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DOCTORAL THESIS:

DESIGN, IMPLEMENTATION AND VALIDATION OF ADVANCED MEASUREMENTS AND COMMUNICATIONS WITHIN PHOTOVOLTAIC PLANTS

PRESENTED BY **JOSÉ IGNACIO MORALES ARAGONÉS** TO QUALIFY FOR THE DEGREE OF DOCTOR FROM UNIVERSITY OF VALLADOLID

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PROGRAMA DE DOCTORADO EN INGENIERÍA INDUSTRIAL

TESIS DOCTORAL:

DISEÑO, IMPLEMENTACIÓN Y VALIDACIÓN DE MEDIDAS AVANZADAS Y COMUNICACIONES EN PLANTAS FOTOVOLTAICAS

PRESENTADA POR **JOSÉ IGNACIO MORALES ARAGONÉS** PARA OPTAR AL GRADO DE DOCTOR POR LA UNIVERSIDAD DE VALLADOLID

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Muy pocos logros pueden considerarse totalmente individuales, y este no es, desde luego, uno de ellos. Un buen número de personas han contribuido a llegar hasta este punto, directa e indirectamente. Los coautores de los artículos aquí presentados son los mas directos responsables de haber llegado a buen puerto al final de este viaje. Mis directores de tesis y mi tutor han contribuido enormemente a esta empresa, no solo por ser imprescindibles, sino también por haber demostrado que lo son y por haber utilizado las herramientas justas en cada momento para mantenerme al pie del cañón. En concreto supieron utilizar el humor (una poderosa herramienta) en la misma medida que la seriedad cuando la ocasion lo requería. A todos ellos les agradezco enormemente su aporte y me congratulo de haberlos encontrado en el camino.

Mi estancia en el Instituto Tecnológico de Costa Rica quedará como uno de los mejores recuerdos de esta tesis. Allí fuí acogido con el calor que siempre muestra América Latina y desde entonces tengo allí una segunda casa. Muchas gracias a los profesores y el personal de la carrera de Ingeniería Electrónica del TEC, pero también a mis ya siempre amigos de Agronomía, Computación y Colegio Científico. Por último un profundo agradecimiento a mi familia, a la que tanto tiempo les ha robado esta tesis, y al que ya no está, a mi padre, que siempre confió en Mi y que siempre estuvo convencido de que llegaría hasta este punto.

PROLOGUE

Under the current regulations for the presentation and defense of the doctoral thesis (RESOLUTION on June 8, 2016, of the Rectorate of the University of Valladolid, which orders the publication of the Agreement of the Governing Council on June 3, 2016, approving the regulations for the presentation and defense of the doctoral thesis at the University of Valladolid), this doctoral thesis is presented as a compendium of publications (fourth article of the mentioned resolution).

In the following paragraph the published articles integrating the compendium of publications for this thesis are enumerated. The full articles are included at the end of this document. The numeration shown in this list is the same used in the text when an article is referenced.

PREÁMBULO

De acuerdo con la normativa vigente de presentación y defensa de la tesis doctoral (RESOLUCIÓN de 8 de junio de 2016, del Rectorado de la Universidad de Valladolid, por la que se ordena la publicación del Acuerdo del Consejo de Gobierno de 3 de junio de 2016, por el que se aprueba la normativa para la presentación y defensa de la tesis doctoral en la Universidad de Valladolid), esta Tesis Doctoral se presenta como compendio de publicaciones (Artículo 4 de la mencionada resolución).

A continuación se enumeran los artículos que se han publicado para conformar el compendio de publicaciones que integran esta tesis doctoral. Los artículos completos se incluirán en el capítulo final de este documento. Las numeraciones que aparecen en este listado serán las mismas utilizadas en el texto para referirse a los artículos.

A1 (Aceptado y publicado)

Título: **Low-Cost Electronics for Online I-V Tracing at Photovoltaic Module Level: Development of Two Strategies and Comparison between Them**

Revista: Electronics,10(6), 671 (2021)

Fecha de publicación: 12 de marzo de 2021

DOI: https://doi.org/10.3390/electronics10060671

Autores: Morales-Aragonés, J. I., Gallardo-Saavedra, S., Alonso-Gómez, V., Sánchez-Pacheco, F. J., González, M. A., Martínez, O., Muñoz-García, M. A., Alonso-García, M. del C., & Hernández-Callejo, L.

A2 (Aceptado y publicado)

Título: **Online Distributed Measurement of Dark I-V Curves in Photovoltaic Plants.**

Revista: Applied Sciences, 11(4), 1924. (2021)

Fecha de publicación: 22 de febrero de 2021

DOI: https://doi.org/10.3390/app11041924

Autores: Morales-Aragonés, J. I., Alonso-García, M. del C., Gallardo-Saavedra, S., Alonso-Gómez, V., Balenzategui, J. L., Redondo-Plaza, A., & Hernández-Callejo, L.

A3 (Aceptado y publicado)

Título: **Low-Cost Three-Quadrant Single Solar Cell I-V Tracer.**

Revista: *Applied Sciences*, *12*(13), 6623. (2022)

Fecha de publicación: 30 de junio de 2022

DOI: https://doi.org/10.3390/app12136623

Autores: Morales-Aragonés, J. I., Gómez, V. A., Gallardo-Saavedra, S., Redondo-Plaza, A., Fernández-Martínez, D., & Hernández-Callejo, L.

A4 (Aceptado y publicado)

Título: **A Resonant Ring Topology Approach to Power Line Communication Systems within Photovoltaic Plants.**

Revista: Applied Sciences, 12(16), 7973. (2022).

Fecha de publicación: 9 de agosto de 2022

DOI: https://doi.org/10.3390/app12167973

Autores: Morales-Aragonés, J. I., Williams, M. St. M., Gómez, V. A., Gallardo-Saavedra, S., Redondo-Plaza, A., Fernández-Martínez, D., Sánchez-Pacheco, F. J., Cuadro, J. G. F., & Hernández-Callejo, L.

A5 (Aceptado y publicado)

Título: **A Power-Line Communication System Governed by Loop Resonance for Photovoltaic Plant Monitoring.**

Revista: Sensors, 22:9207. (2022).

Fecha de publicación: 26 de noviembre de 2022

DOI: https://doi.org/10.3390/ s22239207

Autores: Morales-Aragonés, J. I., Williams, M., St. M., Kupolati H., Gómez, V. A., Gallardo-Saavedra, S., Redondo-Plaza, A., Muñoz-García M.A., J.,Sánchez-Pacheco, F. J. & Hernández-Callejo, L.

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ABSTRACT.

Solar Photovoltaic Plants have led the renewable power capacity growth observed during last years. As a result, operation and maintenance of these installations have become a key task in order to guarantee that they work in optimal conditions at maximum efficiency.

I-V tracing of individual solar modules is the most powerful technique for evaluating the time evolution and ageing of these devices.

This thesis has been focused on the development of a device able to trace this I-V curves without disconnecting the modules from the photovoltaic (PV) string where they are integrated (online measurements), and able to transmit the diagnosis data obtained via a power line communication (PLC) system specific for the cabling topology of PV strings, where the same power wires of the plant are used for communications.

This PLC system has a wider field of application than the hereby described and could serve as a general-purpose PV oriented communications system for local sensors or even control signals.

The research process for the developments described above has driven some other secondary achievements for this thesis, such as a novel laboratory single cell I-V tracer able to draw its characteristics along the three quadrants where the curve has working points, or a theoretical proposal for a double mathematical transformation useful for ease the one diode model parameter extraction from measured I-V characteristics of solar cells.

RESUMEN.

Las plantas solares fotovoltaicas han liderado el crecimiento de la energía removable observado durante los últimos años. Por tanto, el manejo y el mantenimiento de estas instalaciones se ha convertido en una tarea clave para garantizar que trabajan en optimas condiciones y con la máxima eficiencia.

El trazado I-V de módulos solares individuales aparece como la técnica mas poderosa para evaluar la evolución y envejecimiento de estos dispositivos.

Esta tesis se ha centrado en el desarrollo de un dispositivo capaz de trazar estas curvas I-V sin desconectar los módulos de la instalación en que están integrados (medida en línea), y capaz de trasmitir los datos de diagnóstico obtenidos a través de un Sistema de Comunicaciones PLC (Power Line Communication en inglés) específico para la topología del cableado de las instalaciones fotovoltaicas, en el que los mismos cables de potencia de la planta se usan como soporte de las comunicaciones.

Este sistema PLC tiene un campo de aplicación mas amplio que el aquí descrito y se podría usar como sistema de comunicación de propósito general orientado a instalaciones fotovoltaicas para sensores locales o incluso señales de control.

El proceso de investigación para el desarrollo arriba descrito ha impulsado algunos otros logros secundarios para esta tesis, como un novedoso trazador I-V de laboratorio para células solares capaz de representar sus características en los tres cuadrantes donde la célula tiene puntos de trabajo, o una propuesta teórica sobre una doble trasformación matemática utilizada para facilitar la extracción de parámetros correspondientes al modelo de un diodo a partir de las características I-V medidas en la célula.

2.-INTRODUCTION.

Nowadays we live in an energy demanding world. An overwhelming amount of confidence is placed within the ability of Renewable Energy (RE) Systems to meet this global demand and to thwart the occurrence of additional cumulative greenhouse gas emissions induced by fossil fuel use. This is supposed to occur through the rapid erection of new renewable installed capacity and the decommissioning of the more polluting power plants.

Amongst the different Renewable Energy Systems, Photovoltaic Plants have taken special relevance and have shown a significant rise as the costs of associated technologies has been reduced. For instance, an 85% cost reduction in global utility-scale PV levelized cost of electricity (LCOE) between 2010 and 2020 was observed, corresponding to a 1600% (42 GW in 2010 and 714 GW in 2020) cumulative increase in installed capacity [1]. Comparably within the same decade, onshore wind displayed a cumulative increase in capacity of 293% (178 GW:2010, 699 GW:2020).

Self-consumption remained an important driver of the market for new systems distributed in some regions, and corporate purchases of PV solar energy expanded considerably, particularly in the United States and Europe. Around the world, mining, manufacturing and other industries were installing PV (and other renewable) solar plants to supply power for their operations [2]. The increased demand in emerging markets and Europe, due to a large extent to the continuous price reductions, has offset a substantial decline in the market in China that had consequences worldwide [2].

Regarding the last year, in 2022 renewables experienced yet another year of record growth in power capacity, despite aftershocks from the pandemic and a rise in global commodity prices that upset renewable energy supply chains and delayed projects [3]. The role of renewables in improving energy security and sovereignty by replacing fossil fuels became central to discussions, as energy prices increased sharply in late 2021 and as the Russian Federation's invasion of Ukraine unfolded in early 2022. In 2022 Investment in renewable power and fuels rose for the fourth consecutive year, reaching USD 366 billion, and a record increase in global electricity generation led to solar and wind power providing more than 10% of the world's electricity for the first time ever [3].

In this scenario of the PV solar sector, it seems that the large production plants, as well as their energy production, will play a very important role. The observed trend aforementioned evokes great prospects for continued global PV proliferation and focuses great interest in the monitoring, inspection and maintenance of PV plants, regardless of their size [4]–[6] and drives studies to uphold the potential of the technology through the development of multiple PV monitoring systems and algorithms, as documented in [7], [8]. Operation and maintenance (O&M) are the main saving points for investors in solar PV, and for this reason, in recent years there has been a greater emphasis on advanced techniques for PV systems design, operation and maintenance [9].

On one hand, ensuring the health of these systems are preserved has gained significant prominence, especially with several PV installations over the years experiencing compromised lifecycles [7], on the other hand, cost reduction is always necessary to ensure system affordability is universally flexible across the widest range of consumers or socioeconomic groups, i.e. the cost of a monitoring and diagnosis system must be a small fraction of the PV installation itself in order to be potentially applicable for industrial grade.

The functionality of monitoring systems can aid with building long-term consumer trust in the renewable energy (RE) industry by bolstering the general outlook of RE technologies as reliable, long-term investments. As such, it is paramount that continuous cost reduction be applied to these systems to incentivize the consumer base to integrate them with their PV installations.

Regarding monitoring and diagnosis systems for PV installations, several techniques have been explored, developed, and implemented in different ways. Visual inspection is cheap and relatively quick, it can reveal several sources of faults like burned or oxidised cells metallization, delamination, bubbles, broken cells or discoloured anti reflection, scratches or burn in the back of the module, oxidation or corrosion in the junction box and detachment or exposed electrical parts in wires or connectors, but some kind of failures will remain hidden [10]. Going further, proper measurements can reveal failures hidden to the eyes. For example, the offline I-V tracing of the solar modules supplies a lot of information about the module performance, but it must be made disconnecting the module under measure from the installation and interrupting the energy production. **Figure 1** shows a diagram to explain the different monitoring and diagnosis techniques and its classification.

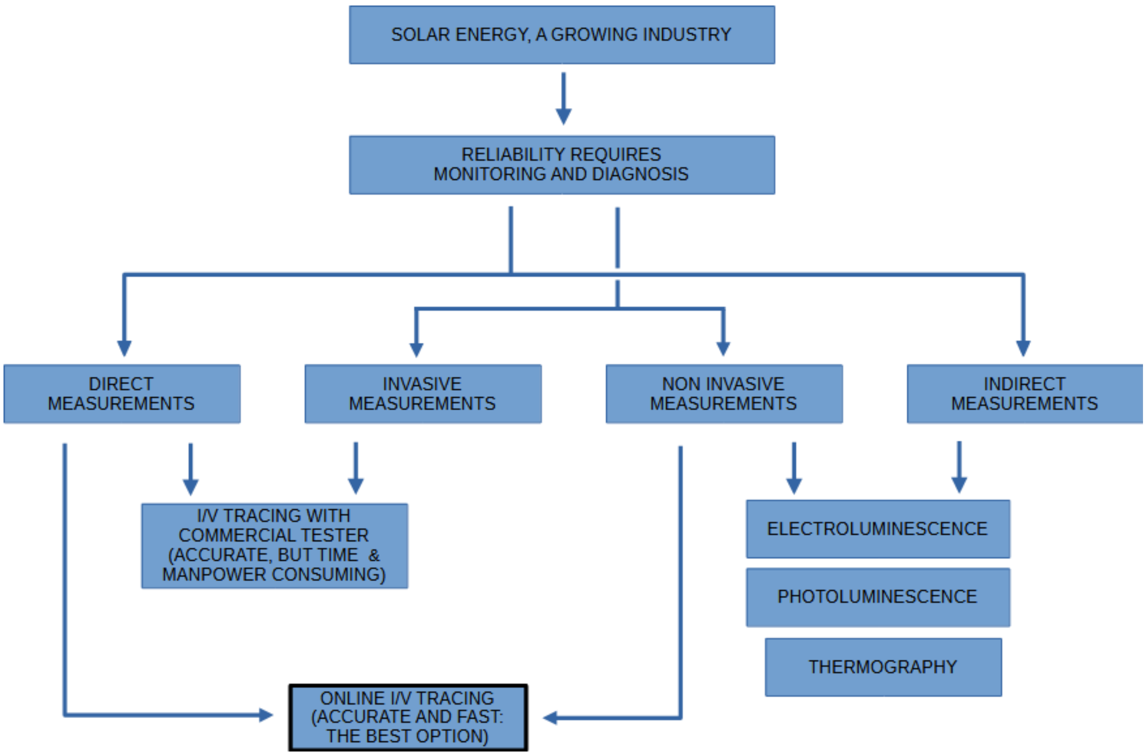


Figure 1

All these techniques imply some kind of measurement, whose results allow us to gather information about the system performance. The first criteria considered for classification is the degree of interference that the measurement causes over the power production. On one hand, if a solar plant must be stopped to measure the modules I-V curves with a commercial tester we say this measurement to be "invasive". On the other hand, if a measurement technique allows us to obtain information about the solar system performance with a very little influence in the power production or without affecting its working cycle at all we say this to be "non- invasive". The last one is the most interesting for us, because this means that the energy production is not interrupted and usually no components are extracted or disassembled for diagnosis purposes. An example of non-invasive measurements could be those taken at night when there is no radiation and no power production.

The second criteria for this classification divides the technique into two groups regarding the kind of measurements taken to obtain an insight of the real state of the system:

- Indirect measurement techniques
- Direct measurements techniques

The indirect measurements techniques can provide an insight of the state of the installation, but usually this information must be induced from side effects, frequently by statistical approaches and techniques as Artificial Intelligence. These techniques are less accurate than direct ones, but they are also less invasive. Among these techniques we can mention:

- Thermography: [11], [12]Analyses the infrared radiation imaging of the cells composing the solar modules for trying to identify different kinds of faults. The images can be obtained by means of fixed infrared cameras or drone on board cameras.
- Electroluminescence (abbreviated EL) [13]: Solar modules, when an electrical current is forced to flow in the opposite direction of the production one, behaves as a radiation source, whose maximum emission wavelength is around 1150 nm. This wavelength corresponds to the minimum gap energy in Silicon. This radiation can be captured by a camera for composing EL images, that in turn, can evidence some faults. One drawback of this technique is that EL radiation can be efficiently captured only by a special kind of cameras, based in InGaAs detectors, and usually they are quite expensive.
- Photoluminescence (abbreviated PL) [14]: Even in the absence of inverse electric current solar modules can emit radiation of 1150 nm wavelength under solar illumination, as a response to the absorption of solar photons that promotes electrons to the conduction band of the semiconductor (Si), and the consequent relaxation, that leads to electron-hole recombination and the emission of a photon whose energy matches the Silicon gap (1150 nm). This technique has the same drawback that EL, as the special InGaAs camera is required for image capturing.

The direct measurement technique implies capturing parameters directly over different points of the plant (even over each solar module). The more usual direct measures are electrical ones (e.g., the current and voltage of the modules or complete strings), but other parameters can be directly measured for diagnosis purposes, such as temperature or power delivered. These techniques are more accurate than the indirect ones, but if we want them to stay in a non-invasive fashion some limitations appear related to the fact that the energy production must be uninterrupted. Under production some direct measurements can be trivially performed as string current, individual voltages, temperature, and power delivered for each module, but they provide insufficient information to predict the individual performance of the modules and to reveal the source of some failures.

For a proper identification of failure sources, the most powerful measurement is the full I-V tracing of individual modules. These curves provide a very useful information of the PV module performance and allow for an easy identification of several malfunction causes. However, the trace of full I-V characteristic of one individual PV module in a non-invasive fashion (not interrupting the energy production) becomes a not straightforward task that requires some research.

There is a lot of literature about photovoltaic I-V tracers. Low cost is one of the most frequent claims of the documents since, as mentioned before, cost is a key parameter for a hypothetical transition to a commercial device. However, despite the low cost design, not all of them can be considered not invasive, and in some cases require the disconnection of the module from the string[15], [16], and also, under the low cost tag there are documents with significant differences in price.

Complexity is also an important parameter for these kinds of devices. If the final goal is to achieve a non-invasive monitoring and diagnosis system able to test individually each solar module, we must think in a device permanently connected to every module within the plant, so it must be as less complex as possible, and even as small as possible. Simplicity usually means robustness, and a small probability of failures, features well appreciated when a high number of devices must be implemented and installed (solar plants can contain thousands of solar modules).

This high demand of I-V tracing individual devices for a whole PV plant monitoring and diagnosis system, encourages us to reduce the cost to a minimum. In engineering, usually scientific research is the first step towards a commercial device, but the cost is not the main priority at least in the first stages. We think that in this case a design effort must be made to achieve a minimum cost, low complexity, robust and reliable device able to become a real option for a commercial device, that in turn, must be the final goal of engineering.

2.1.-Motivation

In some way, engineering could be defined as the art of bringing science to people, in the sense that often the principles of science are the starting point for a practical design that results in devices useful for people. If our interest is only focused on scientific phenomena or in the possibility of reaching some experimental achievements from some theory, we are forgetting to consider the practical feasibility of our research goal. Engineering must consider this last aspect, and sometimes making a feasible and realisable design could be the difficult point.

The scenario exposed before in the introduction makes the monitoring and diagnosis of solar plants a relevant task that must guarantee the optimal performance of these systems. Fortunately, nowadays a huge variety of cheap, little, and simple electronic devices and sensors makes the development of measurement systems suitable for this task simpler and faster. This will become evident when the state of the art will be exposed later.

However, considering that price and simplicity are key points when a design must be massively reproduced (as it would be when a PV plant with thousands of modules want to be fully monitored) a highly specific design remains as the optimal solution, because the general purpose devices despite being simple and cheap from the point of view of the features offered, and allowing extremely fast developments are frequently “much more than we need”.

The use of general purpose programmable devices (like the Raspberry Pi or the Arduino platform) is widely proposed in literature for the implementation of PV monitoring and diagnosis systems, probably because it allows for fast developments and can be programmed in a high level language, but as we will prove in this work, the basic features for this task can be reached with simpler and specific designs without loss of quality, where the main effort is placed in a cheap microcontroller low level programming over a minimalist hardware.

Often, research is strongly result-oriented without paying enough attention to parameters such as the mentioned price and simplicity, that will result quite important for a hypothetical commercial projection, and in this sense, research can also help to optimise these usually secondary goals.

2.2.-Objectives

The global objective of this thesis is to **improve the monitoring and diagnosis tasks within solar panel installations by the proper design of advanced and low-cost electronic devices, able to gather information about the state and degradation of the system with the aim of ease the maintenance process and even predict potential faults in the future**. Thinking about a possible commercial implementation of the different devices that have surged from this research, the low cost has always been a mandatory condition.

Obviously, the monitoring and diagnosis tasks for a solar plant must be based on some kind of measurements taken over the different elements of the installation. The most useful measurements are those that give local information at solar module level, since the modules can be considered the basic building block of the system (e.g., individual solar cells are not electrically accessible for measurements). These measurements supply more details about the plant performance than global ones, especially with electric measurements, because the first can reveal details that remain veiled in a global measurement where the individual characteristics are composed or averaged hiding local faults. In the case of measurements taken by local sensors or devices within each solar module, as electric ones, a reliable communications system is mandatory in order to evacuate the data obtained towards some kind of central hub. What is more, this communication system must have as low a cost as possible in line with the aim exposed in the global objective.

In the introduction, a basic classification of PV monitoring and diagnostics systems was exposed. Among all these systems the most accurate for diagnostics are the direct (usually electric) measurements, and in addition, the non-invasive fashion of these measurements is the most interesting since it can be performed without any power interruption, meanwhile the plant is working. Literature usually refers to this as “online” measurements. The most powerful electric measurement in this line is the Current/Voltage (I-V) PV module characteristic tracing, performed over each module integrated in the plant in an “online” fashion.

This kind of measurements is an example of the aforementioned ones taken by a local device, that requires a communications system for the generated data evacuation, since all the measurements are performed within each solar module, and the corresponding data must be sent to some kind of central hub in order to be analysed. Keeping in mind the low-cost philosophy this is not an easy to solve challenge, because the immediate solutions for communications involve adding some communications line or wireless solutions, and both will add complexity and cost to the final design.

The wireless option also has the drawback of possible incompatibilities, especially near industrial environments where saturation of the electromagnetic spectrum is a real concern. Radioelectric Spectrum distribution and its uses are established by law in different countries, and there are some sections of the spectrum free to use internationally by general applications usually called ISM (Industrial Scientific and Medical purposes) bands. On one hand most of the wireless communications modules suitable for integration in a cheap device work within these bands (ie Zigbee), on the other hand a lot of other control and communications devices uses the same bands, and for this reason we cannot discard the possibility of electromagnetic saturation and the consequent interference in industrial locations where a high number of this devices can be present.

Adding a wired network specific for communications covering all the PV plant surface is not either a suitable solution, because of its cost and complexity.

The best solution found to keep the low-cost condition is to think in a PLC (power line communications) system, using the same cables already installed for power evacuation for communications purposes. Anyway, this solution leads us to face new design challenges, since the cabling topology in a PV plant is not the usual used in PLC systems (two conductors running parallel to each other) and the classic transmission lines theory is not applicable. Some research has been focused on PLC within PV power plants [17]–[22], but usually the designs are too complex, too expensive or perform low bitrates, so in this work a design effort has been made to improve these previous designs.

The discussion above led us to define the following main specific objectives for this thesis:

SO1. Design, implementation, and validation of a low cost online I-V tracer able to get the I-V curve of each individual solar module. This design must include all the necessary elements for the practical I-V curve tracing, data storing and interfacing for data evacuation via a proper communications system.

SO2. Design, implementation, and validation of a low-cost Power Line Communication (PLC) system specific for Solar Plants cabling topology. A previous theoretical approach about propagation modes over the topology of Solar Plants wiring will be mandatory to accomplish this PLC design.

The development of this thesis and the analysis of the state of the art, resulted in some secondary objectives accomplished such as:

- Implementation within the designed online I-V tracer of the ability for measurements of dark I-V curves taken at night by means of a bidirectional inverter, able to inject current through a PV modules string.
- Design, implementation, and validation of an individual solar cell three quadrant I-V tracer for laboratory.
- Development of a mathematical transformation conceived to ease the extraction of the PV module parameters associated with the solar module One Diode Model from dark I-V curves measurements. This transformation has been implemented in an algorithm and integrated in a software for parameters extraction.

As low price and simplicity have been mentioned as two of the main goals, the mandatory communications system needed for data evacuation must also comply with these two characteristics. A later analysis of the options for communication will show that the best choice is a PV specific Power Line Communications system (PLC) intended for a PV string covering.

This PLC PV specific communications system could be a great achievement itself with a wide field of application within solar plants and can find a lot of other possible applications in monitoring and diagnostics, or even in control tasks.

Starting from the state of the art that will be analysed in a later chapter, we will try to improve the existing strategies and devices proposed in literature oriented to the mentioned tasks, making them cheaper, simpler and in turn, suitable for a commercial implementation.

The final system must comply with these minimum characteristics:

- Measurements (I-V tracing) will be made over each solar module composing the plant, leading to a highly detailed information of the plant performance.
- Tracing time must be around 40 ms, that is the optimal time to avoid hysteresis and other undesirable side effects [23].
- Resolution of the I-V curves captured must be higher than 128 points per curve, that is the resolution of a typical commercial I-V tracer (HT Solar I-Ve)[24].

- Evacuation of data must be done through a reliable, low-cost communications system specific for solar plants and integrated with the rest of electronics.
- The minimum extension of the communications system proposed will be each solar string within the plant. Due to commercial inverters maximum voltage limits PV strings has a maximum of about 20 PV modules, a string length about 20-25 meters. Adding a possible extra cable section towards the inverter location of 10 meters, total installation typical length is 35 meters. As the cable must run until the last module and come back, the typical maximum cable length will be 70 meters. To cover all the possible typical cases, the specification will be that the PLC system must be able to work at least with cable lengths of 100 meters.
- The monitoring and diagnostics system energy consumption per module must be a negligible quantity compared to the energy production of the module.

2.3.- State of the Art

Regarding the objectives mentioned in the previous point, we are interested in the State of the Art focused in two main subjects:

- Photovoltaic module I-V characteristics tracers, especially those that can perform the tracing online.
- DC Power Line Communications (PLC) systems, especially those designed for operation within a PV installation.

About the first subject, a lot of scientific literature has been found. The basic idea of the implementation and automatization of local measurements intended for monitoring and diagnostics within solar plants is in fact an old idea. For example, a paper from a date as early as 1986 [25] describes a system with the same basic goals presented here. Of course, at that time there was a narrow spectrum of available devices for this purpose, and this early development is quite complex (and supposedly expensive) from the point of view of that time.

The first task performed was a study about the existing different devices and techniques intended for solar modules I-V tracing. The result of this research gave rise to the paper:

A Review of I–V Tracers for Photovoltaic Modules: Topologies and Challenges.

(Morales-Aragonés JI, Dávila-Sacoto M, González LG, Alonso-Gómez V, Gallardo-Saavedra S, Hernández-Callejo L. Electronics 2021;10:1283. https://doi.org/10.3390/electronics10111283.)

Later a more specific search was performed looking for devices able to trace the I-V curve of complete strings and of individual modules integrated within them.

The general conclusion of this analysis was that most of the systems presented were based on general purpose devices (such as the Arduino or Raspberry Pi) [16], [26], [27] or powerful microcontrollers programmed in high level languages [15] . Even when some of them claim to be low-cost systems, they are not cheap nor simple enough to think of a possible commercial implementation over a solar plant, where hundreds or even thousands of them must be fabricated.

From this point of view, it is clear than the main research effort must be focused on the design of a minimal operational hardware, simple and cheap, suitable for a mass production but able to perform high quality I-V curves of each solar module individually and in an online fashion, avoiding to stop the energy production of the plant for monitoring and diagnosis purposes.

All the documents analysed about online I-V tracers have been mentioned in the references section of the paper:

- **A1: "Low-Cost Electronics for Online I-V Tracing at Photovoltaic Module Level: Development of Two Strategies and Comparison between Them".**

After this article, an extension of the online I-V technique to curves measured in dark conditions was considered. This requires a bidirectional Inverter able to inject current towards the PV string. Consequently, the state of the art of this kind of measurements was also analysed, and the relevant documents has been exposed in the references section of the paper:

- **A2: "Online Distributed Measurement of Dark I-V Curves in Photovoltaic Plants".**

Regarding the PLC solar plant specific communications system, the literature found is not as extensive as the previous one. The relevant documents found are mentioned in the references section of the following presented papers:

- **A4: A Resonant Ring Topology Approach to Power Line Communication Systems within Photovoltaic Plants.**
- **A5: A Power-Line Communication System Governed by Loop Resonance for Photovoltaic Plant Monitoring.**

It was found that a lot of the documents investigated describe devices based on integrated circuits originally designed for the application in traditional Power Line Communication standards [28], [29], that is to say, bipolar lines where two cables run more or less parallel to each other.

Almost none of the articles faces a theoretical analysis about the fact that the cabling topology within a solar modules string is essentially different from the standard PLC support, since there is only one single cable travelling from one module to the next starting and finishing in the combiner box. This topology makes impossible a Transversal Electromagnetic (TEM) propagation of the communication signal, that is the one observed in traditional PLC lines. This circumstance makes the traditional transmission lines theory unusable in the case of PLC over PV plant power wires.

The state of the art of the PLC solar plant specific systems seems to suggest that in this case a previous theoretical approach is needed to successfully optimise communications over this specific physical support.

At this point, the possibility of implementing a loop shaped PLC signal path working in resonance condition was considered. For this reason the state of the art about loop antennas was analysed [30], [31], because there is a close relationship between the signal propagation mode expected in the system here presented and the one observed in this kind of antennas. This was a proper starting point for a first theoretical approach to the resonant loop PLC communications system.

2.4.- Methodology.

Figure 2 shows a schematic of the methodology used to accomplish this thesis. Starting from the main objective proposed and after the analysis exposed in the introduction section, the online I-V tracing was identified as the best option for diagnosis and monitoring purposes and some kind of low-cost communications system to evacuate the data generated by the curves tracer must be considered. Then, the state of the art regarding the two subjects were carefully analysed.

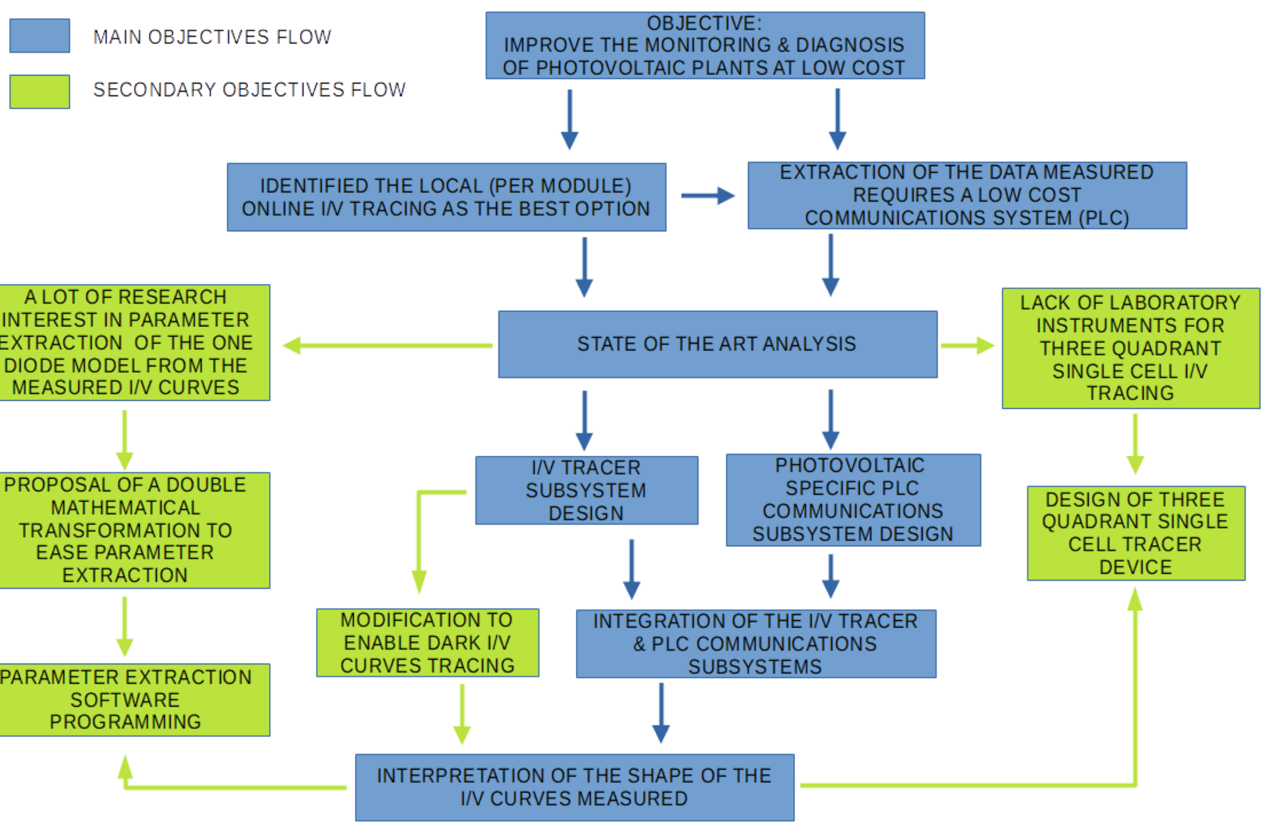


Figure 2

During this analysis, in addition to establishing the systems, circuits and strategies previously conceived for these main objectives, some other fields of interest were detected. Namely, and regarding the interpretation of the I-V curves measured by these kinds of devices, a lot of literature about the solar cell one diode model parameter extraction was found [32]–[35]. As a complement for the main work, we thought that it was worth analysing and trying to improve this task, quite important to finally interpret the measures taken by the system here presented.

This analysis ended up in a proposal for a double mathematical transformation over the measured data, that simplifies the curve adjusting to the one diode model formula, resulting in an easier parameter extraction. This work has not been published yet, but more details can be seen in Annex I.

During a collaboration with other researchers in our department (Ingeniería Agrícola y Forestal Dept, Universidad de Valladolid), they demanded to us the possibility of designing an instrument able to measure the I-V curve of a single solar cell showing not only the usual first quadrant but also the second and fourth quadrants for research purposes. The aim of their research was to investigate the influence over the three quadrant I-V curves of different kinds of provoked faults, and so help to interpret the measured curves' shape by means of artificial intelligence. As the design of the device demanded was closely related to the work here presented, and their research results will help to the proper interpretation of the measures taken by the main system conceived in this thesis, this design was accomplished and now presented in this document. This design has been finally one of the main novelties of this thesis.

To achieve the desired design of the online I-V tracer subsystem, as mentioned in the previous section, the main effort must be focused on the simplicity and low-cost of the hardware. This usually means that the complexity is shifted to the control software responsible to perform properly all the tasks required to get high quality I-V curves from online measurements.

In this case, the first step was the development of a strategy for implementing the mandatory sweep along the I-V curve without the disconnection of the module from the string and affecting as low as possible the power production. At this step, two possible strategies were identified:

- A global sweep for the modules string, even when the measurements were made over each PV module individually.
- A local sweep that affects only the PV module under test.

Both were analysed and implemented as described in the presented paper:

A1: "Low-Cost Electronics for Online I-V Tracing at Photovoltaic Module Level: Development of Two Strategies and Comparison between Them".

After the definition of these general strategies, a minimal hardware able to perform them was designed. For a minimal cost, all the electronics were organised around a very cheap 8-bit microcontroller running at 32 MHz. The use of such a simple and cheap microcontroller shifts the complexity to the software programmed on it. For an optimal performance this software was programmed in assembler, a low-level language close to the processor architecture, much more difficult to develop than the high-level languages but that results in a very effective software.

This option is aligned with a low-cost philosophy since the cost of the hardware is scaled on the size of the PV plant, but the hard task (the low-level programming) is done just one time.

The paper A1 explains in detail the hardware designed and shows the successful results.

After this first design and taking advantage of the presence in our facilities of a bidirectional inverter designed for a previous collaboration with Centro de Información y Red de Creación de Empresas (CIRCE) from Zaragoza (Spain), the design was complemented to be able of tracing dark I-V curves by means of a current injected from the bidirectional inverter. Surprisingly a very few modifications on the hardware were necessary, showing the versatility of the first design. The software was also adapted to detect and perform this kind of measurements. The results of these second measurements are exposed in the paper:

A2: "Online Distributed Measurement of Dark I-V Curves in Photovoltaic Plants."

For the validation of the hardware described for the I-V tracing, the communication with the device was first made through the RS232 serial port of the microcontroller. This means that a host portable computer was locally connected to each individual electronic card performing the measurement.

The validation process for the I-V tracing subsystem was made by a comparison of resolution and accuracy between the curves obtained with the designed device (online) and the same curves taken by means of a commercial device, as described in the presented article A1.

The second of the main objectives: the design of an PV specific PLC communications system, complemented the monitoring and diagnosis system allowing the data to flow between each local I-V tracer and some kind of host in the combiner box, without the necessity of a local connection.

As mentioned in the State-of-the-Art section, a theoretical approach was needed before facing a PLC design over the PV string physical support, since the single cable topology does not allow to assume the classic theory of transmission lines.

This question is analysed in the presented paper:

A4: "A Resonant Ring Topology Approach to Power Line Communication Systems within Photovoltaic Plants".

The possibility of implementing a ring-shaped signal path suitable for a resonant mode of propagation has been also studied in this article.

The theoretical conclusions from this paper have led us to an adapted PLC design specific for the PV string topology, that in turn, has demonstrated to perform better than most of the previous works, and at a very low cost (The final design here presented has a cost under 10 Euros per PV module).

The detailed description of the PLC system designed is shown in the presented article:

A5: "A Power-Line Communication System Governed by Loop Resonance for Photovoltaic Plant Monitoring."

This document describes the design that implements the theoretical approach of A4, including a capacitive serial coupling to the line and the design of a new inductive component able to avoid the core saturation problems when working at high continuous currents.

Validation of the PLC communication system was accomplished by the characterization of some communication quality parameters observed or measured over the system. The simple fact that the digital information transmitted is recovered without errors at the receiver is a validation of the system itself, but for a more precise characterization a measurement of some key parameters was made as shown in the presented article A5:

- Bit Error Rate (BER) - 3 e-3
- Transmission Speed – 143 kbps
- Noise to Carrier Ratio (NCR) – 31 dB
- Inter Symbol Interference (ISI) – 2us

2.5.- Materials

2.5.1.-General Materials.

Since the main work in this thesis has been the design and construction of electronic boards, the materials and methods utilised have been related to this task. The design of the printed circuit boards (PCB) has been made by means of the software "Eagle CAD" from "Autodesk". Electronic simulations have been performed with "LTSpice" from "Analog Devices".

The physical materials were mainly electronic components, and fibre glass printed circuit boards. For testing and adjusting them, the instruments in the "Ingeniería Agrícola y Forestal" Dept. laboratory within "Campus de Soria" of "Universidad de Valladolid" were utilised:

- Soldering Station.
- Desktop Digital Storage Oscilloscope.

- Handheld Digital Storage Oscilloscope.
- Signal Generator.
- Digital Multimeter
- RLC precision meter

For the construction of the printed circuit boards (PCB), optical photolithography was used, and the PCB final cost was around 2 Euros.

Some specific sensors and devices were developed and constructed:

- Anti-Saturation Coils: manually wired over a commercial magnetic core (A5).
- AC signal sensor: a toroidal coil surrounding the cable line, used to detect signal AC amplitude along the PLC cable of a PV string (A4).

2.5.2.-I-V tracing and PLC communications materials.

Regarding the Online I-V tracer and the PLC communications system (articles A1, A2, A4 and A5), the field tests were done on the PV miniplant (composed by a line of 11 solar modules and an inverter) in the “Campus de Soria” of “Universidad de Valladolid”, and validated also during an international collaboration in Costa Rica over the miniplant located in “Tecnológico de Costa Rica”, where the solar modules were arranged in a 3 x 4 modules matrix, thus with a different cable arrangement than the one in our local plant.

The main component for this system is the board installed within each PV module able to perform a local I-V tracing and to send the data through the power lines via the PLC communications system. This board will be referred later as the main board (MB) in the general schematic of **Figure 4**.

Figure 3 shows a picture of the final device installed within each PV module integrating all the functionality described in the presented articles A1, A2, A3 and A4.

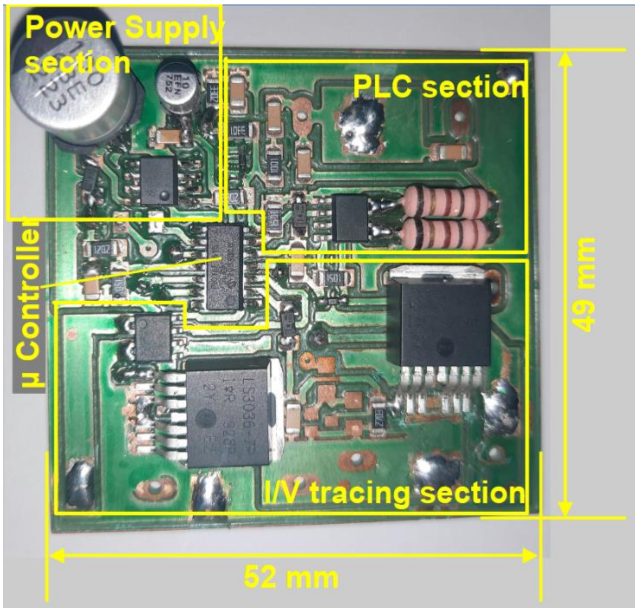


Figure 3: Picture of the final board integrating I-V tracing and PLC communications. The final cost of this hardware was around 10 Euros.

For a fully operational system over a PV string some other boards have been necessary:

- Regarding the PLC communications subsystem, a transceiver board (TRB) intended to be installed within the combiner box was designed. This board acts as a gateway for the communications and interfaces an external host with the string PLC system.
- Also related to the PLC communications system, a tuning board (TB) was designed to close in a loop the signal path in the PV string and to keep in resonance condition the ring-shaped signal path for an optimal propagation.
- For the I-V tracing strategy where the sweep is performed over the complete string (described in the presented paper A1), a sweeping circuit (SB) was designed to be installed within the combiner box.

The first extra board is described in the presented paper A5, the second in the presented paper A4, and the last one is detailed in the presented paper A1.

Even when these different boards were designed in different papers, all of them were conceived to work together integrating a system that, in turn, satisfies the global objective of this thesis, that is to say: improve the monitoring and diagnosis tasks in Solar plants by means of a reliable, simple, and cheap system. A general schematic of this system is shown in **Figure 4**.

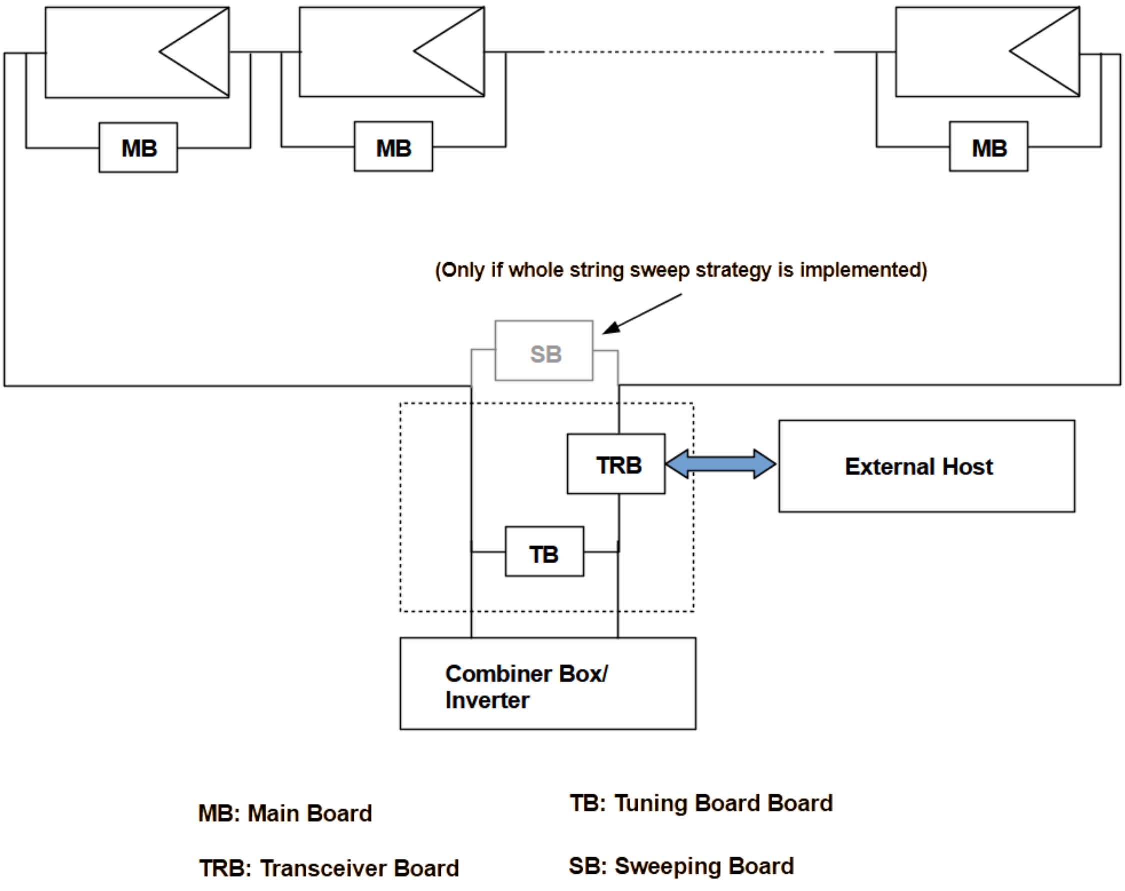


Figure 4: General schematic of the system integrating I-V tracing and PLC communication.

In this figure the ring-shaped signal path established over the power DC cable can be observed: the signal is propagated along the DC cable and in each module travels through the local main board (MB). The tuning board (TB) at the combiner box closes the signal path forming a loop and modifies the reactance in order to keep this loop in resonance condition for the carrier frequency used.

When a I-V curve is demanded, the external host sends a command via serial port to the transceiver board (TRB), who repeats this command towards the string loop modulated in the local carrier. Each command is followed by an identification address unique for each PV module, so the local main board in the corresponding module can recognize the command addressed to it. Then a local sweep is launched by the main board (MB) (or for the whole string by the sweeping board if this second strategy is adopted) and the measurement of the I-V pairs is started (always by the local main board). Finally, the data acquired are sent back to the transceiver board through the loop and re-emitted from the transceiver board to the external host.

A final test of this whole system was performed using the board in **Figure 3** after the installation of all the components corresponding to both: sweeping device and PLC communications system. The tested strategy was the decentralized one with local sweeping within each PV module. The transceiver board (TRB) shown in **Figure 4** were made from a board like the one in **Figure 3** modified with a specific firmware and the addition of RS232 terminal for communication with the external host. The components for the Tuning Board (TB in **Figure 3**) were installed on a protoboard, and over this, the transceiver board (TRB) was connected. This arrangement is shown in **Figure 5**.

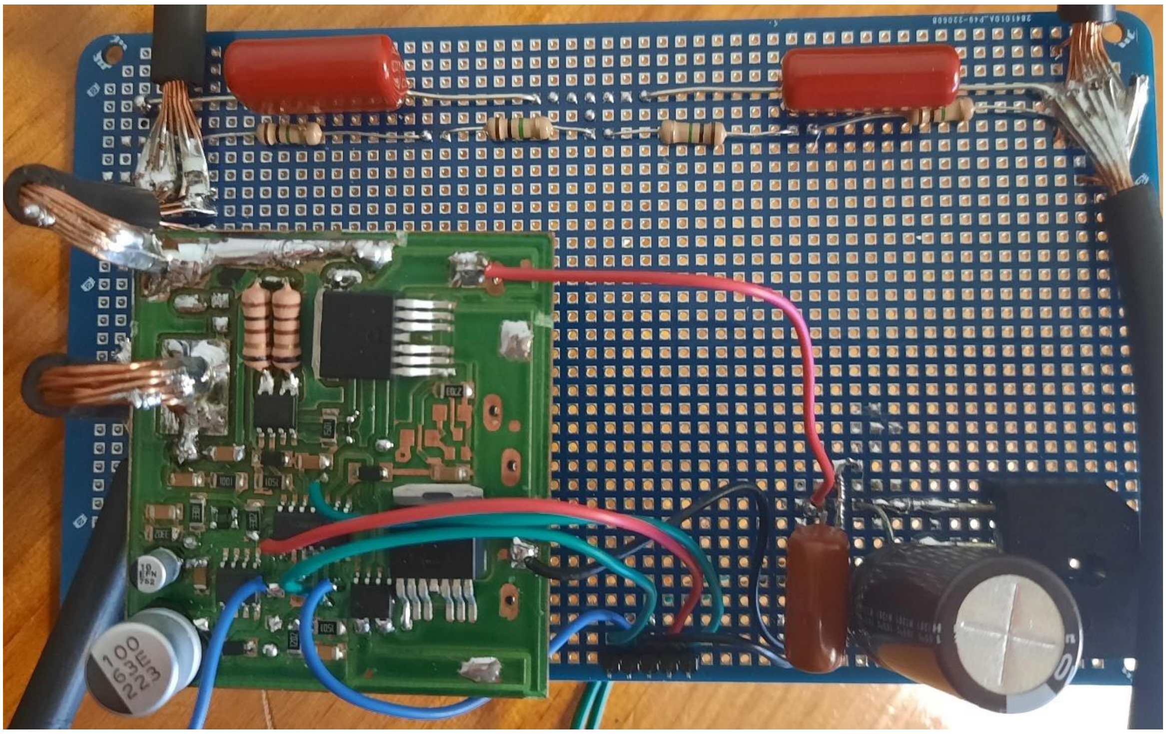


Figure 5: Transceiver Board (TRB) and Tunning Board (TB) integrated in a module ready to connect next to the inverter.

The results of this final test are shown in the next section.

2.5.3.-Three quadrant single cell I-V tracer materials.

Testing of the laboratory device developed in article A3 was done in the Physics laboratory of the Campus Duques de Soria (Universidad de Valladolid), and this was the central device for the measurements taken for the work developed by some other researchers in our department [36], showing its feasibility for a future commercial instrument.

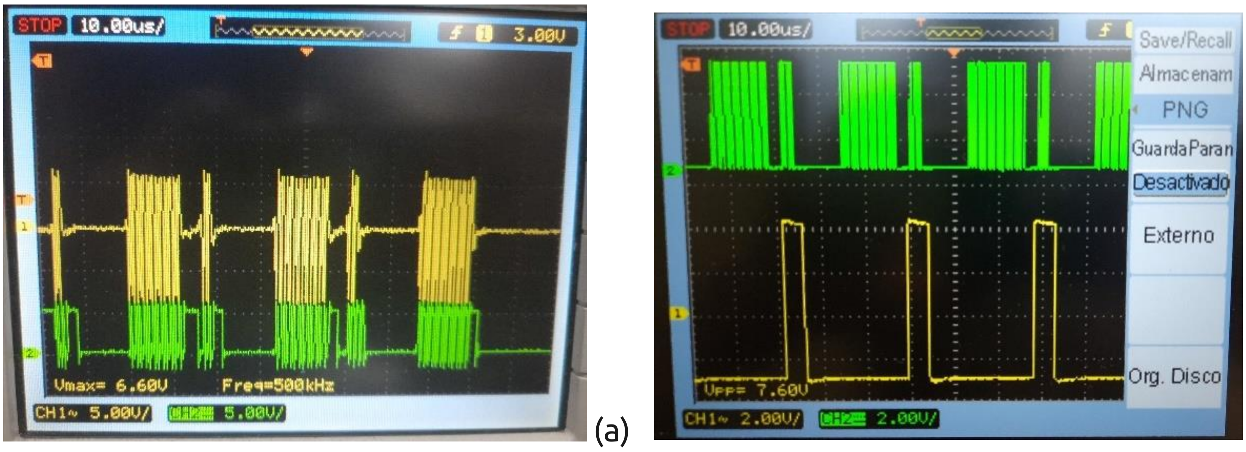
2.6.- Results

The main achievement of this work has been the design, construction, and validation of a low-cost electronic board (MB: main board) integrating all the components necessary to accomplish the two main objectives of this thesis (SO1 and SO2). Combined, all the components result in a very simple and cheap board connected at each solar module able to measure the I-V curve of the module in an “online” fashion, that is to say, without interrupting the energy production of the string where the module is integrated, and to transmit the I-V data to a gateway in the combiner box through the same DC power wires of the PV string.

The final test mentioned in the previous section was made following the schematic in **Figure 4**, and the sequence described under it, adopting the distributed strategy (local I-V sweep within each PV module).

Regarding the PLC communications, for testing the final system, since the focus in this thesis was the physical layer, a quite simple protocol and modulation scheme were adopted, just to test the hardware performance. The modulation scheme was a digital ASK (Amplitude-Shift Keying) very simple. For bit synchronization a fixed time slot of 34 us was assigned for bit duration. Within this slot time, zeroes were represented for a short carrier burst (3us) and ones were represented for a long carrier burst (13 us). In both cases during the remaining time in the slots there was no signal. The protocol used was a serial RS232 one, where the information was coded in ASCII hexadecimal. The command sent to start the I-V tracing is a single ASCII character followed by an additional address ASCII character. The answer containing the data is arranged in lines, where each line sent contain the ASCII-hexadecimal code for 10 bits, corresponding to each sample (voltage or current alternatively).

Figure 6 shows oscilloscope captures of the modulated signal in the line during this test.



(a) (b)

Figure 6. Oscilloscope captures of the communication signal. (a)-Yellow trace is the voltage signal on the line, green trace is the digitally recovered signal by the microcontroller. (b) Green trace is the digitally recovered signal by the microcontroller and yellow trace is a microcontroller internal digital signal indicating if a zero or an one has been received.

The signal received in the transceiver board (TRB) is demodulated by its local firmware and retransmitted as ASCII characters to the RS232 serial port representing the hexadecimal code of the samples. The external host (a portable computer) receive the RS232 signal, that is interpreted and decoded by a python software and finally converted into pairs of numerical values of the samples (volts and amperes). This software writes an output text file where each I-V point (pair of samples) is arranged in lines, voltage first and current second, separated by a space. This data file can be plotted as the I-V curve by some different programs.

The python software used for sending the start command and the module address, and for receiving the data is shown in Annex II. Also, the output of this software for this test is shown in Annex II.

Figure 7 shows the I-V curve (blue dots) obtained from the data output file in the final test. The data from this measurement were processed with the software and algorithm for extraction parameters described in Annex I, and the fitted curve corresponding to the parameters obtained is shown in **Figure 7** superimposed to the data (red line). The same figure also shows the value obtained for the parameters.

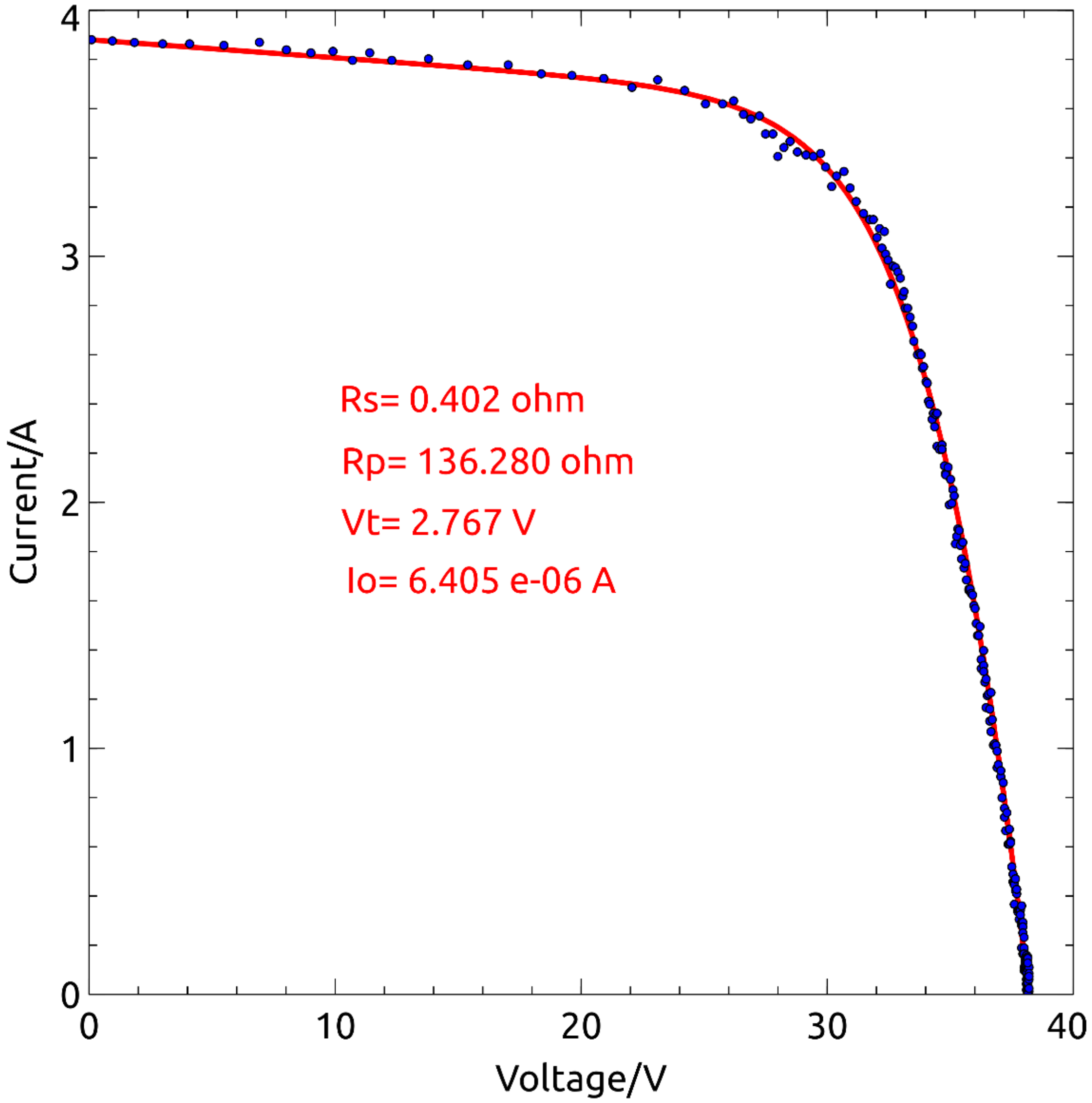


Figure 7: I-V curve (blue dots) obtained with the final board integrating I-V tracing and PLC communications. Results of parameter extraction are also shown, and the corresponding one diode model fitted curve (red line)

In **Figure 8** the window with the parameter extraction software output is shown.

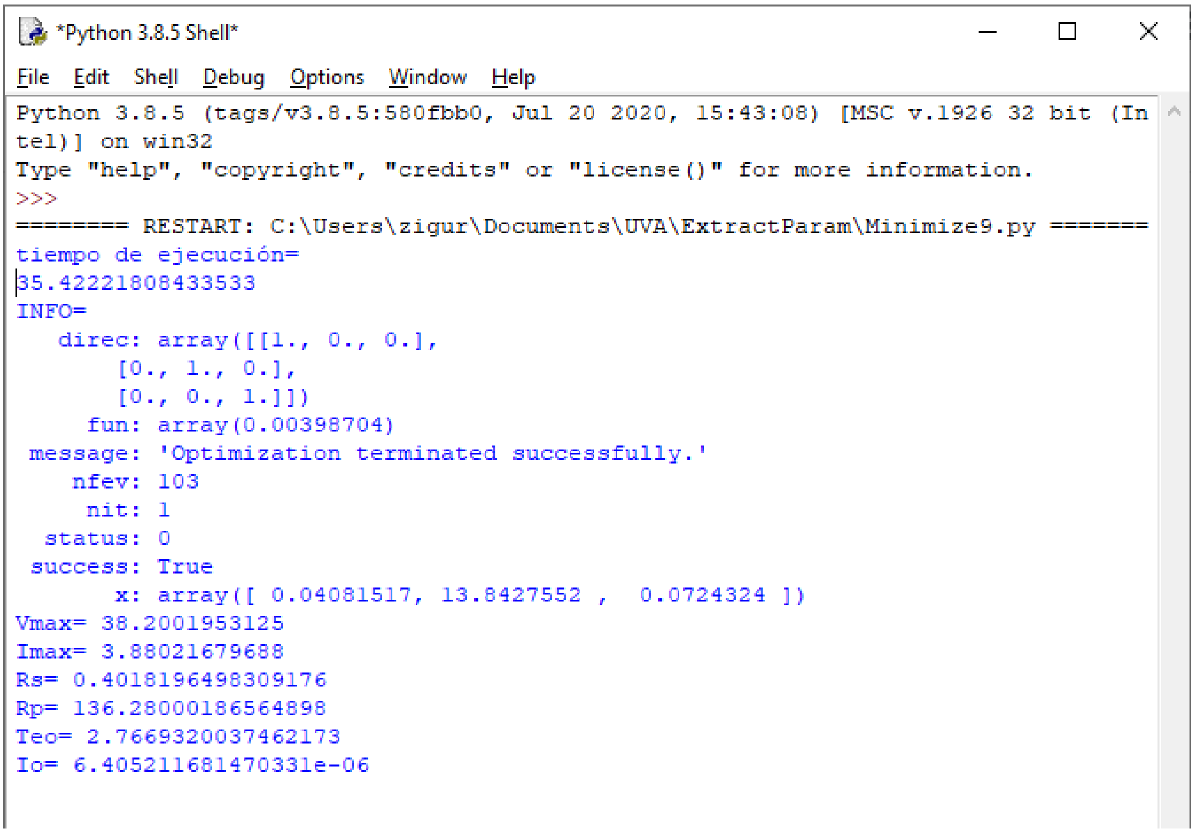


Figure 8: Parameter Extraction Software Output for curve in Figure 5

The main novelties of this PV specific PLC design are the resonant transmission over the ring-shaped topology of the signal path, and the design of the anti-saturation coil described in the presented paper A5.

Regarding the I-V tracing subsystem, the main achievement is the simplicity and the radical cost reduction of the system with respect to other previous works.

As mentioned in the Objectives section (2.2), the development of the work focused on the accomplishment of the two main specific objectives of this thesis, gave rise to the study of some other subjects, and new secondary objectives were faced in direct relationship with the main ones.

The first one was related to the immediate interpretation of the I-V curves obtained by the monitoring and diagnosis system. As the basic element of a PV module is the solar cell, it is quite interesting the study of the influence over its I-V curves of different kinds of external parameters, as for example the partial shadowing, soiling or chemical attacks.

Undoubtedly a classification of the causes of different deviations from the normal shape of the I-V curve is quite useful to help in the interpretation of the measured curves by the system here presented.

For this reason, the design, construction, and validation of a Three Quadrant I-V tracer for single solar cells was accomplished. This work was exposed in the presented paper:

- **A3: "Low-Cost Three-Quadrant Single Solar Cell I-V Tracer."**

The main novelty of this work is the ability of the designed instrument for tracing not only the usual first quadrant I-V curve, but also the sections of this curve located within the second and fourth quadrants. These last sections can provide to the researchers useful information about the behaviour and performance of the solar cell under different situations.

This is a laboratory instrument and were conceived to provide other researchers in the "Ingeniería Agrícola y Forestal" Dept. of "Universidad de Valladolid" of a device for the capture of single cell I-V curves, necessary for their study about the interpretation of I-V curves by means of Artificial Intelligence.

No report or documentation has been found in literature about such a similar instrument like this, so this design seems to be a novelty itself.

The second secondary objective undertaken is also related to the interpretation of the I-V curves obtained by means of the system here presented and is the only one who has a pure theoretical content. One of the most usual methods to characterise the shape of a solar module I-V curve is the extraction of the parameters corresponding to a theoretical model of the module. The usual model used is the one diode model. There is a lot of literature regarding the one diode parameter extraction, and here a new double mathematical transformation over the dark curves measured data was proposed to ease this process (a complex one because the formula describing the model is not an explicit one). Annex I show details about this proposal.

2.7.- Collaboration with other Universities or Research Centers

Some of the work presented in this thesis has been made with the collaboration of researchers from other universities or research centres:

- The state of the art regarding I-V tracer techniques was accomplished with the help of Researchers from Universidad de Cuenca (Ecuador).
- The testing and validation of the online I-V tracing devices designed was performed in collaboration with researchers from Universidad de Málaga (Spain), CIEMAT (Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas) (Spain), UPM (Universidad Politécnica de Madrid) (Spain) and from TEC (Instituto Tecnológico de Costa Rica) (Costa Rica).
- The testing and validation of the Photovoltaic specific PLC communications system was made with the help of researchers from Universidad de Málaga (Spain), UPM (Universidad Politécnica de Madrid) (Spain), Universidad Tecnológica de Bolívar (Colombia), University of the West Indies (Jamaica), University of Pretoria (South Africa), and from TEC (Instituto Tecnológico de Costa Rica) (Costa Rica).

2.8.-Conclusion.

The main goal of this thesis: Improving the monitoring and diagnosis of solar plants by means of a low-cost system, has been successfully accomplished. The resulting integrated device can trace local I-V curves at module level and to evacuate the data obtained through a PLC communications system, responding clearly to the objectives defined (SO1 and SO2). As a result of this primary development process some other achievements have been reached. For example, the PLC communications system designed for evacuating the *I-V* curves measured by the local boards in the PV modules can find a much wider field of application, resulting in a general-purpose low-cost communications system adapted to PV plants topology. Also, the device developed for three quadrant single PV cell I-*V* tracing represent one of the main novelties here presented, since no other instrument with this functionality has been found in literature.

Usually, practical feasibility is closely related to price, and for this reason it is worth making a design effort to get proper working devices at the lowest cost possible.

This has been the main motivation during the development of this thesis, that finally ended up with the central achievement of this work: a compact electronic design able to trace the I-V curves of individual modules within a PV string in an online fashion, and to send the data through a novel PV specific PLC communications system, and all this at a low cost (**Figure 3**).

The PLC system can find applications for transmitting any other kind of data or even control signals, so, as mentioned before, it has a wide range of applicability out of the specific task described here.

As usually happens, along the timeline of a research process around some specific subject some other secondary aspects attract the interest of the researcher. This was the case of the tangential works presented in this thesis:

- The three quadrant I-V tracer.
- The mathematical double transformation proposal for photovoltaic cell one diode model parameter extraction.

The main objectives exposed for this thesis have been accomplished successfully, but the end of this work can be considered also as a new starting point for future research. The three quadrant I-V tracer has been already used for a study for PV cells characterization from measurements through artificial intelligence **[34]**, but it will be a powerful tool for future works involving three quadrant PV cell I-V characteristics measurements.

An article about the mathematical method proposal for photovoltaic cell one diode model parameter extraction is now in process, and the software based in this method could be an interesting tool for following up the PV modules ageing from I-V curves measurement.

Finally, the compact online I-V tracer with specific PV PLC communications is a source of data that can serve not only for its main application of monitoring and diagnosis, but also for research about the time evolution of solar modules efficiency.

Annex I: A transformation proposal for One Diode Model parameter extraction.

A complementary task in this thesis was accomplished for helping in the interpretation of the I-V curves captured by the device here designed: a double mathematical transformation over the I-V data measured has been proposed and analysed for the one diode model of solar cells parameter extraction. The one diode model of the solar cell or solar module has been widely utilised in literature for characterization purposes. **Figure 8** shows the circuit corresponding to this model, whose I-V curve is expected to behave like the solar cell one. Four components are needed for this model: an ideal current generator, a diode and two resistors.

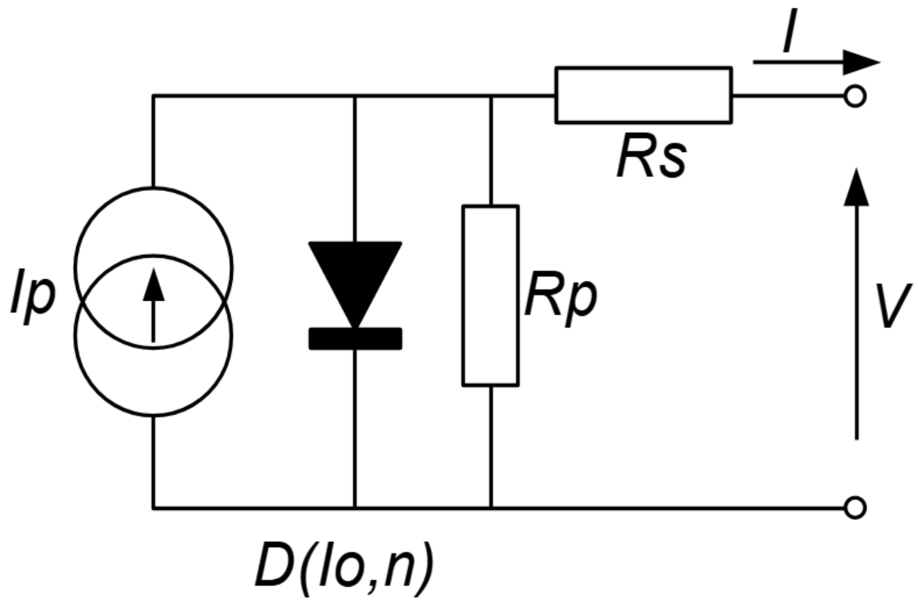


Figure 8

This is the simplest model of solar cells that one can conceive, but it is powerful enough to reproduce the essential electric behaviour of these devices. The model allows the curves classification through five parameters corresponding to values of the lumped components of the circuit:

- Photogeneration current: *Ip*.
- Series resistance: *Rs*
- Shunt resistance: *Rp*
- Diode saturation current: *Io*
- Diode ideality factor: *n*

This model can be easily adapted to represent a solar module in place of a single solar cell. Since a module is made of several solar cells in series, the association of equal single cell model circuits in series can represent the full module. For a module the basic components (generator, diode, Rs and Rp) can be lumped in single equivalent components for simplicity, reducing the circuit to the same topology of the single cell's by proper calculation of the new values for the components.

The mathematical expression that arose from this model circuit and relates solar cell's output voltage (V) and output current (I) is:

$$I = I_p - \frac{V+I\,R_S}{R_p} - I_o\left[e^{\frac{V+I\,R_S}{n\,V_T}} - 1\right]$$

$\left(V_T = \frac{KT}{q}\right)$ $K = Boltzmann\ constant, q = electron\ charge$

This is not an explicit expression for determination of V nor I, and for this reason fitting an experimental curve to the model formula is not a straightforward task.

The PV modules monitoring process by means of the one diode model will be as follows:

- Measures of individual modules I-V curves are taken by the device designed in this thesis.
- These curves are optimally fitted to the one diode model mathematical expression, and then the corresponding parameters are extracted.
- The value of the parameters obtained allow the estimation of the module performance, and its evolution over time can give us information about ageing of the system.

The proposal here described will try to ease the second step. A lot of literature with different approaches to this problem has been found. The non explicit expression of the model leads us usually to computational methods for fitting and parameter extraction. Some complex analytical or pseudo analytical processes have also been described.

One key point is the criteria taken to evaluate the goodness of the fitting when a mathematical curve corresponding to a set of parameters is compared with the measured one. A basic and easy method for this is the least squares one that evaluates the error as a sum of the squared differences between the voltage values in the mathematical and measured curve for the different values of current, or vice-versa. However, the error obtained with this method is strongly dependent on the shape of the curve and does not evaluate properly the proximity of the measured points to the theoretical ones. The fact that measurement errors affect both variables (V and I) make the least squares method especially inaccurate, because error is evaluated only along one variable axis. The ideal criteria for error evaluating is the error calculation through the orthogonal distance between the curves, but this implies a high computational cost for its complexity.

As a trade-off solution between computational cost and proper error evaluation, here a double mathematical transformation over the model formula is proposed. The same transformation will be executed over the measured data curve, and this will be then fitted to the modified model expression obtained before.

The benefits of this transformation over the fitting process are that the simple least squares method can be utilised for error evaluation with results close to the orthogonal distance option for the particular shape of cell (or module) I-V curves. This means that this is not a universal method but one specific for cell or module I-V curves fitting.

The transformation is based on the observation that with a proper escalation of the axes the typical solar I-V curves are not far away from one quadrant of the unity circle. After a normalisation of the axes to get an I-V curve cutting them in V=1 and I=1 we use a polar coordinates system for the least squares error evaluation, and the distance between the measured and theoretical points is evaluated along the radius for the different values of the angle (between 0 and pi/2). For a quarter unity circle shaped curve, this transformation and least squares fitting over the radius leads exactly to a minimum orthogonal distance evaluation. The shape of the I-V curves, close to a quarter unity circle, makes that the distance error evaluated like this is much closer to the ideal orthogonal distance.

This method has been tested over the dark curves measured as described in the presented paper A2: “Online Distributed Measurement of Dark I-V Curves in Photovoltaic Plants.” For dark curves the photogeneration current (*Ip*) is equal to zero, and the curve fitting depends only on four parameters. Considering *Ip=0* and the fact that current (*I*) is injected towards the solar device for dark curves tracing, in place of extracted from it, the model equation for dark curves yields:

$$I = \frac{V - I\,R_s}{R_p} + I_o\left[e^{\frac{V - I\,R_s}{n\,V_T}} - 1\right]$$

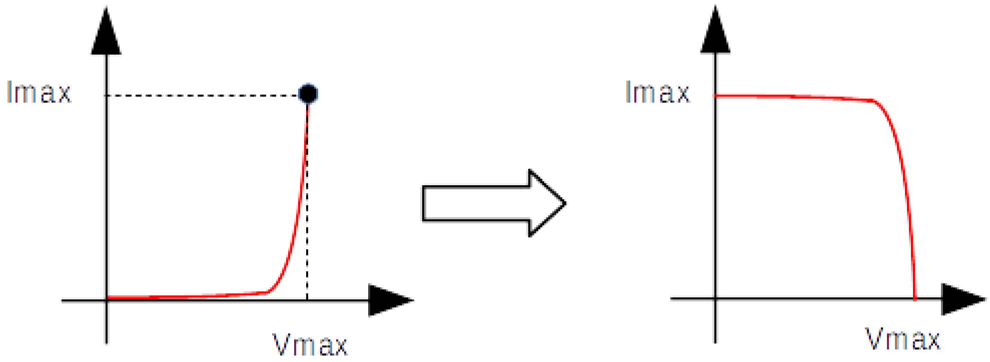
Where the sign of I has been inverted.

Dark curves sweeping always start in I=0, V=0 point and end in I= Imax, V=Vmax point, where Imax is the maximum current injected to the module for measuring and Vmax the corresponding module voltage.

For dark I-V curves, the first step of the double transformation proposed is an inversion and translation over the vertical axis (current) described by:

$$I_1 = I_{max} - I$$

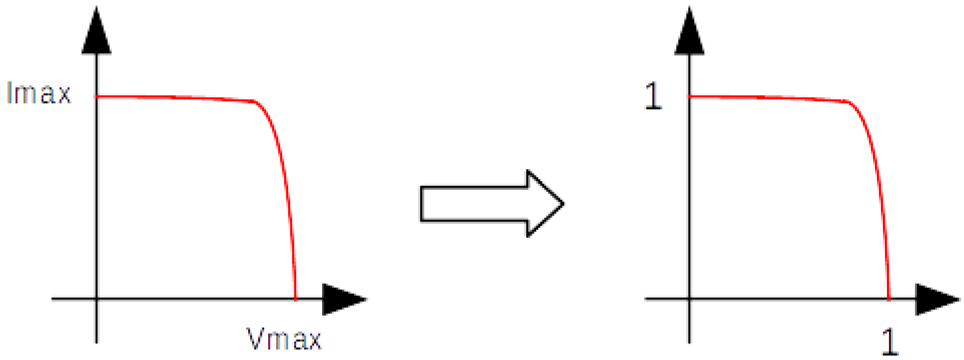
This first step leads to an illumination like I-V curve, suitable for the process aforementioned:



Next, we apply a normalisation to both axes:

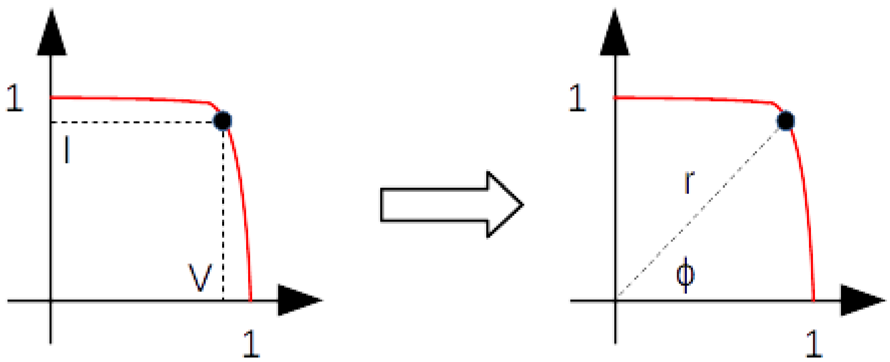
$$I_2 = I_1/I_{max} = 1 - I/I_{max}\ , V_2 = V/V_{max}$$

After this, we get an I-V curve cutting the axes in (1,0) and (0,1), close to a quarter of the unity circle:



Finally, we change to polar coordinates:

$$r = \sqrt{{V_2}^2 + {I_2}^2}\ , \phi = atg(\frac{I_2}{V_2})$$



Applying the same transformations to the One Diode model formula, and taking in account that for dark curves Ip=0, we get the theoretical expression for the model:

$$r = \frac{1 + \frac{R_{s2}}{R_{p2}} - I_{02}\left[e^{\frac{r(cos(\phi) + R_{s2}sin(\phi)) - R_{s2}}{n\,V_{T2}}} - 1\right]}{sin(\phi)\left[1 + \frac{R_{s2}}{R_{p2}}\right] + \frac{cos(\phi)}{R_{p2}}} \quad (1)$$

where the transformed parameters are related to the original ones by:

$$I_{o2} = \frac{I_o}{I_{max}}\ , R_{s2} = R_s\frac{I_{max}}{V_{max}}, R_{p2} = R_p\frac{I_{max}}{V_{max}}\ , V_{T2} = \frac{V_T}{V_{max}} \quad (2)$$

It is quite important to realise that the measured values Imax and Vmax are utilised for the transformation, and then the accuracy of the whole process is strongly dependent on the precision of the measurements of these particular values. For this reason, this point (Imax, Vmax) must be measured with the maximum possible accuracy. The strategy for this was to measure this point several times before starting sweeping and to average all the values to eliminate aleatory influences such as the noise.

Supposing that (*Imax,Vmax*) is a point over the theoretical curve allows us to reduce the number of free parameters from four to three, since fixing three of them, the other one can be analytically calculated imposing that (*Imax,Vmax*) comply with the theoretical formula. The parametric space for computational fitting is then reduced to a three-dimensional one.

Applying this double transformation to the measured values and fitting the corresponding curve by least squares to the expression (1) with the angle as independent variable and the radius as dependent variable, the transformed parameters can be extracted. The original parameters can be then recovered inverting the relations (2).

A.1. Results of the double transformation proposal.

For testing this process, a program was written in Python, implementing the double transformation here proposed for distance error definition between the theoretical and measured curves. The fitting process was performed by a standard minimization algorithm (Powell) through a predefined module in Python (scipy.optimize.minimize).

The test over real measured data showed processing times in the order of tens of seconds with a Intel I7 processor and 16 Gb of RAM, and for all the cases the distance minimization process was convergent.

To estimate the accuracy in the parameter determination, as a first step, synthetic curves were used as input of the program. These curves were generated from the original one diode model formula by iteration with another Python program. Later different levels of artificial noise were added to both variables I and V in order to simulate the measurements errors. This way we know the original parameters values of the curve analysed and they can be varied.

The parameter determination under these conditions were acceptable, showing much more precision in the Rs, Io and n values, but worse results for Rp. This seems to be an intrinsic characteristic of the One Diode model parameter extraction, because the same difficulty for Rp determination is found in all the literature analysed about this subject. Anyway, at this first step, the implementation of the method proposed showed a surprising performance with a very simple software able to run even in minicomputers like Raspberry Pi.

This work has not been published yet, because a proper validation of the results is missing. This validation will be a future work and will require the physical construction of a One Diode model circuit where the real components can be varied, and the parameters adjusted for a later curve measurement. These curves will be then adjusted by our software and the parameter extraction performed. The parameters extracted can be finally compared with those adjusted on the real circuit as a validation of the accuracy of the method.

Annex II: Python software for communications in the external host.

```
from serial import Serial

import os

import time


while True:                    # Bucle de apertura y/o configuracion del puerto serie________________

  try:

    fpor = open('srport')     #intenta abrir el fichero de configuracion de puerto serie

    srport = fpor.readline()  #lee el valor del puerto del fichero srport

    fpor.close()              #cierra el fichero de configuracion del puerto serie

    ser = Serial(srport, 9600, timeout=1)  #intenta abrir el puerto serie configurado

    break                   #si todo fue bien sale del bucle


  except:                     #aqui se llega si fallo la apertura del puerto o del fichero de
configuracion

    print()

    print ("puerto sin configurar o mal configurado...revisar!!!")

    print()

    serport = input("Introducir nuevo puerto serie (/dev/ttyUSB0, /dev/ttyUSB1, ...): ") #se pide y
lee nuevo puerto serie

    print()

    if os.path.isfile('srport'):          #Si existe el fichero srport (conf serie) en el path
actual

      os.remove('srport')     #borra el fichero antiguo srport

    fpor = open('srport','a')           #y lo crea de nuevo

    fpor.write(serport)                   #y aqui escribe el nuevo valor del puerto

    fpor.close()                          # y cierra el fichero

add='3'

coman = "0"


while (coman != "s"):            # Bucle de lectura de
comando________________________________________


  #os.system('clear')    #Limpia la pantalla

  print ("Comandos disponibles:")              #cabecera informativa

  print ("v: leer tension")

  print ("c: leer corriente")

  print ("t: trazar I-V")

  print ("s: Salir del programa")

  print()
```

```
coman = input("Introducir Comando: ")     #se pide y lee comando
os.system('clear')    #Limpia la pantalla

# AQUI EMPIEZA EL BUCLE DE EJECUCION PRINCIPAL____________________________________________

if (coman != "s"):
    try:               # Si hay cualquier error en el bucle, se vuelve al menu

        if (coman=="t"):
            data=open("data.txt", "w")
            ser.write(str.encode('t'))      #Envia Ccomando start
            ser.write(str.encode(add))    #Envia direccion del modulo bajo test
            lin=ser.readline() #leo la ese
            for i in range(1,248):
                lin=ser.readline()
                I=float(int(lin[0:4],16))
                lin=ser.readline()
                V=float(int(lin[0:4],16))
                print(str(V)+" "+ str(I))
                try:
                    data.write(str(V)+" "+str(I)+" "+str(i)+"\n")
                except:
                    print("error escribiendo a fichero")
                    pass
            data.close()

        if (coman=="c"):
            ser.write(str.encode('c'))
            lin=ser.readline()
            if (len(lin)>5):
              print(int(lin[1:5],16))
            else:
              print(int(lin[0:4],16))

        if (coman=="v"):
            ser.write(str.encode('v'))
            lin=ser.readline()
            if (len(lin)>5):
              print(int(lin[1:5],16))
            else:
```

```
                print(int(lin[0:4],16))


          if (coman=="p"):
                 ret=input("introduce retardo (dec):")
                 try:
                     ent=int(ret)
                     if((ent>-1) & (ent<256)):
                        ser.write(str.encode('p'+str(hex(ent)[2:])))
                        lin=ser.readline()
                        print("Se ajusto retardo a: "+str(int(lin,16)))
                     else:
                        print("solo valores entre 0 y 255\n")
                 except:
                     print("entrada no valida\n")
                     pass
      except:                    # AQUI TERMINA EL BUCLE DE EJECUCION PRINCIPAL
          print("error en menu")
          pass


ser.close()
print ("Adios!!")
```

Next page shows the output text data file generated by this software during the general test. Each line contains two samples separated by a space corresponding to one point in the curve: the first one is the voltage and the second one is the current.

0.099609375 0.00000000000
0.9462890625 0.00493164063
1.8427734375 0.01124218750
2.98828125 0.01669140626
4.083984375 0.01669140626
5.478515625 0.02279492188
6.9228515625 0.01058789063
8.0185546875 0.04110546876
9.0146484375 0.05331250000
9.9111328125 0.04720898438
10.7080078125 0.08383007813
11.4052734375 0.05331250000
12.3017578125 0.08383007813
13.7958984375 0.07772656250
15.3896484375 0.10214062500
17.033203125 0.10214062500
18.3779296875 0.13876171876
19.623046875 0.14486523438
20.91796875 0.15707226563
22.0634765625 0.19369335938
23.109375 0.16317578126
24.205078125 0.20590039063
25.0517578125 0.26083203126
25.7490234375 0.26083203126
26.197265625 0.24862500000
26.595703125 0.30355664063
26.89453125 0.32186718750
27.2431640625 0.30966015626
27.4921875 0.38290234376
27.791015625 0.38290234376
27.990234375 0.47445507813
28.2392578125 0.43783398438
28.48828125 0.41341992188
28.787109375 0.45614453126
29.1357421875 0.46835156250
29.4345703125 0.47445507813
29.7333984375 0.46224804688
29.9326171875 0.51717968750
30.181640625 0.59652539063
30.380859375 0.55380078126
30.6796875 0.53549023438
30.9287109375 0.60262890626
31.177734375 0.65756054688
31.4765625 0.70638867188
31.7255859375 0.73080273438
31.875 0.73080273438
32.0244140625 0.80404492188
32.1240234375 0.76742382813
32.2236328125 0.84676953126
32.3232421875 0.77963085938
32.373046875 0.87118359376
32.47265625 0.89559765626
32.572265625 0.99325390626
32.671875 0.92001171876
32.771484375 0.92611523438
32.87109375 0.94442578126
32.970703125 0.96883984376
33.0703125 1.04208203126
33.1201171875 1.02377148438
33.169921875 1.09091015626
33.26953125 1.09091015626
33.369140625 1.12753125000
33.46875 1.16415234376
33.5185546875 1.22518750000
33.66796875 1.28011914063
33.767578125 1.27401562500
33.8173828125 1.28011914063
33.8671875 1.33505078126
33.9169921875 1.32894726563
34.0166015625 1.38998242188
34.06640625 1.39608593750
34.1162109375 1.46932812500
34.166015625 1.48153515626
34.265625 1.54257031250
34.3154296875 1.51815625000
34.365234375 1.57308789063
34.4150390625 1.52425976563
34.46484375 1.51815625000
34.46484375 1.65243359376
34.564453125 1.66464062500
34.6640625 1.64633007813
34.6640625 1.66464062500
34.763671875 1.73177929688
34.8134765625 1.76229687500
34.8134765625 1.76840039063
34.9130859375 1.73788281250
34.962890625 1.89047070313
35.0126953125 1.78671093750
35.0625 1.88436718750
35.1123046875 1.82943554688
35.162109375 1.85384960938
35.2119140625 2.04916210938
35.3115234375 1.98812695313
35.26171875 2.01864453126
35.361328125 1.99423046876
35.4111328125 2.05526562500
35.4609375 2.11019726563
35.5107421875 2.04305859376
35.560546875 2.14681835938
35.6103515625 2.12850781250
35.66015625 2.19564648438
35.759765625 2.23837109376
35.759765625 2.23226757813
35.8095703125 2.23226757813
35.859375 2.25057812500
35.9091796875 2.25668164063
35.958984375 2.29940625000
36.0087890625 2.31161328126
36.05859375 2.37264843750
36.1083984375 2.42147656250
36.158203125 2.42147656250
36.2080078125 2.38485546876
36.2578125 2.51913281250
36.2578125 2.55575390626
36.357421875 2.54354687500
36.357421875 2.56796093750
36.357421875 2.48251171876
36.4072265625 2.61068554688
36.45703125 2.59847851563
36.45703125 2.71444531250
36.5068359375 2.66561718750
36.556640625 2.65951367188
36.6064453125 2.72054882813
36.6064453125 2.76937695313
36.65625 2.65341015626
36.65625 2.81210156250
36.7060546875 2.76327343750
36.755859375 2.86703320313
36.8056640625 2.86092968750
36.85546875 2.86703320313
36.9052734375 2.95858593751
36.9052734375 2.89144726563
36.955078125 2.94637890626
37.0546875 2.99520703126
37.0546875 2.97079296876
37.1044921875 3.08065625001
37.154296875 3.01962109376
37.2041015625 3.16000195313
37.2041015625 3.12338085938
37.25390625 3.21493359376
37.3037109375 3.14169140626
37.353515625 3.26986523438
37.4033203125 3.20883007813
37.4033203125 3.26986523438
37.453125 3.25765820313
37.453125 3.26376171876
37.5029296875 3.36141796876
37.552734375 3.42245312501
37.552734375 3.39193554688
37.6025390625 3.42245312501
37.6025390625 3.43466015626
37.6025390625 3.51400585938
37.65234375 3.41024609376
37.65234375 3.45907421876
37.7021484375 3.47128125001
37.7021484375 3.45297070313
37.751953125 3.53841992188
37.751953125 3.54452343751
37.8017578125 3.53841992188
37.8017578125 3.57504101563
37.8017578125 3.57504101563
37.8515625 3.53231640626
37.8515625 3.53841992188
37.8515625 3.55673046876
37.9013671875 3.52010937501
37.9013671875 3.59945507813
37.9013671875 3.58724804688
37.9013671875 3.69100781251
37.951171875 3.58724804688
37.951171875 3.62997265626
37.951171875 3.60555859376
37.951171875 3.71542187501
38.0009765625 3.77035351563
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37.951171875 3.62997265626
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38.0009765625 3.78256054688
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38.05078125 3.76425000001
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38.05078125 3.76425000001
38.05078125 3.73983593751
38.1005859375 3.74593945313
38.05078125 3.75204296876
38.1005859375 3.78256054688
38.1005859375 3.76425000001
38.1005859375 3.76425000001
38.1005859375 3.77645703126
38.1005859375 3.79476757813
38.1005859375 3.75814648438
38.1005859375 3.81918164063
38.1005859375 3.73373242188
38.1005859375 3.74593945313
38.150390625 3.80697460938
38.1005859375 3.76425000001
38.150390625 3.72762890626
38.150390625 3.73373242188
38.150390625 3.78256054688
38.150390625 3.80087109376
38.150390625 3.79476757813
38.150390625 3.81918164063
38.1005859375 3.83749218751
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38.150390625 3.88021679688
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38.2001953125 3.77035351563
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38.150390625 3.86190625001
38.150390625 3.81307812501
38.150390625 3.87411328126
38.150390625 3.83138867188
38.2001953125 3.86800976563
38.150390625 3.88021679688
38.2001953125 3.85580273438
38.150390625 3.75204296876
38.2001953125 3.81918164063
38.2001953125 3.81918164063
38.2001953125 3.80697460938

Annex III: Resumen en español de las secciones de Objetivos y Resultados.

Objetivos.

El objetivo global de esta tesis es **mejorar las tareas monitorización y diagnóstico de las instalaciones de energía solar mediante el diseño de dispositivos avanzados de bajo coste capaces de obtener información sobre el estado y la degradación del sistema, con la finalidad de facilitar el proceso de mantenimiento e incluso predecir potenciales fallos en el futuro**. Pensando en una posible implementación comercial de los diferentes dispositivos que han surgido de esta investigación, el bajo coste ha sido siempre una condición indispensable.

Tras un análisis del tipo de dispositivos y posibles configuraciones capaces de cumplir este objetivo global, se concretan los dos siguientes objetivos específicos principales:

SO1.->Diseño, implementación y validación de un trazador I-V “en línea” de bajo coste capaz de capturar la curva I-V de cada módulo solar individual. Este diseño deberá incluir todos los elementos necesarios para el trazado de la curva I-V, almacenamiento de los datos e interconexión con un sistema de comunicaciones apropiado para la evacuación de los datos.

SO2.-> Diseño, implementación y validación de un sistema de comunicaciones PLC (“Power Line Communication” en inglés) de bajo coste, específico para la topología del cableado de una planta solar. Para completar el diseño de este sistema PLC, una aproximación teórica previa será necesaria sobre los modos de propagación sobre esta topología del cableado de una planta solar.

El desarrollo de esta tesis y el análisis realizado sobre el estado del arte ha resultado en algunos otros objetivos secundarios cumplidos como:

- Implementación dentro del diseño realizado del trazador I-V “en línea” de la capacidad de realizar medidas de curvas I-V en oscuridad con ayuda de un inversor bidireccional capaz de inyectar corriente a través de una asociación serie de módulos solares.
- Diseño, implementación y validación de un trazador I-V de células solares individuales a tres cuadrantes para laboratorio.
- Desarrollo de una transformación matemática concebida para facilitar la extracción de los parámetros de un módulo solar asociados con el modelo de un diodo a partir de medidas de curvas I-V en oscuridad.

Resultados.

El principal logro de este trabajo ha sido el diseño, construcción y validación de una placa electrónica de bajo coste ("MB: Main Board" en inglés) que integra todos los componentes necesarios para cumplir los dos principales objetivos de esta tesis (SO1 y SO2). Combinados, todos los componentes resultan en una placa muy sencilla y barata conectada a cada módulo solar capaz de medir la curva I-V del módulo "en línea", es decir, sin interrumpir la producción de energía de la asociación en la que el módulo está integrado, y capaz de trasmitir los datos I-V hacia una centralización en la caja de conexiones a través de los mismos cables de potencia.

Se llevó a cabo una prueba final de este sistema de acuerdo con el esquema mostrado en la **Figura 4** y la secuencia que se muestra debajo del mismo.

Las **Figuras 3 y 5** muestran respectivamente fotografías de la placa principal (MB) y el módulo que incluye las placas TRB ("Transceiver Board" placa transceptora en inglés) y TB ("Tunning Board" placa de sintonización en inglés) utilizadas en la prueba final.

La **Figura 6** muestra capturas de osciloscopio de la señal de comunicaciones PLC en la línea y en diferentes puntos de su procesamiento.

La **Figura 7** muestra la curva I-V obtenida en esta prueba general (puntos azules), junto con la curva ajustada (línea roja) mediante la transformación matemática propuesta en esta tesis para la extracción de parámetros correspondientes la modelo de un diodo. El valos obtenido para los parámetros se muestra también en la figura.

Por último, la **Figura 8** muestra la salida del programa de ajuste escrito en Python que implementa la trasformación matemática propuesta.

Además, el Anexo II incluye el programa en Python mencionado y la salida de texto de este programa correspondiente a los datos representados en la **Figura 7**

Otro de los logros expuestos en esta tesis ha sido el diseño, construcción y validación de un trazador I-V de laboratorio capaz de capturar curvas I-V de células solares individuales en los tres cuadrantes en que éstas tienen puntos de trabajo. Este instrumento ha sido la principal herramienta para las medidas que dieron lugar al artículo de la referencia [36] cuyos autores son compañeros de departamento del autor de esta tesis.

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PUBLISHED ARTICLES

The DOI corresponding to the articles presented as a compendium for this thesis are included below

A1

Título: **Low-Cost Electronics for Online I-V Tracing at Photovoltaic Module Level: Development of Two Strategies and Comparison between Them**

DOI: https://doi.org/10.3390/electronics10060671

A2

Título: **Online Distributed Measurement of Dark I-V Curves in Photovoltaic Plants.**

DOI: https://doi.org/10.3390/app11041924

A3

Título: **Low-Cost Three-Quadrant Single Solar Cell I-V Tracer.**

DOI: https://doi.org/10.3390/app12136623

A4

Título: **A Resonant Ring Topology Approach to Power Line Communication Systems within Photovoltaic Plants.**

DOI: https://doi.org/10.3390/app12167973

A5

Título: **A Power-Line Communication System Governed by Loop Resonance for Photovoltaic Plant Monitoring.**

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