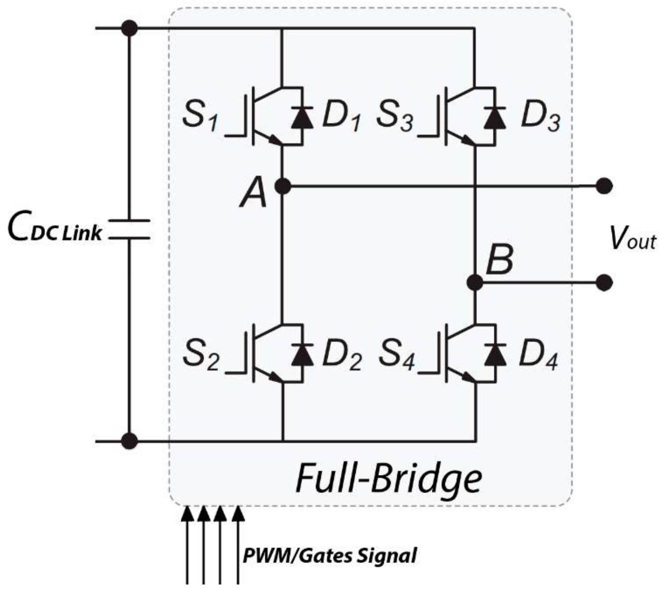

Figure 2.15: *Full Bridge structure of control*

The number of switches determines the current delivered by each one, thus is tightly related to the current and thermal stress caused by the Conduction losses.

Chapter 3

Thermal effect on components reliability

Reliability is defined as “the probability that a system, including all hardware, firmware, and software, will satisfactorily perform the task for which it was designed or intended, for a specified time and in a specified environment” [21].
Due to a high capacity of dealing with high current, IGBTs are widely used in power electronics with a heavy inductive load such as power converters, motor drives, etc.. As addressed before (see 1.1.3) the PV Inverter reliability is considerably limited by the used IGBT modules and their lifetime. The failures are mainly induced by the thermal cycles experienced due to operational use, which causes degradation on the IGBT module package [22].
Some crucial failure mechanisms are the bond wire lift-off and solder delamination [23], and both failures are affected by two different perspectives of thermal stress: high-temperature mean and mismatch between coefficients of the thermal expansion (CTE) of the used packaging materials [22].
Additionally, the packaging degradation forces the IGBT to work even more frequently at high-temperatures, decreasing the safety margin of operation and consequently, their ruggedness [22].

Thermal stress causes

The above-mentioned complex assembly structure of IGBTs leads to different mechanisms of failure [14] mainly due to the necessity of adjacent layers for heat dissipation.

The challenge is to design a match between thermal impedances with a satisfactory dissipation capacity without suffering severely from mechanical dilatation problems caused by mismatch on those parameters. On a continuous search for improvement, an optimum equilibrium between robustness and accessible price is the must. In order to support decisions on the design challenge, a detailed understanding of the common operating conditions is needed, expressing knowledge about both average thermal stress and cyclical stress.

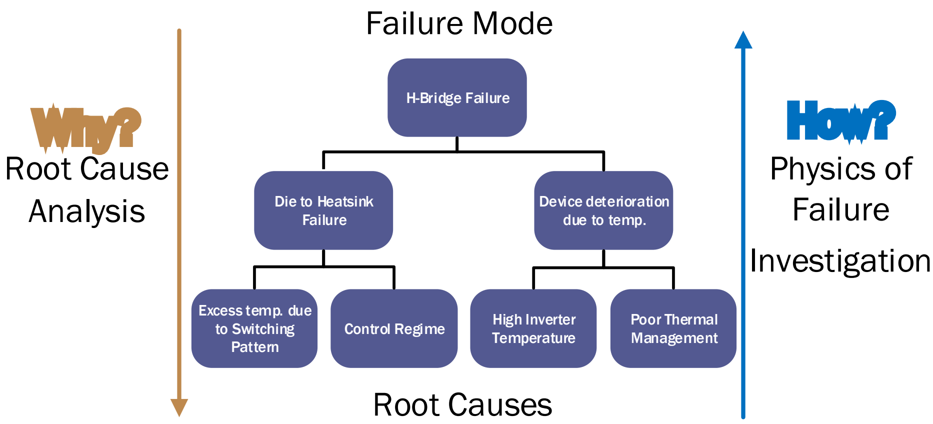

Figure 3.1: *A simplified analysis of root causes and failure mode on IGBTs*

3.1 Thermal energy losses origin

The power loss dissipated in the power device is the main cause of thermal stress. This power loss is due to the voltage drop between its collector-emitter gates during the current conduction:

$$P_{instant.loss} = i_c \cdot v_{ce} \qquad \text{Eq. 1}$$

where i_C is the collector current through the switch and v_{CE} is the instant voltage between the collector and emitter terminals. While the instant energy losses can be expressed on instant values, it can be resumed into 02 different processes: the transitional switching losses and the constant conductions losses.

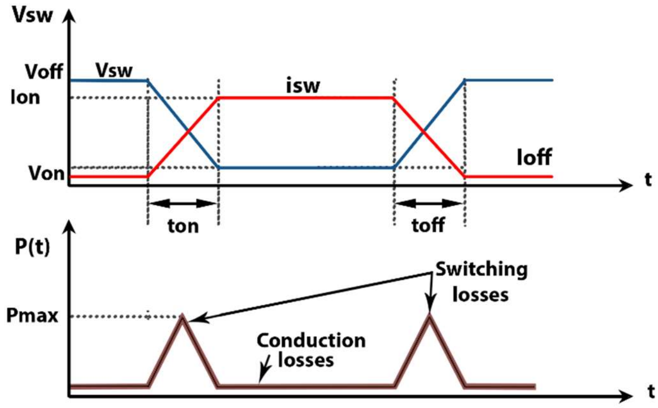

Figure 3.2: *The energy waste on Conduction losses and on switching losses*

Switching losses

When a switch transits from the closed state (conducting or ON state) to the open state (non conducting or OFF state), a time delay is demanded to finish the current flowing through the switch. During this time (t_{ON} or t_{OFF}), a specific voltage together with the remaining current express energy stress through the semiconductor as following:

$$E(t) = \int_0^t P_{instant.loss} \cdot dt = \int_0^t i_c(t) \cdot v_{ce}(t) \cdot dt \qquad \text{Eq. 2}$$

Considering both opening and closing events:

$$E(t) = E_{on} + E_{off} \qquad \text{Eq. 3}$$

Being this relation easily defined that:

$$E_{on}(t) = \int_{t_{on}} i_c(t) \cdot v_{ce}(t) \cdot dt \qquad \text{Eq. 4}$$

and complemented by:

$$E_{off}(t) = \int_{t_{off}} i_c(t) \cdot v_{ce}(t) \cdot dt \qquad \text{Eq. 5}$$

Regarding the freewheeling diode, the main power loss is due to reverse recovery.

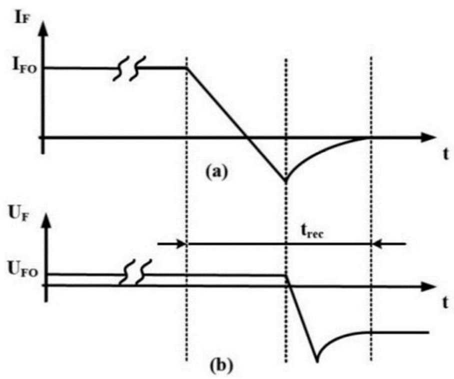

Figure 3.3: *Reverse waveforms of the freewheeling diode: Current (a) and Voltage (b)*

Similar to the switching energy dissipation of the IGBT, the diode recovery energy E_{rec} can be defined as:

$$E_{rec}(t) = \int_{t_{rec}} i_f(t) \cdot v_f(t) \cdot dt \qquad \text{Eq. 6}$$

Variables relevant for this process are:

- The time for each transition that the technology demands;
- The voltage level between the collector and emitter;
- The current conducted immediately before and during the transition;
- The duty cycle of a PWM applied to the switch, as a determinant for the repetition rate of the period's t_{ON} andt_{OFF}.

After all, considering the use of an IGBT for a VSC (Voltage Source Converter) operating a sinusoidal AC output reaches the analytical estimate of the power switching losses [44]:

$$P_{SV} = \frac{6}{\pi} \cdot f_s(E_{ON.IGBT} + E_{OFF.IGBT} + E_{rec.DIODE}).\frac{V_{DC}}{V_{ref}} \cdot \frac{i_L}{i_{ref}} \qquad \text{Eq. 7}$$

Where V_{DC} is the DC link operational voltage, $i_L$is the peak value of the ac line current, V_{ref} is the blocking state voltage of the IGBT occurring before the corresponding commutation and i_{ref} is the on-state current after the commutation.

Conduction losses on the IGBT

The conduction losses can be represented as the product of the instantaneous conducted current $i_C(t)$ and the corresponding collector-emitter voltage $v_{CE}(t)$ [24], thus also determining the power wasted on the process:

$$P_{instant.loss} = P_{cond} = i_c \cdot v_{ce} \qquad \text{Eq. 8}$$

While under control of a PWM signal, a pessimistic estimate can be done proportional to de duty cycle (δ):

$$P_{cond.IGBT} = \delta \cdot i_c \cdot v_{ce} \qquad \text{Eq. 9}$$

On the other hand, during the off state of the IGBT the current flows through the freewheeling diode, determining another power loss:

$$P_{cond.diode} = (1 - \delta) \cdot i_{diode} \cdot v_{diode} \qquad \text{Eq. 10}$$

This close relationship with the duty cycle makes the average power losses directly depending on the modulation function that is used. While analyzing the entire power converter, different publications expressed [25], [26] formulas for reckoning the conduction losses depending on the modulation function are presented (such as $M_{SVM}(\omega t), M_{STM}(\omega t)$, etc.), and can better detail the energy flow during the conduction periods and the total wasted energy.

3.2 Semiconductors and the heat transfer through the dissipation thermic circuit

The energy described, the above-mentioned energy losses on IGBTs, originate in the silicon chips and must be removed from there. For accelerating that, heat sinks are used.

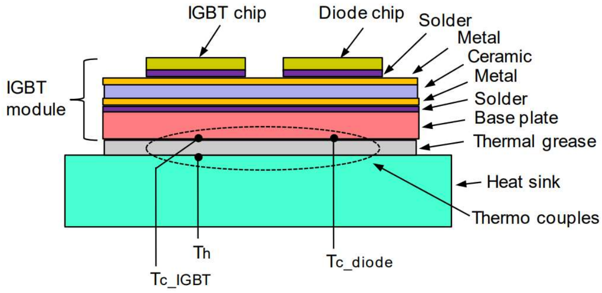

Figure 3.4: *A simplified view of an IGBT assembly*

In order to estimate the energy flow and the temperature on different points of it, a detailed thermal modelling of the entire arrangement (semiconductor and PCB) can be demanded. A practical approach is the use of datasheet manufacturer's data, fitted on a thermic circuit model:

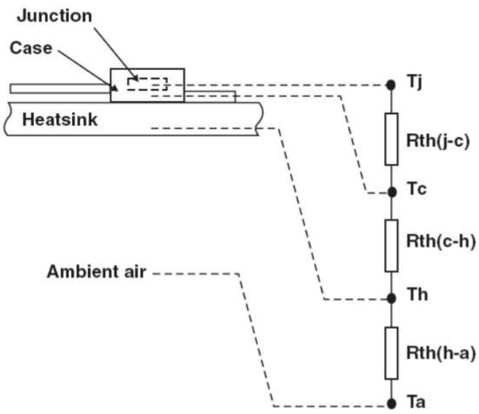

Figure 3.5 *Thermal equivalent resistance scheme [38]*

That makes the general definition [37] of thermal resistance as:

$$R_{th(j-a)} = R_{th(j-c)} + R_{th(c-h)} + R_{th(h-a)} \qquad \text{Eq. 11}$$

And by that, the junction temperature can be expressed by:

$$T_j = P_{loss} \cdot \left(R_{th(j-c)} + R_{th(c-h)} + R_{th(h-a)}\right) + T_a \qquad \text{Eq. 12}$$

3.2.2 LOOK-UP Table based loss modelling for energy dissipation

Most manufacturers turn available information illustrating the energy consumption of their semiconductors. Using this data, interpolation can be conducted on look-up tables, in order to estimate the energy consumption during switching or conduction states.

Among all the possible models and techniques available for predicting and to explain the thermal flow on IGBTs the 1-D models can be shortened to the Cauer Network and the Foster Network.

3.2.3 Thermal Networks

While developing 1-D models, each thermal impedance model is dependent from the geometry and physical properties of the assembly different layers (e.g., IGBT or diode chip, chip solder, substrate, substrate solder, and baseplate):

$$R_{th} = \frac{1}{k} \cdot \frac{d}{A} \qquad \text{Eq. 13}$$

$$C_{th} = c_p \cdot \rho \cdot d \cdot A \qquad \text{Eq. 14}$$

where d is the material thickness, A is the cross-sectional area, k is the thermal conductivity, ρ is the density, and c_p is the specific heat capacity [27] for the material.

The two main models of network used by thermal studies on IGBTs are the Cauer Network and the Foster Network. Nevertheless, on studies about the thermal behavior of IGBTs, the Foster network presents an easier application and is largely used due to more practicality on experimental measurements. The parametrization of the Thermal Impedance (Z_{th}) can be developed with a known number of thermal branches (n) in the RC network, together with information about the R_{th} and C_{th} [28]:

$$Z_{th} = \sum_{m=1}^{n} R_{th\_m} \left(1 - e^{-\frac{t}{R_{th\_m} \cdot C_{th\_m}}}\right) \qquad \text{Eq. 15}$$

The main disadvantage of this model is that it does not recreate the physical nodes along the heat transfer paths, representing only the input and output ports of the modelled thermal equivalent. Therefore, it is not efficient in understanding thoroughly the behavior of the device, but only an approximate thermal response for a certain heat flux input. [29]

For the execution, the temperature rise ΔT should be determined by fixing the case at a constant temperature T_{ref}, and following evaluation of the changes of T_J versus time t should be carried out [15]. Therefore, for the following steps, the definition of transient thermal impedance used should be:

$$Z_{th} = \frac{T_j(t) - T_{ref}}{P} \qquad \text{Eq. 16}$$

If the thermal system can be assumed to be a linear and time-invariant (LTI) system, then obviously the transient thermal impedance corresponds in system theory to the step response of the system with zero initial condition, and therefore it contains the full thermal description of the system [15]. The transient junction temperature under any power dissipation profile $P(t)$ will be able to be predicted by applying the following equation [24]:

$$T_j = T_0 + \int P(t) \cdot Z_{th} \cdot (t - t_0) \cdot d\tau \qquad \text{Eq. 17}$$

Where T_0 is the initial temperature and $d\tau$ is the time derivative of the thermal impedance, which corresponds to the thermal impulse response of the system. This method treats the thermal problem as a system with the power loss as input and the temperature rise as output. It focuses only on the thermal transient behavior of the system thus the physical structure is not concerned about. Because of the advantages mentioned above, the manufacturer of IGBT module usually provides the transient thermal impedance curve of the junction to case Z_{cj} to the users to carry out thermal analysis and a typical thermal impedance curve for IGBT module is shown in Fig. 3.8.

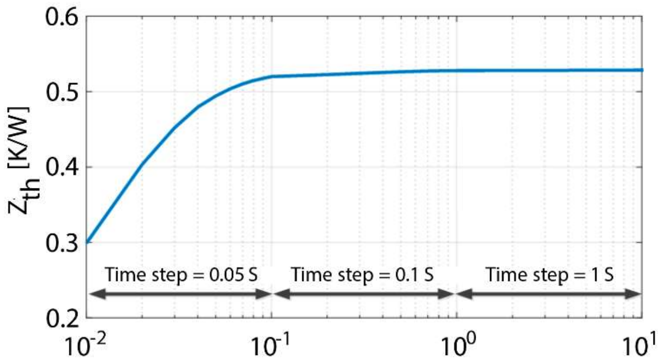

Figure 3.6: *Typical transient thermal impedance curve*

3.4 High-temperature thermal stress and High variation cycles

Different causes for the overheating on PV Inverters are possible. Among them, misfunction or bad design at the fan system, air filters blocked of even load parameters are common ones. Although is possible that a high ambient temperature is the only inevitable cause, bringing the question of the mission profile consequences to the heat cycle life of the component.

'Thermal cycling'

There is a large-area of soldering joint between the ceramic insulator and the base plate, which accomplishes a good thermal conductivity. Temperature oscillations of that base plate can be described as a type of 'thermal cycling'.

While the expansion coefficients for copper and solder material match reasonably well, the ceramic material differs by a factor of 2 or more. When expanding its dimensions, mechanical stress to the soldering joint is expected, leading to accelerated aging. Finally, the thermal resistance increases, the temperature oscillations become even larger, and the device fails.

Material	Expansion Coefficient ($\mathbf{10^{-6}/K}$)
Silicon	4.1
Copper	17
Aluminum	24
Molybdenum	5
Solder	15-30
Ceramic	5-9

Table 3: *Expansion coefficients for different materials (resumed) [42]*

3.4.1 Temperature cycles and their consequences for thermal stress

The "Power cycle life" can be predicted using the power cycle curve which is the curve of the number of cycles as a function of temperature swing, and different parameters such as duration of the thermal pulses can play a significant role on the question.

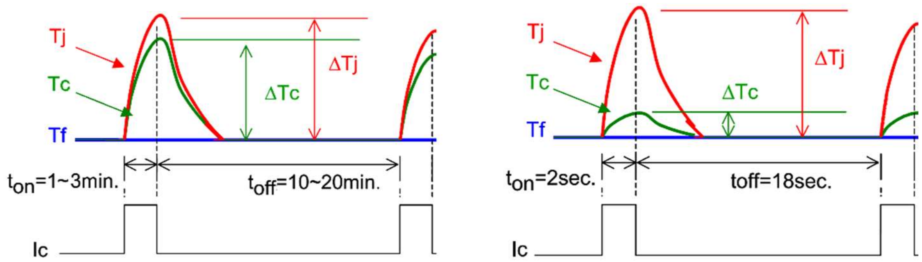

Figure 3.7: *Short pulse and long pulse patterns of the current flow of* ΔT_J *power cycle and temperature change [37]*

The proportion between these different situations is better expressed by Equation 18, where is represented by the parameter t_{ON}. Therefore, long cycles can also be a source of accumulated damage due to a thermal variation on the case temperature.

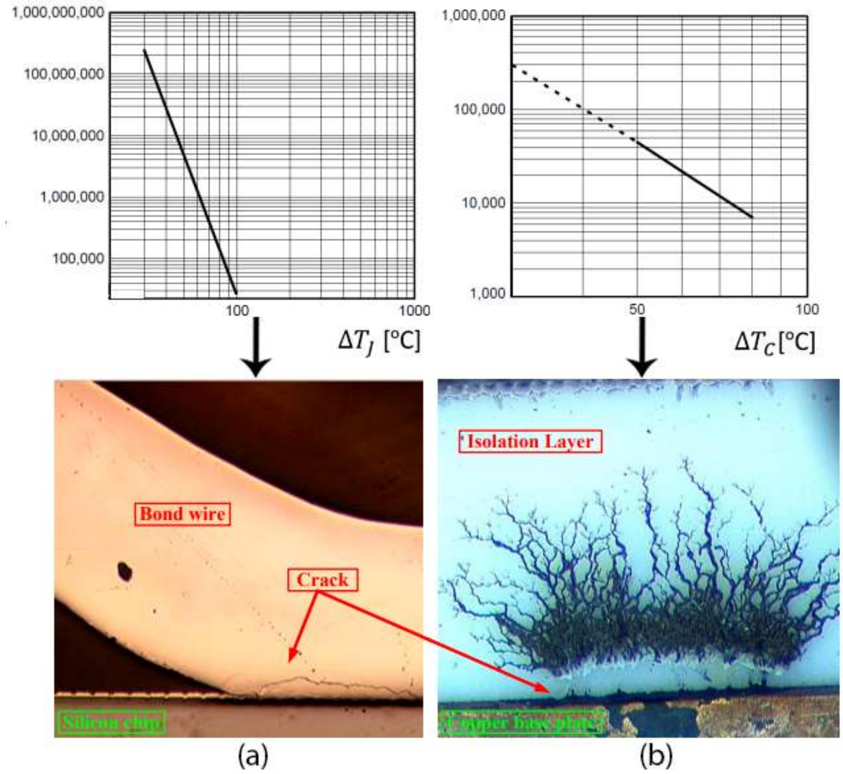

Figure 3.8: *(a) Junction temperature Swing and the failure caused as a crack at the interface between the silicon chip and the bond wire and (b) Case temperature swing causing a Thermal cycle power cycle causing deterioration of the soldered area between the DCB insolation layer and the base plate [36]*

3.5 Reliability evaluation techniques and procedures

Some facts have a determinant influence on the quest for the reliability of switches, being them IGBTs or MOSFETs [30]:

- Periodic cycles alternating between the ON state (high current / low voltage) and OFF state (low current / high voltage) have clear significance;
- During switching, the switch is briefly (for a fraction of seconds) subjected to a transition during which it experiences very high power (high current / high voltage), thus producing heat added to the produced during the conducting state;
- High power generates lots of heat, and in case of having an improper heat-sink or heat management system, the degradation of the switch lifetime and an eventual catastrophic failure are inevitable.

Following these facts, the Power cycling capability of power semiconductor modules is mostly modeled by a Coffin-Manson law, i.e. the number of cycles to failure (N_f) is assumed to be proportional to swing of junction temperature in a form of $\Delta T_J{}^{-\alpha}$ [31]. The relation between the variables is expected to be a straight line when plotting $Log(N_f)$ over $Log(\Delta T_J)$, and can be mathematically expressed by [34]:

$$N_f = A \cdot \left(\Delta T_J\right)^{\alpha} \times (ar)^{\beta_1 \Delta T_J + \beta_0} \times \left[\frac{C + (t_{on})^{\gamma}}{C + 1}\right] \times exp\left(\frac{E_a}{k_b \cdot T_{jm}}\right) \times f_d \qquad \text{Eq. 18}$$

where N_f is the number of cycles expected to be demanded from the component to cause a failure [34], the mean junction temperature is expressed as T_{jm}, the cycle amplitude as ΔT_J , and the duration period of the cycle as t_{ON}. All other parameters have to be predefined in order to proceed with the assessment.

Finally, for the planned assessment, the Lifetime Consumption (LC) is then calculated by using the Miner's rule [32] as:

$$LC = \sum_i \frac{n_i}{N_{fi}} \qquad \text{Eq. 19}$$

This is also called as Accumulated Damage (AD), where the LC is considered broadly a clear measure of the projected stated use of electronic components.

3.5.1 Cycle Counting applied for Lifetime estimation

In order to predict the lifetime of a component that will be subject to a variable load, a cycle counting method is required. The major advantage of doing so is to reduce the complex record into a resumed list of events useful for comparison to constant amplitude test data [35].
The rainflow cycle counting method is one of the most popular cycle counting techniques used in fatigue analysis [32]. For that purpose, only the extreme points are needed and other points in the stress load profile need to be discarded.

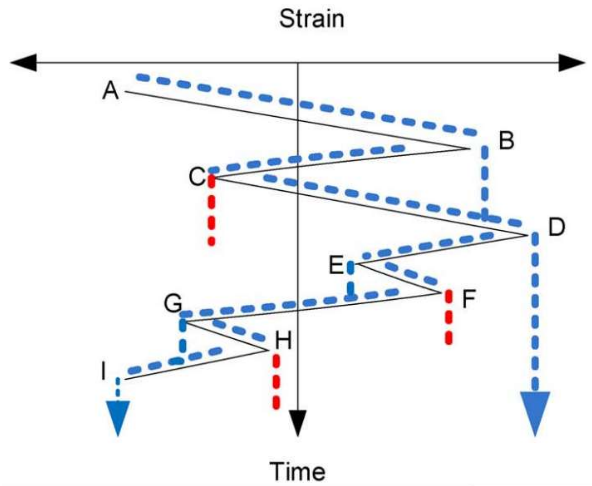

Figure 3.9: *Stress-strain plot*

The application of a rainflow algorithm to semiconductor reliability studies is a common ground due to the close relationship between stress and strain on thermal expansion of power modules layers. On this matter, the strain is the ratio of change in length of a material to its actual length as a result of a change in temperature (ΔT_J) [33].

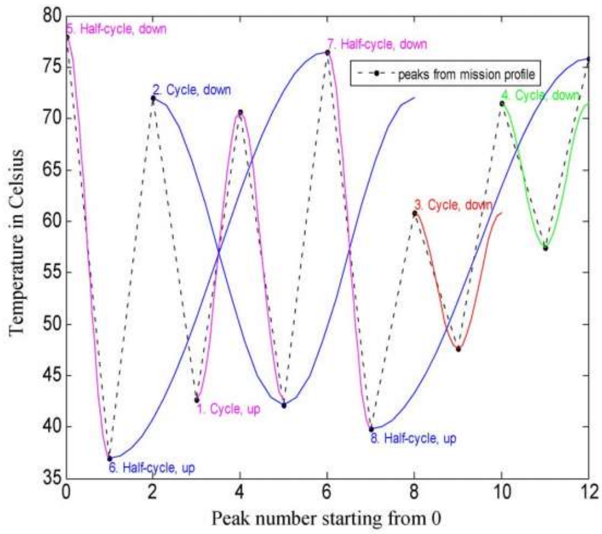

Figure 3.10: *Rainflow algorithm tracking a signal (dashed line)*

Complementing the Equation 17, the algorithm should supply information about the cycles on their range, mean value and duration. Nevertheless, more complex analysis can demand more data.

Count	Range	Mean	Start	End
1	3	21	0	1
1	4	23	1	2
1	4	22	2	3
1	8	20	3	4
1	9	20	4	5
1	8	19	5	6

Table 4: *Basic Information from a rainflow counter algorithm*

Together with the relation expressed by Equation 18, this data can express the accumulated damage produced by one cycle experienced by the component. Is expected that when the cycles measured correspond to damage equals to 1, failure is expected.

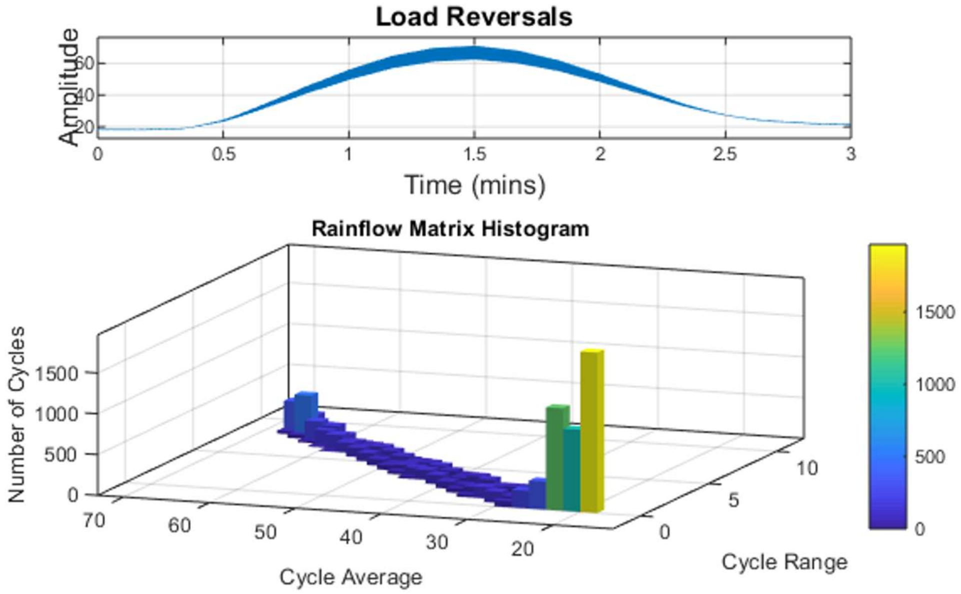

Figure 3.11: *Rainflow General histogram result*

3.5.2 Workflow for reliability analysis

The work developed through the Reliability perspective of different control strategies considers:

- Realistic data from a PV system together with Solar Irradiation and Ambient temperature from a site measurement used as Input for a computational model;
- Simulation of different strategies with different strategic parameters, generating different scenarios to be analyzed;
- Analysis of the thermal cycles and their effect on Lifetime Consumption;
- Comparison and Analysis of the cost in energy production demanded by each increment on the lifetime increment caused by each strategy.

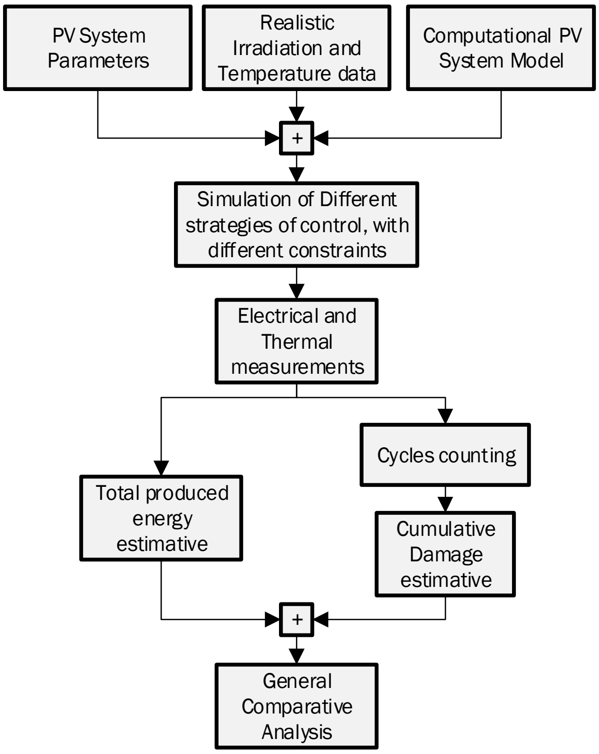

Figure 3.12: *Workflow developed*

Chapter 4

Reliability Assessment and Energy Production

4.1 Simulations and comparisons

A PLECS model of a PV system was used to produce the data for the presented studies. As mentioned before (*see 1.3 Project Limitations*), the studies considered a monophasic PV system, with 02 strings of 08 panels, with 200Wp each. The total of 3200Wp is converted by a two-stage PV Inverter, with a Full Bridge configuration on the DCAC converter, also set with the configuration described in Table 5:

PV rated power	3.2 kW
Boost converter inductor	$L = 2\ \mathrm{mH}$
PV-side Capacitor	$C_{\mathrm{PV}} = 22\ \mu\mathrm{F}$
DC-Link Capacitor	$C_{\mathrm{DC}} = 10.000\ \mu\mathrm{F}$
RL-Filter	$L = 5\ \mathrm{mH}$, $R = 0.15\Omega$
Switching Frequency	Boost Converter: $f_{\mathrm{b}} = 20\ \mathrm{kHz}$, Full-bridge inverter: $f_{\mathrm{inv}} = 20\ \mathrm{kHz}$
DC-link voltage	$v_{\mathrm{dc}}^{*} = 400\ \mathrm{V}$
Grid nominal voltage (RMS)	$V_{\mathrm{g}} = 230\ \mathrm{V}$
Grid nominal frequency	$\omega_0 = (2\pi \times 50)\ \mathrm{rad/s}$
MPPT algorithm sampling rate	$100\ Hz$
MPPT perturbation step size	$v_{\mathrm{step}} = 1\ \mathrm{V}$

Table 5: *Parameters of the Two-Stage Single-Phase PV System simulated*

The principal mission Profile used to stress the model was conceived with variable input and considers:

- Data for a specific day in Spain, considering smooth and cloudless increments on the Ambient temperature and Solar irradiation;
- A downscale proportional reduction an 18 hours period to 180 seconds, assuring a simulation compatible with the steady state of every temperature level;
- The Heat sink was set for the Junction Temperature to achieve around $100\ ℃$ at $25℃$ and $1000\ W/m^2$;

The following data for the mission profile was used:

DATE	T_{amb} (℃)	SOL. IRRAD (W/m^2)
2016-07-01T05:00:00Z	17.9	0.65
2016-07-01T06:00:00Z	18.6	31.68
2016-07-01T07:00:00Z	20.2	157.02
2016-07-01T08:00:00Z	22.5	338.51
2016-07-01T09:00:00Z	24.8	510.87
2016-07-01T10:00:00Z	26.5	660.76
2016-07-01T11:00:00Z	27.7	777.09
2016-07-01T12:00:00Z	28.7	841.78
2016-07-01T13:00:00Z	29.3	855.78
2016-07-01T14:00:00Z	29.6	809.37
2016-07-01T15:00:00Z	29.5	713.33
2016-07-01T16:00:00Z	29.2	571.49
2016-07-01T17:00:00Z	28.6	403.27
2016-07-01T18:00:00Z	27.6	221.73
2016-07-01T19:00:00Z	26.0	70.16
2016-07-01T20:00:00Z	23.4	4.91
2016-07-01T21:00:00Z	21.9	0.0005

Table 6: *The Mission Profile for a day in Spain [40]*

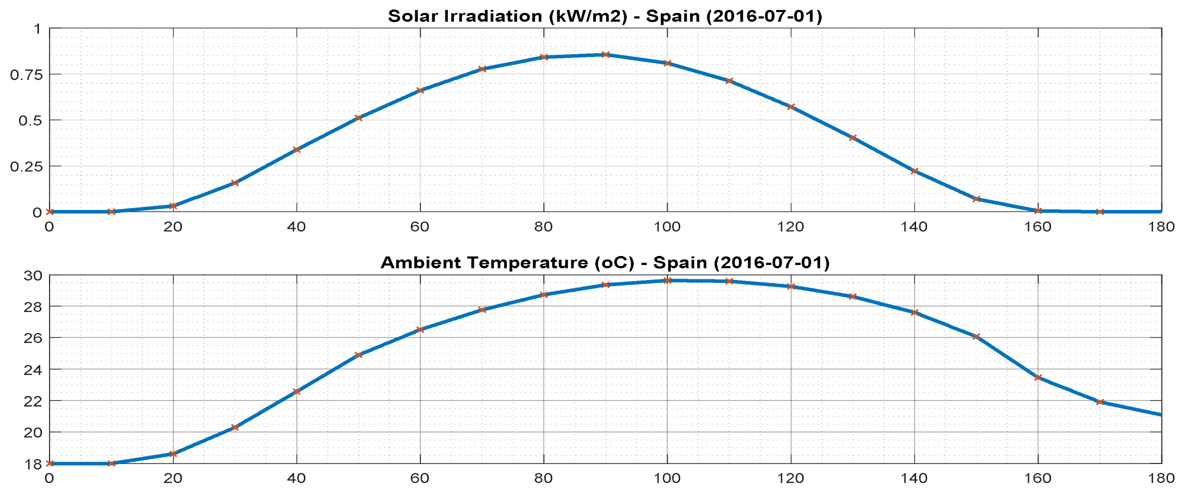

Figure 4.1: *The Ambient Temperature and the Solar Irradiation profiles, plotted in seconds*

The following scenarios were chosen to explore the strategies impact on reliability and energy production:

Flexible MPPT	
Fixed parameter:	Scenario 1 - $P_{lim} = 75\%$
Maximum power: 3200Wp	Scenario 2 - $P_{lim} = 67.5\%$
	Scenario 3 - $P_{lim} = 60\%$
Smart Derating Control	
Fixed parameters:	Scenario 1 - $Tref = 26℃$
Shutdown Power: 1325W	Scenario 2 - $Tref = 24℃$
Shutdown Temp.: 60℃	Scenario 3 - $Tref = 20℃$
Active Junction Temperature Control	
No fixed parameters	Scenario 1 - $T_{J\_Max} = 65℃$
	Scenario 2 - $T_{J\_Max} = 60℃$
	Scenario 3 - $T_{J\_Max} = 55℃$
	Scenario 4 - $T_{J\_Max} = 45℃$

Table 7: *The studied scenarios for each Control Strategy*

For the final section of the model used for data creation, an IGBT was selected for the Full-bridge inverter. The model selected was the SGP30N60 due to its power capacity compatible with the PV array, with its own thermal profile fitted to the Infineon SGP30N60 Datasheet. Finally, a simplified dissipation thermal circuit representing the Heatsink operation was defined as with a thermal resistance of 1.5 $℃/W$, balanced by the same ambient temperature input applied to the PV panels subsystem.

4.2 CPG and Strategies studied for lifetime improvement

In order to observe the impact of control strategies and study the Lifetime improvements of PV inverters, the reliability of IGBTs is addressed regarding time for fail and lifetime consumption.
A simple observation of Equations 18 and 19 can find a direct dependence between the number of cycles expected to happen before a failure of the component and three specific variables:

- The mean junction temperature when the thermal cycles happen (T_{J_mean});
- The range of the thermal cycles achieved (ΔT_J);
- The speed of each cycle (t_{ON}).

In truth, the speed of each cycle is heavily influenced by the switching frequency applied to each power switch and the modulation technique, especially regarding the low-amplitude cycles [43]. But the mean temperature and the range of the thermal cycles are tightly influenced by the power output supplied the PV Inverter.
That justifies Power output control as a logical approach to influence the lifetime of the switches, and different strategies are available for implementing the CPG. Their impact on energy production and accumulated damage estimated are presented as it follows.

Scenarios Limitation

The simulations developed considered only a local set for the limitation parameters, being them supposedly defined after studies around the Mission profiles for the specific site.
Regarding the analysis, they considered the ambient temperature to which the PV panels are exposed is the same those used for the heat sink reference.

4.3 Control strategies comparison and analysis

4.3.1 Flexible MPPT

When defined as a local and steady strategy, this strategy demands analysis and precise estimates about the general mission profile expected for the PV Inverter. For implementing it, the integration of energy storage systems or controllable loads can be applied [39], but the incrementation of the MPPT algorithm is the simplest one.

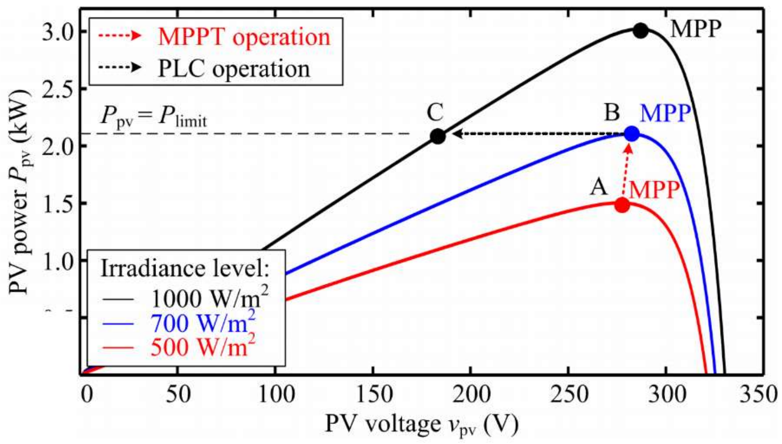

Figure 4.2: *Flexible MPPT avoids the MPP at 1000W/m2 level, holding the produced power at the P_{Lim}[39]*

The clear orientation applied to this strategy is:

- If the power production is above the reference (P_{lim}), then produce less;
- If the power production is below the reference, then operate under MPPT.

For a field application, a hand of scenarios should be tested, defining through simulations or even experimental indirect measurements the Junction temperature applicable to each scenario.

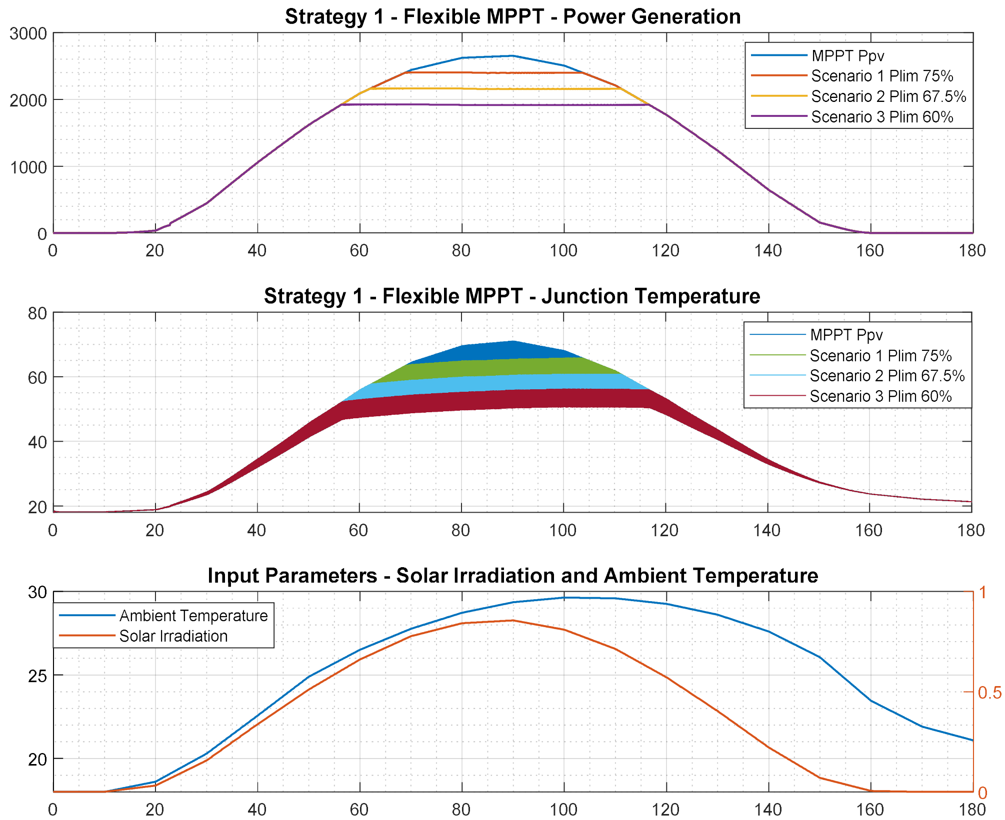

Figure 4.3: *The operation of the Flexible MPPT*

While the Junction temperature is used as a parameter, a goal matching the reliability view as lifetime and energy production sets a power limit at which a Junction temperature is expected to be a limit.

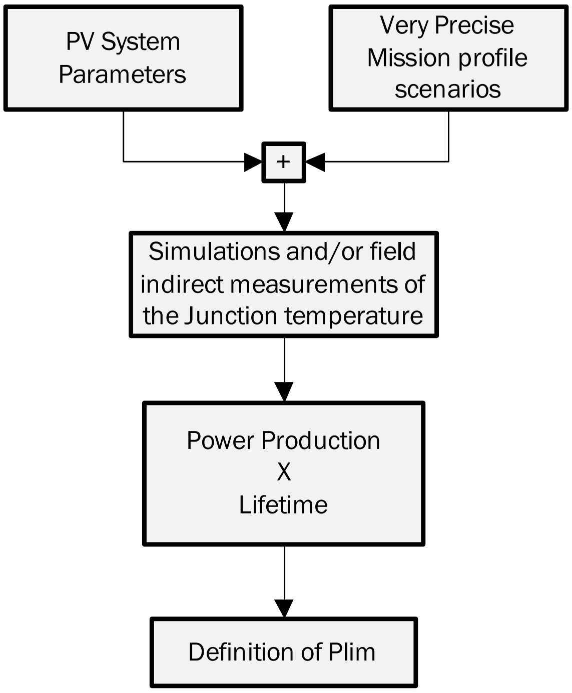

Figure 4.4: *A simplified scheme for the process to define the Power Limit for a flexible MPPT*

The process of parameter definition can be operated locally or under external super visioning. On the second case, different profiles can be adopted, but on the former the better is the data about the mission profile, the better tuned is the parameter.
In any case, the evaluation process produces a referential power Limit for guiding the power curtailment. At a simple simulation, the total output capacity can serve as a reference to the limitation, defining a reference of Power limit being a fraction of the maximum peak power possible:

4.3.2 Smart Derating Control

This strategy requires a good understanding of the general mission profile expected for the PV Inverter, especially from the Ambient temperature perspective.

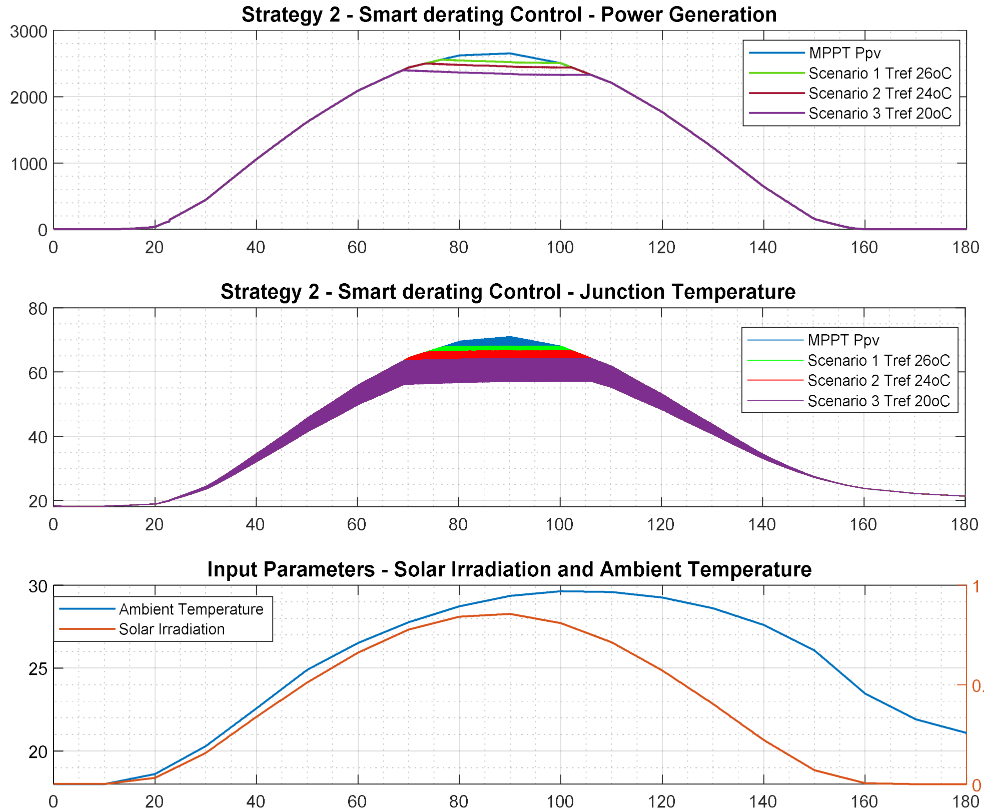

Figure 4.5: *The operation of the Smart derating Control*

Using 2 main temperature parameters (Ambient or room Temperature and Maximum Operational Temperature), this strategy presents a flexible approach to the CPG.

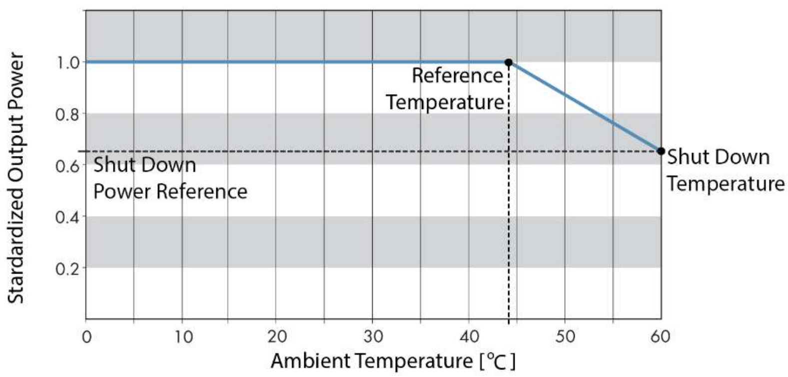

Figure 4.6: *Smart derating triggered by the ambient temperature increment derating from 100% till the shut-down temperature*

This flexibility brings the possibility of imposing a higher limit for the PV Inverter while on the CPG state if the ambient temperature is low compared to the critic levels, therefore producing more energy while under a small temperature uprising.

Regarding Lifetime consumption, the capacity to adapt the power limitation to possible heavy variations on the room temperature promises good results, due to a tight connection between that one and the Junction Temperature.
Therefore, while accepting more flexibility on the room temperature, the junction temperature becomes more dependent on the heatsink thermal dissipation capacity and speed. If this parameter is known and fierce enough, a smart arrangement promises profitable results.

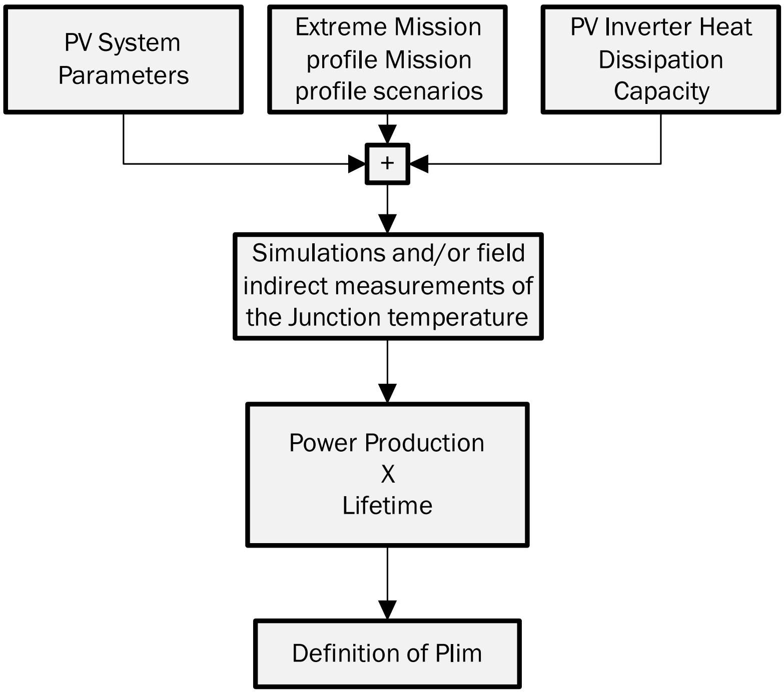

Figure 4.7: *A simplified scheme for the process to define the configure references for the Smart derating control*

For a fine tune, this process demands previous clear information about the scenarios when the Ambient temperature will be higher (thus increasing the Junction temperature) simultaneously with high irradiation periods. On those scenarios, the cumulative heat of the ambient would be incremented by the extra power generated at the IGBT, accelerating the accumulated damage and leading the PV Inverter to eventual failure.
One final observation exposes that the Smart derating control operates an Ambient dependent version of the locally predefined Flexible MPPT, and by that an even more flexible solution.

4.3.3 Active Junction Temperature Control

Despite the many problems in the existing methods for real applications, smoothing the junction temperature fluctuation can significantly improve the life expectancy of an IGBT [45]. While different techniques can be applied to implement this control, it always demands some level data processing and sometimes precise measuring for online implementation [45].

Regarding the mission profile expected for the PV Inverter, the extreme limits can be relevant for the feasibility of this control. At this strategy, a careful adoption of parameters should consider that in order to implement it, not too low or impracticable Junction temperature goals should be set.

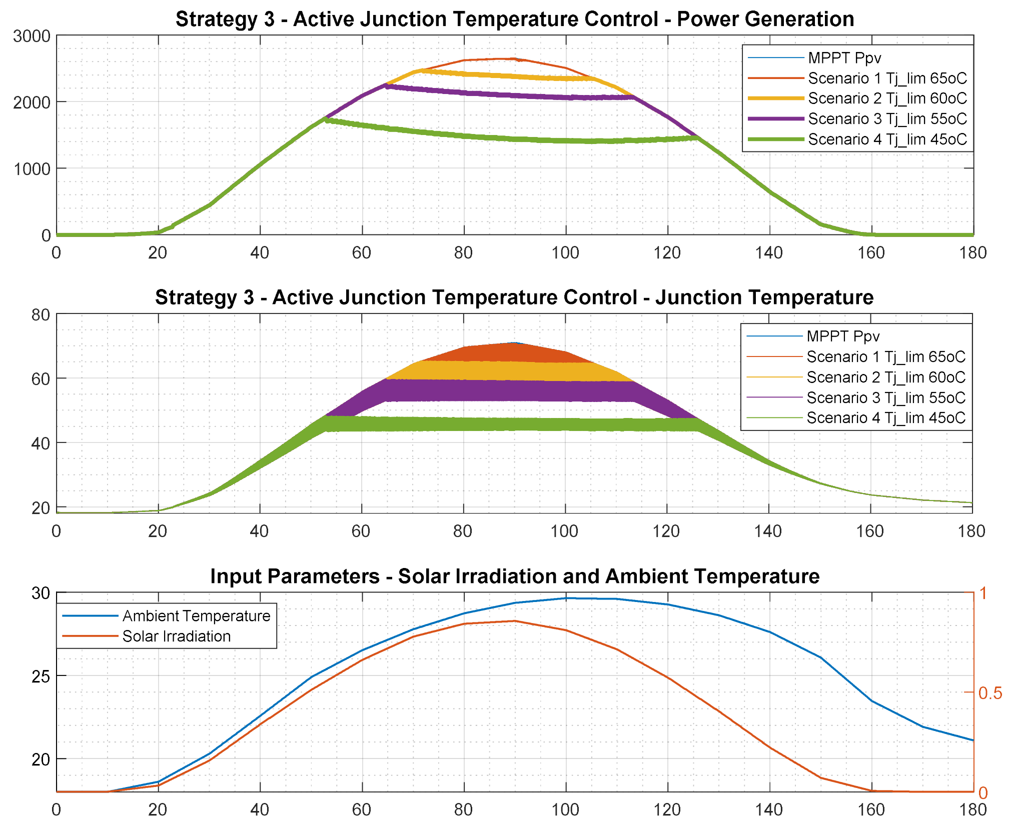

Figure 4.8: *The operation of the Active Junction Temperature Control*

Another indirect consequence is that on this strategy the time demanded by the thermal dissipation circuit of the heatsink plays a relevant role, limiting the speed for the control response while tracking its target.

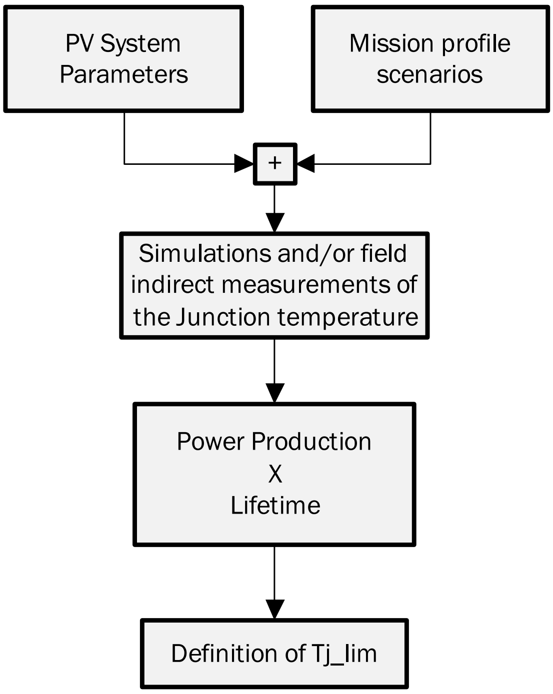

Figure 4.9: *A simplified scheme for the process to define the reference of maximum Junction Temperature*

4.4 Strategies Comparison and Analysis

4.4.1 Energy Production perspective

All the control strategies defined to improve the reliability are realized moving the operating point of the PV Inverter to outside the MPP, thus the inevitable first conclusion is the inevitable curtailment of the energy production.

Even though the subject pursued is a reliability increment for the switches and the inverter, if the energy production is the original motivation of the system existence for sure cutting the production becomes a negative aspect in any scenario.

Still analyzing the local inverter reliability aspect, the first strategy (Flexible MPPT) studied brings a sense of control of this parameter, defining on the calculations a clear and oriented selection for the energy flow limitation.

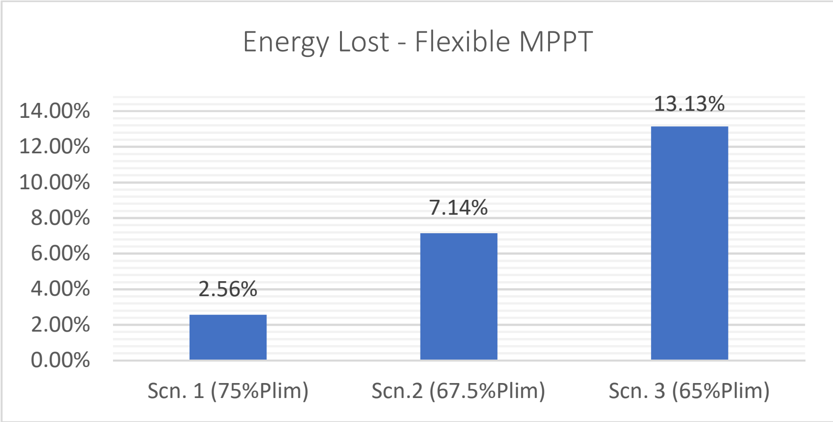

Figure 4.10: *Energy lost compared to the MPPT production*

The 03 scenarios were analyzed referentially to the installed capacity, and for sure they show how aggressive can be the power curtailment.
While the MPPT considered an energy production of 206.615J for the simulated period (or 21.45kWh for a proportional 18hour excursion), a reduction of 13.57% on the energy production would be very costly for the investment balance, increasing significantly the return of the initial investments.

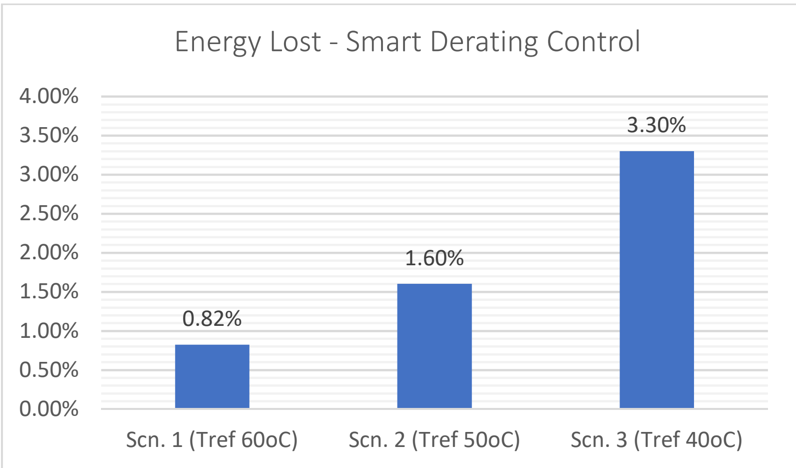

Figure 4.11: *Energy lost compared to the MPPT production*

On the opposite direction, the scenarios tested for Smart derating Control expressed a less aggressive curtailment despite the significant decrement on the Reference Temperature. That is for sure a result of the proportional derate that is effective after the Ambient Temperature crosses the reference, but still at a very small level.
But regarding the extraction of the maximum energy available, the strategy that shows more flexibility to different profiles of Solar

Irradiation is the third strategy studied, the Active Junction Temperature Control.

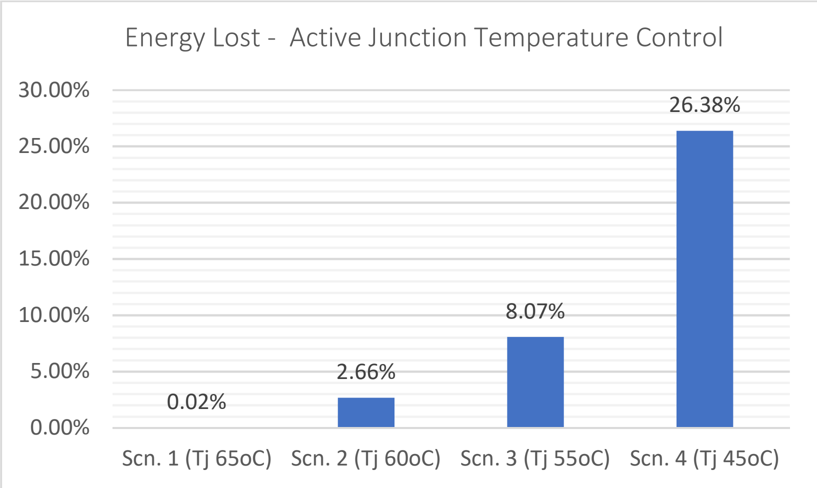

Figure 4.12: *Energy lost compared to the MPPT production*

This strategy expressed a variable capacity to reduce the energy production, and a goal for Junction Temperature for reasonable variable mission profiles.
Considering that the mean junction temperature during the thermal cycles is a crucial parameter for the following definitions around Lifetime Consumption, this strategy can be useful if well-tuned.

4.4.2 Thermal Cycles perspective and performance

As mentioned before, the accumulated damage to the IGBT is tightly related to 03 major parameters exposed in Equation 18 and Equation 19:

- ΔT_J as each thermal cycle range;
- T_{J_mean} as the mean temperature during each thermal cycle;
- t_{ON} as the period of duration relative to each cycle.

While the t_{ON} is related to the modulation technique applied and the T_{J_mean} is heavily dependent from the ambient temperature, possible variations on ΔT_J can be the target to influence.

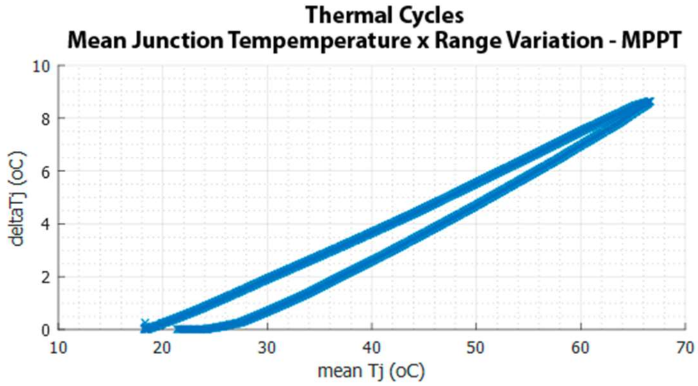

Figure 4.13: *The relation between the higher range cycles and the mean temperature on thermal cycles*

Additionally, the positive slope of a simple scatter plot of the thermal cycles marks the trend on the relation between these two parameters. Therefore, for strategies capable of bringing down the mean Junction temperature, also the average range of the thermal cycles should decrease in a cumulative influence on Lifetime Consumption.

While observing this parameter, if a cycle counting algorithm is applied becomes possible to observe the range of the cycles arranged on values grouped from those smaller than 1℃, and then those between 1 and 1.5℃, and those between 1.5 and 2℃, and so on.

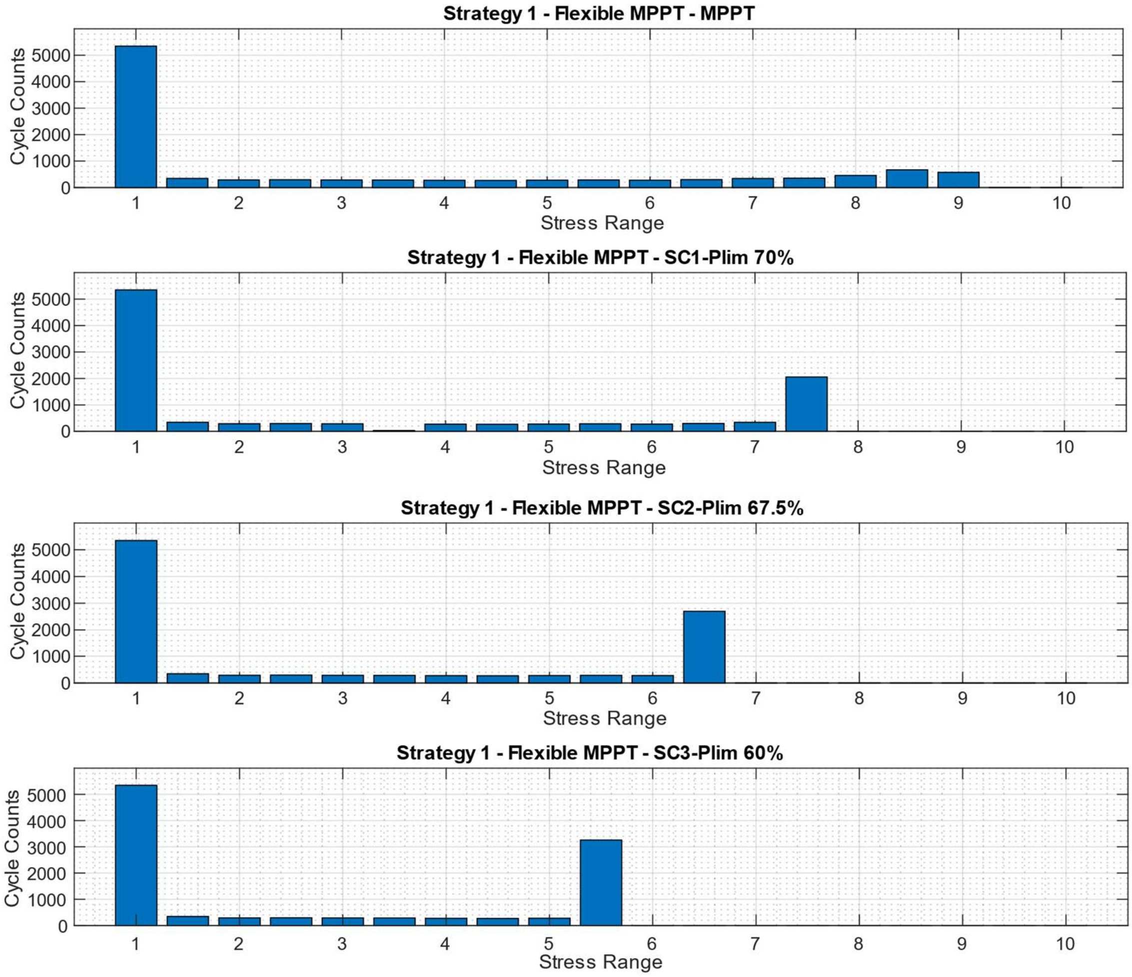

Figure 4.14: *The influence of the Flexible MPPT on the thermal cycles*

The effectivity observed when Strategy 1 is applied became so justified observing this perspective of the cycle's temperature range. A clear impact of the power curtailment is exposed to the limitation observed between the MPPT simulation and Scenario 1, while the 8 to 9℃ cycles are eliminated. Moreover, when the limitation parameter for this strategy is more aggressive, Scenarios 2 and 3 reduce even more the amount of higher cycles and eliminate the 8℃ and 7℃ thermal cycles.
A similar effect of eliminating the higher thermal cycles was observed on the Smart derating Control.

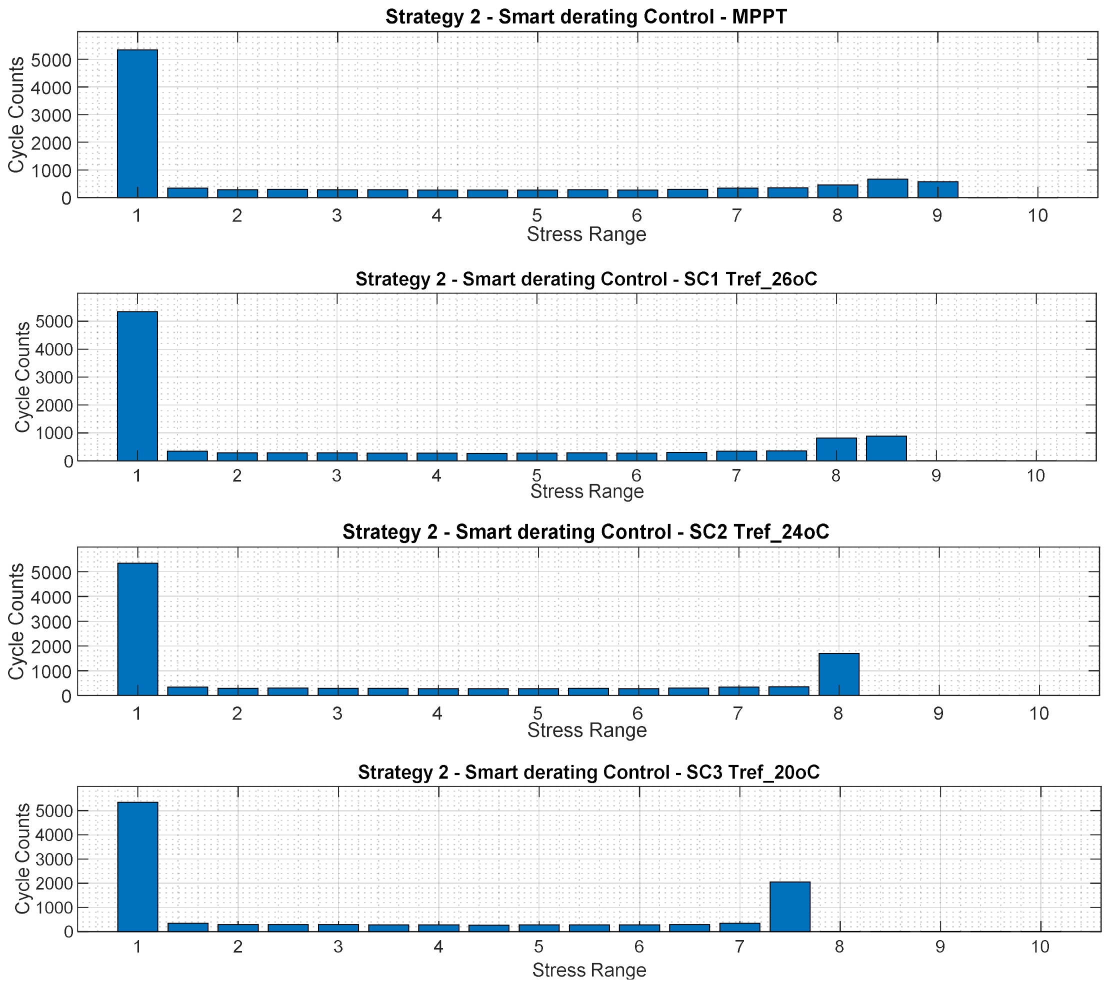

Figure 4.15: *The influence of the Smart derating Control on the thermal cycles*

The data exposed by the Strategy 2 showed that even its first scenario was capable of interfering on the 9℃ range cycles, though the more aggressive derating parameters (Scenarios 2 and 3) achieve much better performance on absolute values.

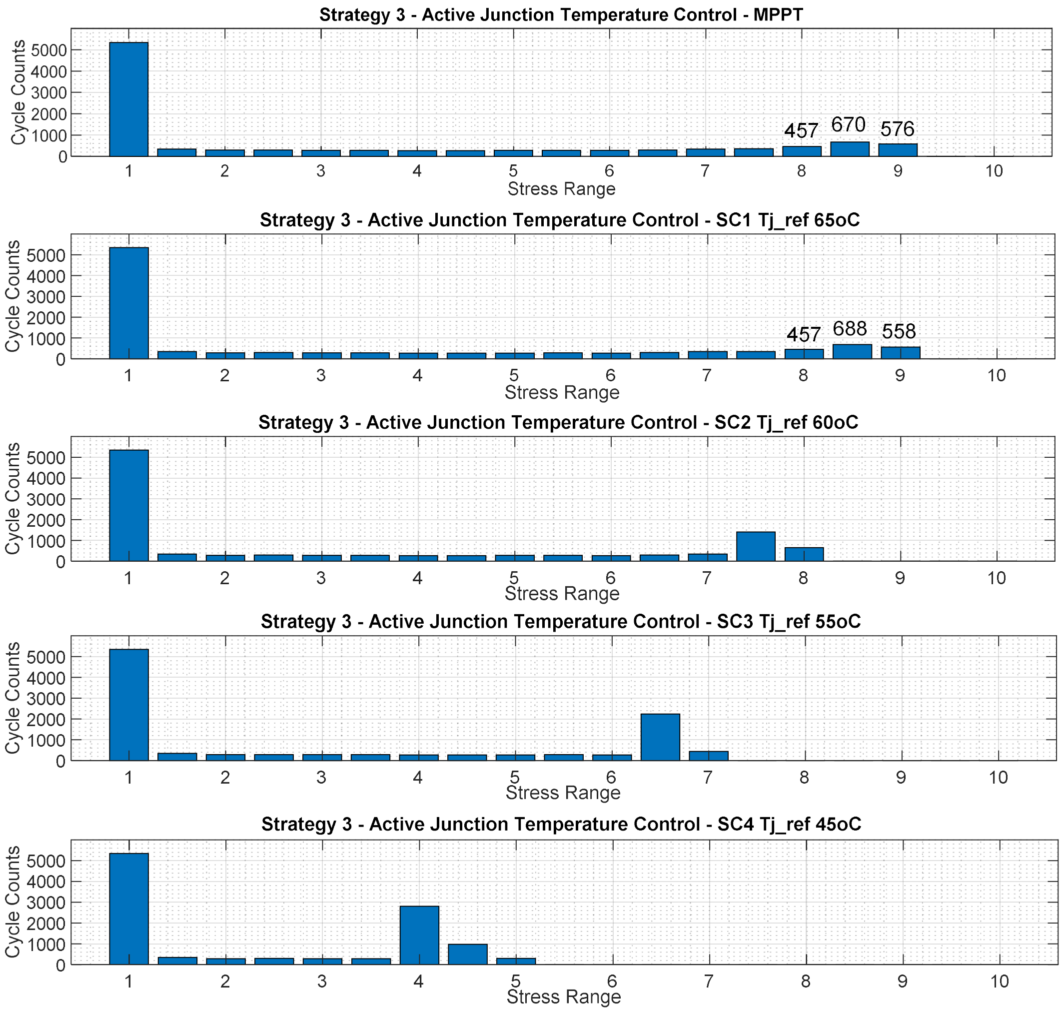

Figure 4.16: *The influence of the Active Junction Temperature Control on the thermal cycles*

The third strategy studied showed an efficient and strong capacity to influence the range of the thermal cycles experienced by the IGBT. While the maximum level observed value during MPPT at the Junction temperature was around 71℃, the control operating at 65℃ seems to marginally perturb the range of the cycles.

On that case, any changes on the lifetime could probably be a consequence of changes on the mean junction temperature during the thermal cycles, regardless of the range of them.

Still regarding the third strategy, is relevant to notice how much can be the range of thermal cycles be depleted, as seen on the performance of the extreme fourth scenario ($T_{J\_ref} = 45℃$). Despite a possibly expensive cost of higher depletion on the produced energy, the capacity of this strategy to directly use the thermal junction as a parameter opens possibilities for complementary different approaches.

4.4.3 Lifetime Consumption perspective

The simulated data showed a total Lifetime Consumption of 1.4272E-12 at an absolute value and MPPT control. Is expected from all the strategies a capacity decrement this value, representing a reduction on the accumulated damage that would be proportional on a real-life daily excursion.

This perspective is observed using the Accumulated Damage reduction, expressing it on proportional values for the LC measured in comparison to the MPPT scenario.

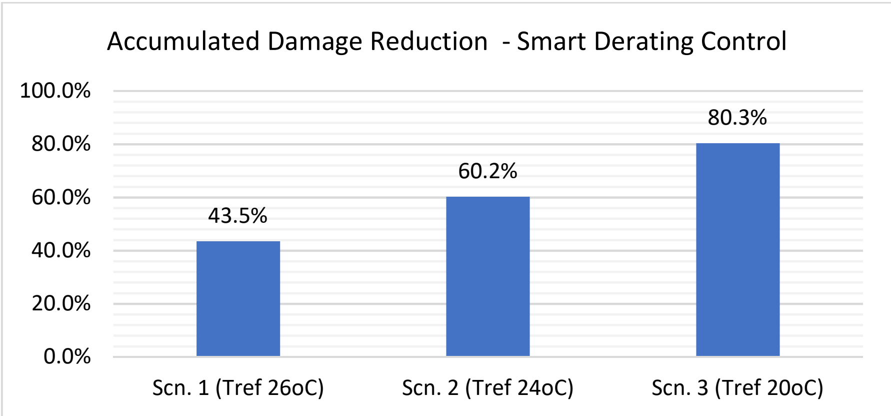

Figure 4.17: *LC reduction in comparison with MPPT use*

On this aspect, the first strategy studied (Flexible MPPT) performed a reduction of close to one order of magnitude on the accumulated damage caused to the switches, with an LC no higher than 56% of the MPPT performance. That comes in direct consonance with the exposure on figure 4.14, where a severe depletion on the range of the thermal cycles could be observed.

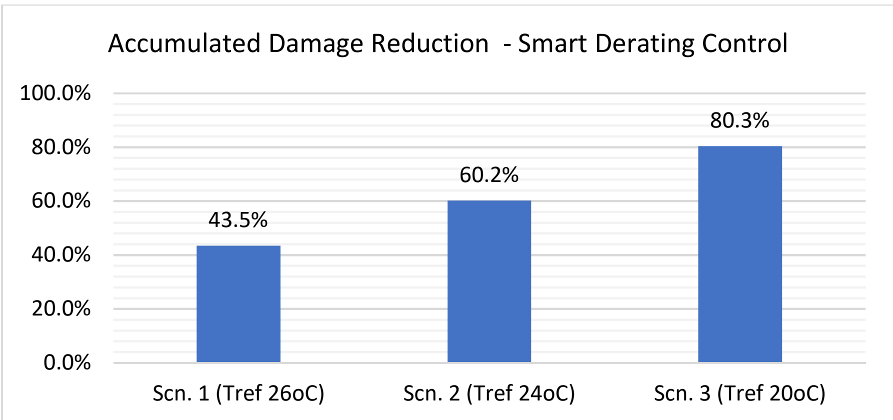

Figure 4.18: *LC reduction in comparison with MPPT use*

A relatively similar performance could be observed on the Smart Derating control. That is relevant because this strategy brings the Ambient Temperature as an online parameter for the derating, and if that is easy to implement is possible to actively adapt the energy production to a variant site profile. The result is aligned with the exposure of figure 4.15, representing a direct increment on the lifetime due to a direct reduction of the range of thermal cycles.

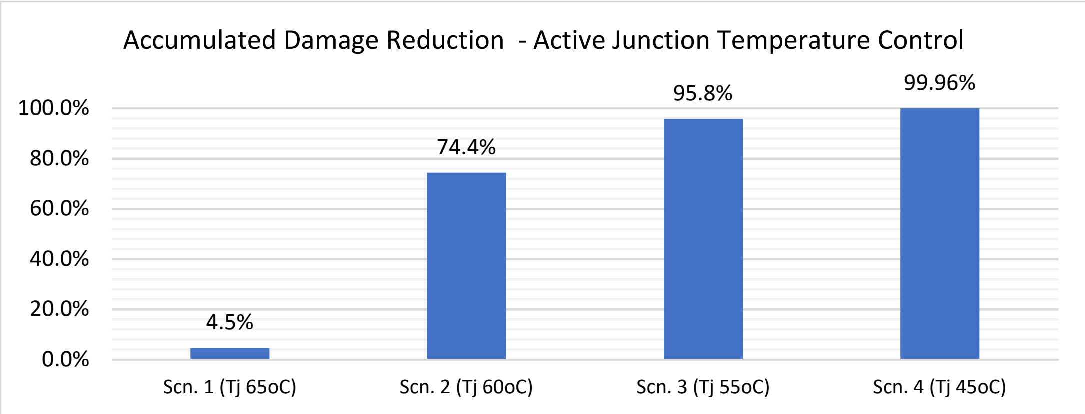

Figure 4.19: *LC reduction in comparison with MPPT use*

The same level of reduction on damage is observed while using Junction temperature as a parameter, as expressed above by the Active Junction Temperature Control strategy.

Nevertheless, is important to notice that while setting a parameter close to the maximum Junction Temperature (Scenario 1) for the tested profile ($\approx 70°C$), the strategy shows a very small reduction on the LC proportionally to the other scenarios. This result was expected since the figure 4.16 exposed a marginal influence of larger cycles resulting from Scenario 1, but also a stronger influence on them caused by the parameters of other scenarios.

4.4.4 Overall comparison

An overall perspective around the control strategies is possible to achieve if a global reference composes the analysis of the PV power curtailment. That final perspective is relevant because while implementing any strategy to increase the lifetime of devices and their components if in one hand is desired to minimize the decrement of Energy production, on the

other hand, the percentual LC reduction is desired to be higher as possible.
A proportional parameter can be described as:

$$Rank = \frac{\%\ of\ LC\ reduction}{\%\ of\ energy\ lost} \quad \text{Eq. 20}$$

That relation is, following the description above, desired to be as high as possible. Both parameters should be calculated on its unitless percentual level related to the reference value (MPPT scenario). On this matter, is possible to compare all the strategies under the same lens.

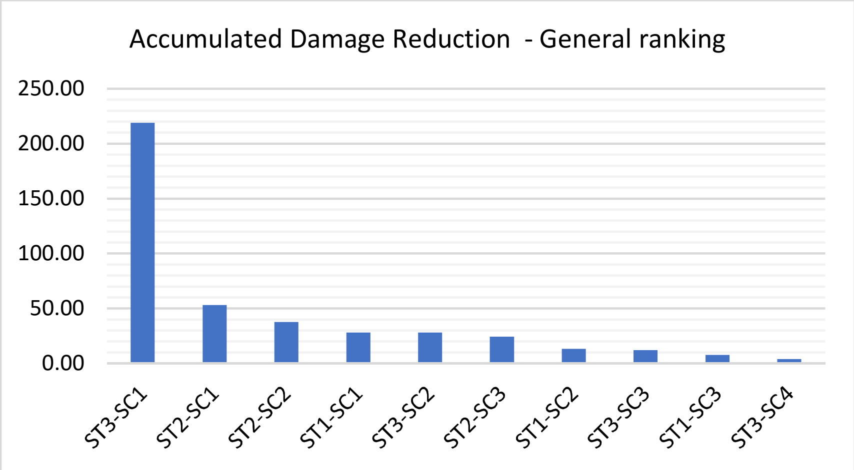

Figure 4.20: *General LC reduction over Energy Lost*

This overall perspective shows a clear difference in the impact of different scenarios from different strategies. At the common ground of the ranking, is observed that the relatively small reduction on the Lifetime Consumption brought by the Scenario 1 ($T_{J\_ref} = 65°C$) of the Strategy 3 (Active Junction Temperature Control) came at a very low price on energy production, making this scenario by far the most attractive. Additionally, the Strategy 2 (Smart derating Control) represented an important total sum at the ranking, with good positioning on the 2nd, 3rd and 6th positions. Nevertheless, disregarded the highest scorer most of the other scenarios expressed a similar performance regarding the energy cost and the improvements on the Lifetime delivered.

4.4.5 The challenge of tunning the Control Strategies

The undeniable gain observed by the performance presented by the Scenario 1 of the third strategy ($T_{j\_lim} = 65°C$) can be credited to a precise tune between the cut of the higher range thermal cycles and the small amount of energy lost. On that matter, one complementary question emerges: "How feasible is to expect from each control strategy to achieve such higher attractive results?"

In order to briefly explore this topic, another simulation was developed with a different mission profile and one scenario as reference for each strategy, accounting with an attempt to reach the same tune and higher profit. Considering a good basis of historical data recorded, the simulation set was:

- For Strategy 1 (Flexible MPPT), a $P_{lim} = 1800W$ due to a historical maximum of $1900W_p$ at that site;
- For Strategy 2 (Smart derating Control), a $T_{ref} = 41°C$ for starting the derating due to a historical maximum of $44°C$ at the site;
- For Strategy 3 (Active Junction Temperature Control) a $T_{j\_lim} = 65°C$, for a maximum of $71°C$ on the past at his inverter.

From this excursion resulted:

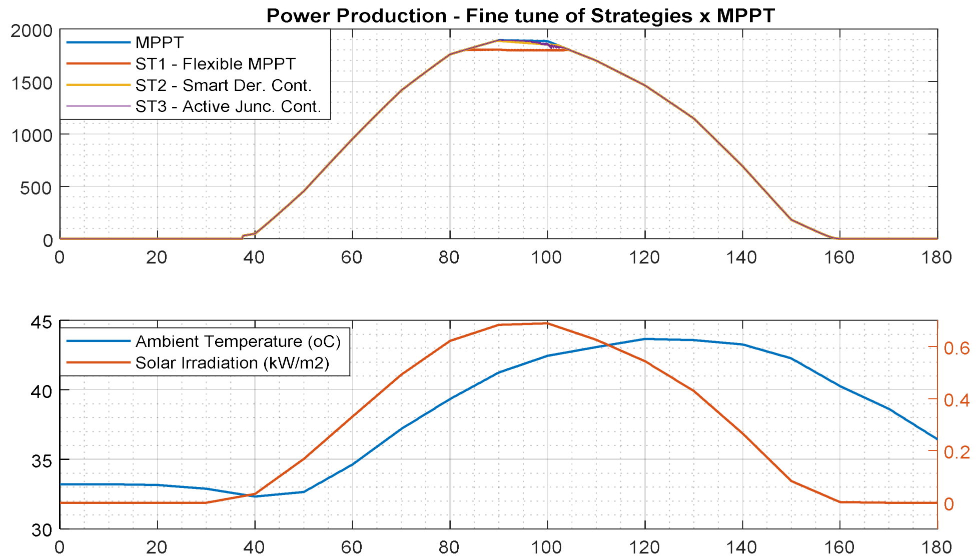

Figure 4.21: *Power generation with previously tuned parameters for a site in Fatick, Senegal [41]*

Scenario	%of MPPT Energy Lost	%of LC avoided
ST1	1.02%	29.6%
ST2	0.17%	14.2%
ST3	0.11%	11.7%

Table 8: *Power generation and LC performances for the Senegal Mission profile and guessed parameters*

Using the same ranking proposed by the equation 20, very different performances are seen regarding the overall comparison:

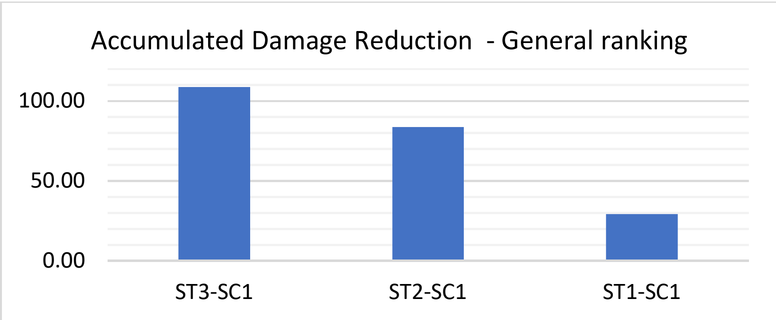

Figure 4.22: *Overall comparison - General LC reduction over Energy Lost*

Is noticeable that Strategies 3 and 2 are capable to achieve the excellent balance between energy lost and reliability improvement with simple guessed parameters. On the opposite direction, the Flexible MPPT strategy expressed a long variation on its parameter (total power, from 0W to 1900W), bringing imprecision for any tune on power limit even when based in educated guesses.

Differently, Smart derating Control and Active Junction Ambient Temperature Control both expose smaller variation ranges on its parameters. While here the ambient temperature varies from 33℃ to 44℃, a fine tune is more feasible on these strategies and tend to bring more operational gains regarding both energy saving and Lifetime improvement.

Chapter 5

Conclusions

All the three control strategies expressed a significant capacity to decrease the lifetime consumption of the IGBT on a reasonable scale, thus justifying their use as a method for interfering on the lifetime of PV Inverters. While the energy cost of a power curtailment may be undesired in any scenario, it was proven that a balanced analysis comparing lifetime increments and energy losses is feasible to develop.

All the analysis around the theme is justified by, as presented on *chapter 1*, the fact that PV systems are playing a significant role on the energy grow, and are attracting a large portion of the investments on energy grow worldwide. As would be expected from any large investment, a reliable and predictable production can improve the attractiveness of the Solar energy for the energy market. On *chapter 2*, the reliability of these systems is exposed as tightly related to the PV inverter and its power switches.

The thermal degradation mentioned and exposed in *chapter 3* is a significant share of the causes for reliability depletion, thus justifying the search for countermeasures to better manage the lifetime of power switches such as IGBTs. While specific parameters such as the investment done on the PV system and maintenance details can be brought to the scenario for expressing a better opinion about the attractiveness of Control Strategies for PV Inverters, the significant effects on lifetime caused by the use of the studied strategies become undeniable.

Despite the possible differences between the simulated results and real field results, the strategies listed and presented in *chapter 4* were stressed through different scenarios under a straight group of variables that should represent similar and proportional global parameters.

Still on *chapter 4*, the discussion about different strategies for CPG has demonstrated that not just higher power curtailment could bring positive effects for the reliability of PV Inverters but also small curtailments could bring very cost-effective impacts.
On that matter, the Flexible MPPT expressed a powerful capacity to reduce the energy circulating on the PV system, being able to cut immediately the long-range thermal cycles and decrease the accumulated damage expected for 1 work day. Nevertheless, its application comes at a high price on energy production, making this strategy not fitted when considering weather forecast deviations. A final conclusion for this strategy is the undoubted dependence between the cost-effectiveness of its application and a very well-defined mission profile. In cases where the static limit was set too low such as on the third scenario (*ST1SC3*), the cost-effectiveness of the improvements on reliability becomes highly unattractive.
While exploring the performance of the Smart derating Control, on the other hand, the expected smartness of the strategy expressed the capacity to adapt the Power limit to an increasing Ambient temperature, therefore limiting the increasing damage caused by higher range thermal cycles. This interactive limitation to the power production obviously ends up producing more energy than the static limit of the Flexible MPPT, and if allied with a predictable and fierce energy dissipation capacity at the heatsink can answer to eventual mission profile deviations at a small cost on energy lost.
Finally, the Active Junction Thermal Control expressed very effective results, especially under the balanced perspective between energy lost and reliability improvements. Good results were obviously expected considering that the Reliability Assessment presented on this study considers the information coming directly from the junction temperature, thus limiting this parameter directly should have heavy impacts. Among others, the major drawback of the application of this strategy is the hardware needed for implementing it, but its direct influence on the Reliability control could justify the investment in its use.
Moreover and as a general perspective, a conclusion emerges not from the simulated data but from the analysis of the strategies as an operational procedure. While the major simulations developed here considered a cloudless day in Spain without intermittence on the irradiation, this scenario isn't completely realistic. Even more, the ambient temperature at

which a PV inverter is exposed can easily be higher than the ambient temperature due to particularities on the installation and the facilities. Complementarly, the additional simulation with the data wheater data from Senegal showed how hard can be to guess previously the best parameter for each strategy, especially for the Flexible MPPT control. In any case, small deviations on the expected mission profile can lead to heavy losses on the energy production in every control strategy.

The final direction of this understanding regarding operational implementation demands two major qualities from a solution: flexibility compatible with the installation and previous good information about the Mission profile. On that matter, all the roads lead to a high dependence between the cost-effectiveness of a selected strategy and the weather forecast used for defining the parameters.

Therefore, complementary studies can follow this one by including on the mission profile a broader range of scenarios as input for the PV system. That could bring more reliable measurements simulating the answer of the PV system to real life endurance.

The main contribution of this thesis was presented in *chapter 4*, where the major impact of the control strategies was compared regarding the energy cost of each one, and their capacity to impact reliability was dismembered. Subsequentially, a common parameter brought one perspective to rank different scenarios of the different control strategies. This overall comparison can support a field decision and making the strategy a more strategic choice regarding the accumulated thermal stress and the energy produced.

In any case, the significant dependence between the weather forecast and the mean Junction temperature points to an inevitable trend towards flexible strategies and adaptable parameters applied together with well-tuned knowledge about the Mission profile in a form of site historical conditions.

References

[1] The International Energy Agency – IEA – GECO: 2018 Global Energy & CO2 Status Report. Available: http://www.iea.org/geco/ (visited on 03 of March 2019).

[2] IEA – International Energy Agency - 2018 Snapshot of Global Photovoltaic Markets. Available: http://www.iea-pvps.org/fileadmin/dam/public/report/statistics/IEA-PVPS_-_A_Snapshot_of_Global_PV_-_1992-2017.pdf (visited on 03 of March 2019).

[3] R. Kaplar, R. Brock, S. DasGupta and others, "PV inverter performance and reliability: What is the role of the IGBT?," *in Photovoltaic Specialists Conference*, Jun. 2011.

[4] Flicker, J.; Kaplar, R.; Marinella, M.; Granata, J., "PV inverter performance and reliability: What is the role of the bus capacitor?", *in Proceedings of the IEEE 38th Photovoltaic Specialists Conference*, Jun. 2012.

[5] C. J. Felgemacher, "Investigation of Reliability Aspects of Power Semiconductors in Photovoltaic Central Inverters for Sunbelt Regions" *in Elektrische Energiesysteme,* Jan. 2018.

[6] H. Wang, K. Ma, and F. Blaabjerg, "Design for reliability of power electronic systems," *in Proc. of IEEE Industrial Electronics Society Annual Conference (IECON), pp. 33-44*, 2012.

[7] Electropedia: The World's Online Electrotechnical Vocabulary - Section 192-01 - Reliability. IEC. Feb. 2015. Available: http://www.electropedia.org/iev/iev.nsf/display?openform&ievref=192-01-24 (visited on 13/05/2019).

[8] A. Golnas, "PV System Reliability: An Operator's Perspective," *in 38th Photovoltaic Specialists Conference*, Jun. 2012.

[9] L. Tanga, Z. Shia, X., "Ventilation Analysis and Simulation for Inverter of Photovoltaic Power Plant", *in 10th International Symposium on Heating, Ventilation and Air Conditioning*, Oct. 2017.

[10] M. Díez-Mediavilla, C. Alonso-Tristán, M.C. Rodríguez-Amigo, T. García-Calderón, M.I. Dieste-Velasco, “Performance analysis of PV plants: Optimization for improving profitability”, *in Energy Conversion and Management 54(1):17-23*, Feb. 2012.

[11] A. Ahadi, H. Hayati, S.M.M. Aval, “Reliability evaluation of future photovoltaic systems with smart operation strategy”, *in Frontiers in Energy, vol. 10, issue 2, pp. 125–135*, 2016

[12] R. Zehringer , A. Stuck , T. Lang, “Material requirements for high voltage, high power IGBT devices”, *in Mat. Res. Soc. Symp. Proc. Vol. 483,* 1998.

[13] E. Collins, M. Dvorack, J. Mahn, M. Mundt, M. Quintana, “Reliability and Availability analysis of a Photovoltaic System” - *Sandia National Laboratories*, 2009.

[14] K. Upadhyayula and A. Dasgupta, “Guidelines for physics-of-failure based accelerated stress testing,” *in Photovoltaic Specialists Conference (PVSC), 2011 37th IEEE, pp. 345–357*, Jan. 1998.

[15] H. Wang, M. Liserre, F. Blaabjerg, P. de Place Rimmen, J. Jacobsen, T. Kvisgaard, and J. Landkildehus, “Transitioning to Physics-of-Failure as a Reliability driver in power electronics,” *in Emerging and Selected Topics in Power Electronics, vol. 2, pp. 97–114*, Mar. 2014.

[16] J. Flicker and S. Gonzalez, "Performance and reliability of PV inverter component and systems due to advanced inverter functionality," *in Photovoltaic Specialist Conference, pp. 1-5*, 2015.

[17] M.Lokanadham, K.Vijaya Bhaskar, “Incremental Conductance Based Maximum Power Point Tracking (MPPT) for Photovoltaic System”, *in International Journal of Engineering Research and Applications (IJERA), vol. 2, Issue 2, pp.1420-1424*, Mar.-Apr. 2012.

[18] Y. Yang, P. Enjeti, F. Blaabjerg, and H. Wang, “Grid code modifications to ensure widescale adoption of photovoltaic energy in distributed power generation systems,” *in IEEE Ind. Appl. Mag., vol. 99, no. 99, pp. 1–10, in press,* Sept.-Oct. 2015.

[19] ENERGINET.DK - Technical regulation 3.2.5 for wind power plants above 11 kW - REVISION 4, Jul. 2016.

[20] Bobrowska-Rafal, M.; Rafal, K.; Jasinski, M.; Kazmierkowski, M.P., "Grid synchronization and symmetrical components extraction with PLL algorithm for grid connected power electronic converters - A review", *in Bull. Pol. Acad. Sci. Tech. Sci., 59, 485–497*, 2011.

[21] Reinhold, Nostrand., M. Weik., *Communications Standard Dictionary, 2nd ed., Ed. New York,* 1989.

[22] V. K. Sundaramoorthy E. Bianda, G. J. Riedel, "A study to improve IGBT reliability in power electronics applications", Oct. 2015.

[23] M. Ciappa, "Selected failure mechanisms of modern power modules", *in Microelectronics Reliability, Vol.42, pp.653-667*, 2002.

[24] Ahcene Bouzida, Radia Abdelli, M'hamed Ouadah, "Calculation of IGBT Power Losses and Junction Temperature in inverter drive", *in 8th International Conference IEEE, 2016: 768–773*, 2016

[25], F. Casanellas, "Losses in PWM inverters using IGBTs", *in IEE Proc.- Electr. Power Appl., vol. 141, No. 5*, Sept. 1994.

[26] L.K. Mestha, P.D. Evans, "Analysis of On-State Losses in PWM Inverters", *in IEE Proceedings, vol 136, Pt. B, No. 4,* July 1989.

[27] Wu, R., Wang, H., Pedersen, K. B., Ma, K., Ghimire, P., Iannuzzo, F., & Blaabjerg, F., "A Temperature-Dependent Thermal Model of IGBT Modules Suitable for Circuit-Level Simulations" *in IEEE Transactions on Industry Applications*, 2016.

[28] Infineon Application note 2015-10, Thermal equivalent circuit models, V1.01, 2015.

[29] O. S. Senturk, S. Munk-Nielsen, R. Teodorescu, L. Helle and P. Rodriguez, "Electro-thermal Modeling for Junction Temperature Cycling-Based Lifetime Prediction of a Press-Pack IGBT 3L-NPC-VSC Applied to Large Wind Turbines," *in IEEE Energy Conversion Congress and Exposition (ECCE), pp. 568 - 575*, 2011.

[30] Bayerer, R., Licht, T., Herrmann, T., Lutz, J., Feller, M., “Model for power cycling lifetime of IGBT modules – various factors influencing lifetime”, *in Proceedings of CIPS, pp. 37–42. Nuremberg*, 2008.

[31] Junji Yamada et. al: The latest High-Performance and High-Reliability IGBT Technology in New Packages with Conventional Pin Layout”, *in PCIM* 2003.

[32] H. Huang and P. A. Mawby, “A lifetime estimation technique for voltage source inverters,” *in IEEE Trans. Power Electron., vol. 28, no. 8, pp. 4113– 4119,* Aug. 2013.

[33] I.R. GopiReddy, L.M. Tolbert, B. Ozpineci, J.O.P. Pinto, “Rainflow Algorithm-Based Lifetime Estimation of Power Semiconductors in Utility Applications” *in IEEE Trans. Ind. Appl. 51*, 2015.

[34] U. Scheuermann, R. Schmidt, and P. Newman, “Power cycling testing with different load pulse durations,” *in Proc. of PEMD 2014, pp. 1–6*, Apr. 2014.

[35] M. Matsuishi and T. Endo, “Fatigue of metals subjected to varying stress,” *in Proc. Jpn. Soc. Mech. Eng., Fukuoka, Japan,* , pp. 37–40, Mar. 1968.

[36] R. Künzi Paul Scherrer, “Thermal Design of Power Electronic Circuits”, *in Proceedings of the CAS-CERN Accelerator School: Power Converters*, May 2014.

[37] Fuji Electric Co., “Chapter 11–Reliability of Power Module”, *in web reference,* May 2011,.

[38] STMicroelectronics Application note AN4544, IGBT datasheet tutorial, 2014.

[39] Sangwongwanich, A., Yang, Y., and Blaabjerg, F. “Development of Flexible Active Power Control Strategies for Grid-Connected Photovoltaic Inverters by Modifying MPPT Algorithms”, *in Int. Future Energy Electronics Conference and ECCE Asia, pp.87-92*, 2017.

[40] Spain, Country average data - Open Power System Data – Available: https://data.open-power-system-data.org/weather_data/ (accessed in 27-05-2019)

[41] Senegal, Fatick average data - energydata.info Solar Radiation Measurement Data - World bank group. Available: http://energydata.info/dataset/senegal-solar-measurement-data-2016-2017 (accessed in 27-05-2019)

[42] Barrie D. Dunn, "Materials and Processes: for Spacecraft and High-Reliability Applications - Appendix 1: Coefficient of (Linear) Thermal Expansion for Selected Materials" 1ed., *Springer International Publishing*, 2016

[43] Q. Gestes, N. Degrenne, "Impact of Modulation Frequencies on the Lifetime of Power Semiconductor Modules for EV Applications", *in Annual Conference of the prognostics and health management society*, 2017.

[44] M.H. Bierhoff, F.W. Fuchs. "Semiconductor Losses in Voltage Source and Current Source IGBT Converters Based on Analytical Derivation", *in Annual IEEE Power Electronics Specialists Conference*, 2004.

[45] Bo Wang, Luowei Zhou, Yi Zhang, Pengju Sun, "A method of active junction temperature control for IGBT", *in 43rd Annual Conference of the IEEE Industrial Electronics Society,* 2017

[46] J. Lutz, H. Schlangenotto, U. Scheuermann and R. De Doncker, "Semiconductor Power Devices: Physics, Characteristics, Reliability", *Springer-Verlag Berlin Heidelberg*, 2011.

[47] S. M. Sze, "Semiconductor Devices-Physics and Technology", *John Wiley & Sons, New York*, 1985.

[48] Y. Yang, A. Sangwongwanich, F. Blaabjerg. "Design for Reliability of Power Electronics for Grid-Connected Photovoltaic Systems", *in CPSS Trans. Power Electron. Appl., Vol. 1, No. 1,* December 2016.