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Reliability and fault-tolerance of photovoltaic systems

ABSTRACT

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2. Prof. Todor Atanasov Stoilov - external

The PhD materials are available for everybody interested in Technical faculty of Southwest University, building 1, office 1604.

The doctoral student is on independent form of education at Electrical engineering, Electronics and Automation department, Technical faculty of Southwest University.

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Title: Reliability and fault-tolerance of photovoltaic systems

GENERAL CHARACTERISTIC OF THE DISSERTATION

Relevance of the problem

In the last few years, many commercial and residential photovoltaic (PV) installations have constructed, many of them are now over 10 years old are close to midlife design service. The last few years more and more failures occur in old installed systems and many of them could have been avoidant. The main problem is the unexpected reduction of electricity production in photovoltaic parks after a few years of operation. There is a need to explore the causes of reduced production and ways to recover from the problems but also improvements that can be made to increase energy production and reducing the maintenance costs. Special emphasis have to be placed on ways of early diagnosis of failures with the combined use of specialized electronic measuring equipment and analysis of operation data. It is important to study ways that old photovoltaics can contribute more linear grid feed and suggestions for improving photovoltaic systems (PVS) with and without repowering of PV parks. A modelling of the factors that can affect PV Inverter Reliability and modelling of reliability of PV installations have to be researched. The existing methods that can lead to increase the reliability and performance of PV parks could be improved.

Goal and objectives of the dissertation

The main goal of the dissertation is to investigate present failures in PV systems and to analyze the reasons for the decrease in their productivity; to introduce a systematic approach to grouping failures and to analyze the role of the load on the components performance and how it affects the systems reliability; to investigate the effect of various factors on reliability, fault tolerance and yield reduction of PV systems.

For accomplishment of the set goal it is necessary the next objectives to be done:

1. To investigate and analyze existing failures in PVS.
2. To analyze modern methods for analyzing and predicting the reliability of PVS.
3. To analyze the reasons for the decrease in the productivity of the PVS.
4. To propose a systematic approach to the analysis of the load on the components to determine the reliability of the PVS.
5. To develop a method for increasing the fault tolerance and efficiency of the PVS.
6. To investigate specific factors in the design of the PVS depending on the geographical location and climatic features of the installation site.
7. To propose a methodology for regeneration of photovoltaic parks with reduced electricity production.

Scientific relevance

The existing failures in PVS have been studied and the reasons for the decrease in their performance have been analyzed. A systematic approach has been introduced for grouping failures and analyzing how the load on the components affects the reliability. It is suggested a method for early prediction of failures and a predictive assessment of the reduction in productivity in accordance with the operational conditions of photovoltaic parks. The influence of various factors from the "Installation" and "Operation" phases on the reliability, fault tolerance and reduction in PVS yield is studied. Empirical real time data was collected using a telemetry system and additional data was collected from the PVS operation logs, covering the period from their installation to the present. A study and analysis of the causes of the sharp and unforeseen decrease in the productivity of some photovoltaic systems has been conducted. A methodology for the regeneration of photovoltaic parks with reduced electricity yield has been proposed. A new approach to the service and maintenance of PVS is proposed, which reduces the costs and increases the period of trouble-free operation, increasing their reliability and efficiency. A model has been adapted for a differentiated approach and specific factors have been appointed and studied in the design of photovoltaic systems depending on the geographical location and climatic characteristics of the installation site.

Practical application

The solutions described in PhD work are used in installations near the villages of Kosmio and Kalamokastro, town Komotini, PV park near the village Ammaranta, PV park near the area Platanitis, Greece.

Scientific publications

The basic results of the dissertation are included in 5 publications; 4 of them are presented at international conferences - one is printed in IEEE jurnal, tree are pending printing.

Dissertation structure

The dissertation is laid out in 175 pages. It consists of an introduction four chapters and a list of 123 references. It contains, 23 tables, 52 formulas, 142 figures.

BRIEF CONTENT OF THE DISSERTATION

Chapter 1. Literature review

In chapter one there is an induction to the photovoltaic basic concepts, modelized the PV module but also analyses failures that occur at PVS. The failures are divided into three categories - Design, Hardware and Weather phenomena. There are proposed effectives ways to diagnose some common types of failures that appear to PVS.

1.1. Solar Cell

Solar cells or usually known as photovoltaic (PV) cells can convert the irradiance the sun instantly to electricity through the photovoltaic effect. The crystalline silicon based solar cells are mainstream technology in PV cells were used at residential, commercial and utility PV projects all over the word. Crystalline silicon is the crystalline form of silicon and is categorized into two main types, the first one is polycrystalline silicon which consisting of small crystals and the second one type is the monocrystalline silicon which is made up from a single continuous crystal. Solar cells made of crystalline silicon are often called conventional, as they were developed in the mid of decade of 50's and until today are the most frequently type that used in PV installations from PV developers. Since they are made in slices of 150–180 μm thick cutting the silicon ingots. Many times, solar cells are called wafer-based PV.

1.1.2 Crystalline solar cell manufacturing process

The fundamental material that is utilized in solar cell manufacturing is natural sand which contains silicon. The silicon is commonly produced from quartz sand in an hight energy demands electric arc furnace operating at intense temperatures.

1.1.3 Solar Cell model

Solar cells are p-n junction where an electric field develops which as in a regular diode result in the separation of the charge carriers. In case of solar irradiance with sufficient energy into semiconductor material the electrons are released. The correlation frequency and photon energy are outlined as follows:

$$\boldsymbol{W = h * \mu} \qquad (1)$$

where h = Planck constant (6,626·10-34Js), μ = frequency (Hz).

The model of the cell Includes diode and current source connected parallelly and one series resistor and one shunt resistor. Current source current Is closely related to the solar irradiance. Diode expresses PN junction of a solar cell. The output current of the cell Is determined [5] as shown below:

$$\boldsymbol{I_{pv} = I_{ph} - I_0 \left[exp\left(\frac{v_{pv} + I_{pv} * R_s}{a * V_t}\right) - 1\right] - \left(\frac{v_{pv} + I_{pv} * R_s}{R_{sh}}\right)} \qquad (2)$$

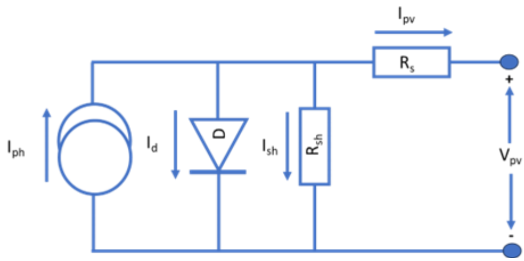

Fig.1. Single diode model of solar cell

For the single diode model, five variables to be extracted Iph, I_0, Rs, Rsh, and a. The perfect understanding that key specifications of solar cells is essential for the design, quality control of solar cell and manufacturing procedures fine optimization.

1.1.4 Crystalline solar panel main components

Solar modules are manufactured in many configurations which meet different installations needs. The most common configuration globally uses the following parts: Photovoltaic cells, Hardened antireflective glass 1.6 to 4mm, Anodized AL. frame, Two transparent EVA film layers, White Polymer rear back sheet in monofacial design, Plastic or Polymer Junction box, bypass diodes, cables, DC connectors

1.2 Electrical characteristics of photovoltaic solar panels

The manufacturer factory of the photovoltaic modules gives a technical data document in which contains the mechanical, the electrical characteristics and guarantee data. All PV modules are evaluated at Standard Test Conditions (STC).

1.2.1 Temperature effect on solar panels

The silicon crystalline wafer topology is mostly used in PV module manufacturing has a negative power temperature coefficient. Because of that coefficient with increasement of temperature, the conversion efficiency of the PV module will decrease. Open circuit voltage (V_{oc}) is the rate of recombination in a Silicon based solar cell s equivalent to:

$$V_{OC,Tmodule} = Voc_{stc} - \left[Coef_{Voc}\% * \left((T_{stc} - T_{module})\right)\right] * Voc_{stc} \quad (3)$$

where $V_{OC,Tmodule}$ denotes the voltage that have in open circuit conditions at normal ambient temperature T_{module}, is the temperature of solar cells panel at the time of measurement, $V_{OC,STC}$ is the open circuit voltage at STC and T_{STC} are the STC temperature (25C^o).

The equation between I_{SC} and temperature is:

$$I_{sc,Tmodule} = Isc_{stc} - \left[Coef_{Isc}\% * \left((T_{stc} - T_{Tmodule})\right)\right] * Isc_{stc} \quad (4)$$

Where $V_{SC,Tmodule}$ denotes the sort circuit current at ambient temperature, T_{module} is the temperature of cells module, $Isc_{,STC}$ is the sort circuit current at STC and T_{STC} are the STC temperature (25C°).
The equation between Power output and temperature is:

$$\boldsymbol{P_{out,Tmodule} = P_{stc} - \left[Coef_{P}\% * \left(\left(T_{stc} - T_{Tmodule}\right)\right)\right] * \ P_{stc}} \qquad (5)$$

where $P_{OUT,\ Tmodule}$ denotes the power output at ambient temperature, T_{module} is the temperature of cells module, $Pout_{,STC}$ is the power output at STC and T_{STC} are the STC temperature (25C°).

1.2.2 PV module model

The module model of one-diode has very good precise modelling in many cases. DC output power is calculated using a single diode model for, any given module, with weather input data regarding irradiance, temperature and windspeed by this equation:

$$\boldsymbol{P_{pv} = \eta_{PV,STC}\left[1 + \frac{\eta}{\eta_{PV.STC}} * \left(T_a - T_{STC}\right) + \frac{\mu}{\mu_{PV}} * \frac{9.5}{5.7+3.9v} * \frac{(NOCT-20)}{800} * \left(1 - \eta_{PV,STC}\right) * G_{g,t}\right] * \ A_{PV} * S} \qquad (6)$$

where $\eta_{PV,\ STC}$ is the conversion efficiency of the PV panel at standard test conditions (STC), μ is the temperature coefficient of the PV module of the output power (%/°C), Ta is the external environment temperature (°C) near the PV module, T_{STC} is the normal standard test conditions temperature usually set at 25 °C, v is the wind speed (m/s) that prevalent near the PV module , NOCT is the internal nominal operating cell temperature (°C) at specific values of solar irradiance, A.M. and wind speed , A_{PV} is the PV array surface in square meters (m^2) related to the array installed power and Gg, t is the global sloped irradiance (W/m2), and S is the PV system effective absorbed global solar irradiance.

1.3. PV inverter basics

The PV inverter is a critical and complex equipment of the photovoltaic system. Yearly the PV inverter working thousands of hours under non ideal environmental. The generated direct power from the PV modules inverted to alternating into PV inverter according to the local grid conditions. The manufacture features that each PV inverter have they make them suitable for different applications.

1.3.1. Solar Inverter Types

PV inverters were design for grid connected applications are categorized into four basics groups: String inverters, Central inverters, Microinverters and Hybrid Inverters.

1.3.2 Solar inverter main block diagram

A solar inverter is a connected net of power electronics, logic units, connectivity systems and management boards all above systems are enclosure usually in water resistance case. All grid connected PV inverter where ascertain a dysfunctional power line must automatically disconnect in compliance with locally regulations and safety rules, which differ depending on the region.

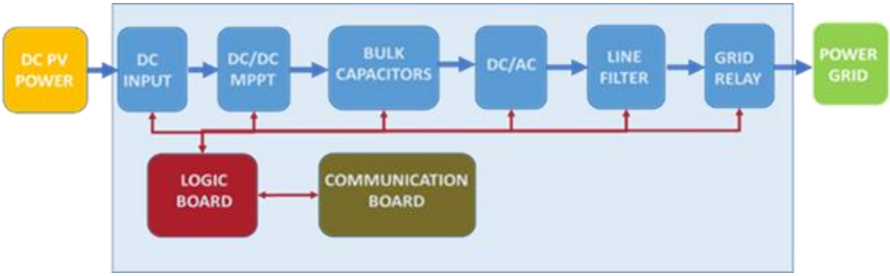

Fig. 2. Solar inverter main block diagram

1.3.3. The main electrical characteristics of solar inverter

The manufacturers of PV inverter provide a specification datasheet for their products in which contains the electromechanical specifications. The main of these are presented below: Maximum DC power, Maximum DC voltage, Maximum input current, MPP voltage range, AC nominal power, Nominal AC voltage and frequency.

1.3.4 Solar grid connected PV system main block diagram

A grid-tied PV installation is a power electricity producing system which is linked to the power distribution grid. A grid-tied PV system includes PV modules, inverter(s), AC and DC power distribution boards, wiring, grid connection equipment, power transformer and support base for the PV panels.

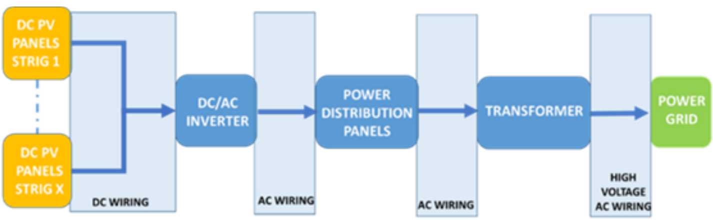

Fig. 3. PV system block diagram with a string inverter

1.4. Categorization of the PV failures and the existing methods and procedures of their resolution

In the last few years there is an exponential growth of residential, commercial and utility photovoltaic installations. After more than a decade of operation many of these installations are near or little above midlife service. These failures can be categorized into three main categories considering the roots its: Design, Hardware and Weather phenomena.

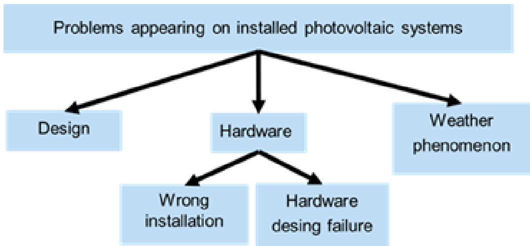

Fig. 4. Categorization of the most common roots of failures on installed PV systems

1.4.1. Design

When designing a photovoltaic system many parameters must be considered. It will first be necessary to determine whether the place where the installation is to take place has the correct prerequisites. The meteorological statistics data of the area must also be considered at the design of the installation. Another factor to consider is the site accessibility year-round for repair works. When designing a photovoltaic system should be taken into account factors as the shadow caused by static objects such as a mountain but also some dynamic elements such as neighboring tree plants that are about to grow tall in the future and shade the PV panels. Also need to watch out for neighboring activities that produce a lot of dust. In many installations it has been found that the electrochemical compatibility between materials has not been sufficiently studied.

1.4.2. Hardware

The hardware PV equipment failures that come into surface can be classified into two primary groups:

- Manufacture faulty design - production process errors
- Omissions during installation procedure -wrong handling

1.4.3. Damage caused by weather phenomena

Extreme weather phenomena can cause damage on photovoltaic equipment which is usually costly and needs a lot of time to repair.

1.4.4. Problems and the most common existing methods and procedures of their resolution

All photovoltaic equipment came with instructions for cycling maintenance were in most of cases deeply described at the installation manual. Every manufacturer provides detailed maintenance instructions for its PV hardware, without treating it as part of an integrated PV system. Unfortunately, the majority of the issues are handled once they arise since the checklist where the engineer of the installation made that fits to the specific photovoltaic system is not followed. These checklists highlight the necessity of providing them to the service crew and adhering to them carefully. The service crew typically consists of certified electricians, although they generally lack of specialization in photovoltaic hardware as well as in the knowledge of usage special measuring instruments engineered for evaluation of performance and health of photovoltaic installations. The most common usable devices of measure equipment are I-V curve testers, insulation testers, infrared cameras and irradiance meter.

1.4.5. More effective ways to deal with problems

When an early diagnosis and the proper repair of a faulty situation can be made, substantial economic advantages may arise to the photovoltaic installation as the total yield losses will be limited. A crucial resource for early identifying issues is the telemetry data were the PV inverter uploads to the monitoring portal system. Also, the usage of a thermal imager can point out short-circuited diodes, busbars interconnection problems, PID effect, corroded cell, overheated inverters- distribution boards.

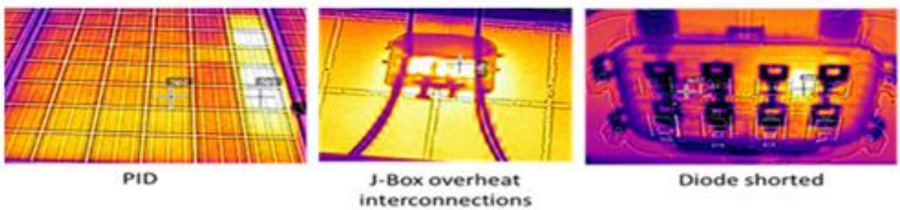

Fig 5.Thermal images, which are taken during the research

1.5. Achievements of chapter 1

The first chapter is an introduction to the basic structure of the subsystems that make up a photovoltaic system. More specifically, reference is made to the mode of operation but also to the mathematical modernity of the photovoltaic cell, then the blog diagram of an integrated photovoltaic system is presented. In the middle of the chapter there is a categorization of the failures that occur in a photovoltaic system during its operation. Then some ways of diagnosing the problems and some ways of solving them using new methods are presented. At the end of the chapter, some real examples of fault detection are given with the use of infrared photography but also with the analysis of data from the telemetry of the photovoltaic system.

Chapter 2. Fault-tolerance research data analysis

2.1. Statistical data

The questionnaire was developed to gather the statistical data were collected in recent years. The data collected concern in research of 23 commercial (9706 solar panels) and 34 residential (1428 solar panels) PV installations. The data outlined in this chapter were obtained through on-site inspections of the photovoltaic systems, electrical, environmental measurements, thermal and physical images were taken.

2.2. Statistical analysis of failures that occur in photovoltaic parks

Data were collected regarding the construction materials of the park such as panels, inverters and mounting systems as well as the maintenance methods, also data of annual energy production were collected. Comparing the actual annual energy yields with those were expected, deviations were observed which in some cases are significant. The efficiency of photovoltaic parks given by the term 'Performance ratio' (PR) which is the ratio of the annual expected energy production by actual annual energy production where PV park was achieved. The results are grouped into three categories depending on the result of the division and then the results are converted into a percentage. In the first category (CAT 1) belong the photovoltaic parks which in the worst year of operation gave performance ratio between 92% and 100%, in the second category (CAT 2) belong the photovoltaic parks which in the worst year of operation gave performance ratio between 80% and 91% and the in the third category (CAT 3) belong the photovoltaic parks which in the worst year of operation gave performance ratio under 80%. The data collected from the 23 parks show that 39.1% of the parks belong to the CAT 1, 43.5% to the CAT 2, 17.4% to the CAT 3.

2.2.1. The most common PV parks failures

Many photovoltaic installations suffer from multiple problems at the same time. The most common failure is current leaks that appears at dc cables especially at undergrounds installations and in soils that retain water for long periods. The second most common are photovoltaic panel failures which usually concern a rapid and unexpected reduction in the efficiency of photovoltaic panels.

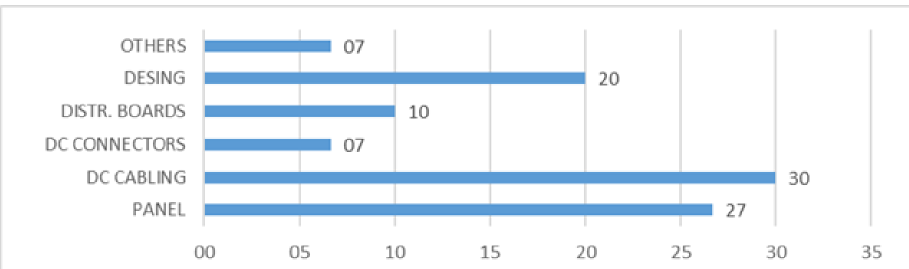

Fig 6. The most common PV parks failures as a percentage

2.2.2. Weather phenomena

Another category of damage to photovoltaic parks is damage caused by extreme weather. Many times, damage could have been avoided if proper planning and implementation had been done. The statistical data from survey shows that 52.2% of the parks have been damaged at least once since the start of their operation until today by a weather phenomenon. Solar trackers (77.8%) suffer more frequent damage in combination with fixed bases (22.2%).

2.3. Cost effective Improvements that can be made in photovoltaic parks in order to increase the annual yield but also to reduce maintenance costs

Based on the data evaluation were collected from the 23 field PV systems revealed that, along with the other failures the 26.1% of field PV systems experienced operational issues because of flawed design. In several parks positioned close the coastline, issues caused by the salt mist have been pinpointed. These issues could be prevented from the design phase, ensuring the usage of appropriate salt-resistant components. A further concern in the planning and building of certain PV installations that was observed is while there was a lot of surface area to install the PV arrays in the field, finally the system was installed in a portion of the plot where, in the winter months, there are inter-row shadings between the rows. Another common recorded issues are the usage of incompatible D.C. connectors was identified which results in insufficient sealing and/or contact along with failing to maintain the cooling clearances in the mounting area of the inverters which sometimes can causes overtemperature issues.

2.4. Ways to improve the reliability of photovoltaic parks

At the initial stage of design attention should be paid to the following points: a) The geographical location and the peculiarities of the climate that prevail at the area of the installation, b) The correct distances and inclinations between the rows should be study for the installation area. c)The design does not interfere with the installation and operation recommendations provided by the equipment manufacturer. d)Have multiple layers of safety and protection so one failure will not lead to another. e) The design should secure that there is no incompatibility between components of the equipment. f) Have the provision so that the replacement of damaged equipment can be done quickly with easy access. g) Future-proofing design.

At the stage of construction attention should be paid to the following points: a) To follow the design plan. b) Proper supervision. c) The equipment must be installed in the correct order and in accordance with the manufacturer's rules and checklists. d) Transport and handling of the equipment must be made according to the manufacturer's specifications. e) The workforce must be trained and specialized.

2.5 Failure rate comparison between residential photovoltaic and commercial grid connected systems.

The comparison between the two categories of photovoltaic systems reveals big differences in the failure rate but also in the type of failures. The generally picture of residential PV systems seems better.

2.6. Solar panel failures caused by material-manufacturing process

The current review of solar panel failures which are due to manufacturing process or material quality. The panel failure data reveals that the most common problem with photovoltaic panels is the PID, followed by failures related to the bypass diodes that the panels have inside the Junction box. The research reveals that the photovoltaic panels show multiple failures or do not show at all this may be due to the quality of the materials but also to the way of assembly and quality control followed during the manufacturing process of the panel.

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Fig. 7. Failures of solar modules in commercial installations as presentence

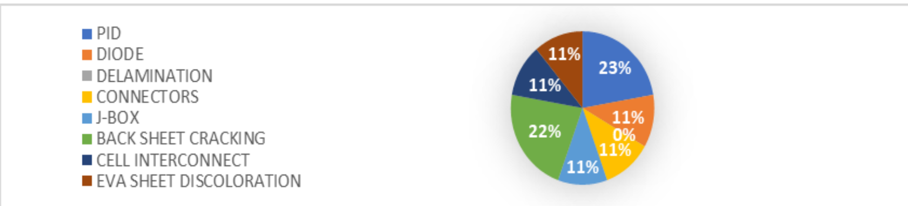

Fig. 8. Failures of solar modules in residential installations as presentence

2.7 Solar inverter reliability

2.7.1 String inverter

The most common type of string inverter is the two-stage transformerless inverter contains of a boost DC-DC converter at the primary lever and after in second lever there is an H-bridge inverter which is and the output were connected to 230 VAC line system. There is an array of DC link capacitor between the two stages of the inverter and on the AC output there is a LCL a filter is applied for regulate the overall harmonic distortion from the output voltage and current oscillations. Each of these elements contributes to power loss in the inverter. Typically, these losses are released as heat, causing an increase at internal thermal condition of the solar inverter. The thermal stress as a result of power losses of power electronics components is linked to certain wear-out and overheat failure modes of the PV inverter, thus impacting the system's reliability performance.

2.7.2. Power Losses

Power losses in combination with environmental temperatures can create temperature variations inside the inverters, this results in distinct types of elements which have incompatible coefficients of thermal expansion, causing poor connections or even and total disconnection in the contact areas after several cycles, ultimately leading to faulty inverter. The main losses of an inverter are concentrated to: loss during switching, Magnetic components loss, Conduction losses, Capacitance losses, Sensors and conduction losses.

2.8. Solar inverter service life

The survey shows that more than half of the inverters in either residential or commercial installations have suffered some kind of failure. More specifically, 65% of the commercial ones have suffered some kind of failure, while only 35% of the inverters that started operating 10-12 years ago have remained functional without needing to change any component of the inverter. On the other hand, in the household category, 56% have suffered some kind of failure, while 44% of the inverters that started operating 10-12 years ago have remained functional without needing to change any part of the inverter.

2.9. Types of inverter failure

This chapter provides the outcomes of the research are presented in relation to the types of failures that occur in commercial and residential photovoltaic inverters. DC capacitor failure is a common cause of inverter failure in both residential and commercial inverters.

2.10. Pareto Analysis of Types of inverter failure

Using of Pareto Analysis method, it is possible to drawn some useful information about the roots of most commons external installations faults that usually leads to internal inverter failures. The three most common faults are DC capacitor failure (23,4%), Internal DC current leakage (19,5%), DC relay failure (14,3%) represent the 57,2% of total recorded fault and is strongly connected with the condition of DC circuit external of the inverter. In the most cases of in such failures the onsite inspection reveals low insulation resistance or/and arcing or/and sort-circuit citations.

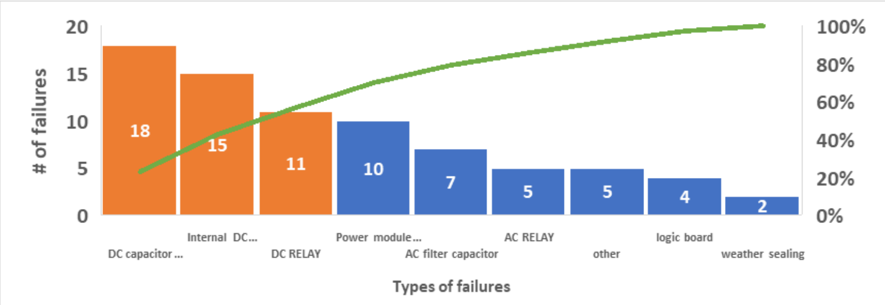

Fig. 9. Pareto analysis of commercial PV inverter faults

2.11. One-way Analysis of Variance

It is possible to run an analysis of variance of the data of inverter fault were recorded during research. As data input is used the types of failures and the number of incidents. The hypothesis (H_0) which investigates is if the faults is equal. The alternative hypothesis (H_1) is that at least one fault is unequal to other. The One-way Anova analysis of commercial inverter faults reveal that F > Fcrit and the P value is less than 5% so is true the alternative hypothesis (H1).

2.12. Yearly working hours of PV inverter

From data analyses precept for commercial PV installations with fixed mountings that: a) Average operating hours of inverters 4022 hours per year. b) The average produced kilowatt hours per year and per kilowatt of installed capacity is 1,364 kwh. c) Average inverter Output 0.339 kWh per kWp of installed capacity per working hours.

2.13. Working yeas of PV inverter

The frequency of inverter failures recorded by the research in relation to the years of operation in PV installations. The survey reveals a peak of failures between the 7th and 10th year of operation which translates from 28600 to 39700 hours of operation during this time period inverters have the highest chances of suffering some kind of malfunction.

2.14. Reliability curve

The reliability analysis is a technique that measures the likelihood of success of an entity (component, system or part of the system), i.e., its capacity to perform its functions for a duration Δt under particular environmental and operational conditions. The failure rate is not uniform over time, as it fluctuates depending on the life stage of the component. Overall, the life cycle of a system or a component is categorized into three main phases: the burn-in, the useful life and the wear-out. A common pattern of the failure rate as it varies with time, known as “bathtub curve”.

2.14.1. Reliability metrics (MTBF – MTTR – MTTF)

Mean time between failures (MTBF) represents the expected time interval among inherent failures of a mechanical or electronic system during regular operational life MTBF can be determined as the mean time among failures of a system. The mean time to failure (MTTF) indicates the predicted time to failure for non-repairable systems. Mean time to repair (MTTR) serves as a core measure of the maintainability of repairable elements, indicating the typical time it takes to repair a malfunctioning part or device.

2.15. Solar inverter reliability metrics

When a PV inverter fails in the power circuit or the control circuit, the entire machine is usually replaced with a refurbished one that has been recertified. This procedure applies to all PV inverters that are under warranty. Inverters that are out of warranty and are sent for repair to the official manufacturing company, the faulty component is replaced, but they also mandatorily refurbished the rest of the machine by replacing critical parts that they consider some wear. For the above reasons, should classify an inverter as a single system, and when an integral fault occurs, it is replaced or completely rebuilt, so below the individual failures are analyzed by calculating the MTTF mean time to failure of the inverter components.

2.1.6. Theoretical model of PV inverter reliability

The reliability of a Photovoltaic (PV) inverter is a critical factor that directly impacts the long-term performance and economic viability of solar power systems.

2.16.1. Factors that can affect the PV Inverter Reliability

PV inverter reliability is affected by both external and internal factors. External factors include environmental conditions like temperature, humidity and salt mist all above external factors can trigger and accelerate internal failure modes. Also, abnormal electrical stress related to electrical components such as power semiconductors, capacitors and relays can trigger and accelerate internal failure modes. In the default failure rate of manufacture of inverter (can added the external factors. The sum default failure rate of manufacture of inverter ($\lambda_{def}(t)$) and external factors ($\lambda_{ext}(t)$) are representing the total failure rate of a photovoltaic (PV) inverter denoted as ($\lambda_{total}(t)$that influence its reliability over time (formula 7).

$$\lambda_{total}(t) = \lambda_{def}(t) + \lambda_{ext}(t) \qquad (7)$$

The external failure mechanisms affecting inverter reliability can be classified into:

- Abnormal Electrical Stress: Voltage surges, power fluctuations, and DC, AC distortions leakages and arcs that can cause component failure.
- Environmental Stress: Exposure to extreme temperatures, humidity, salt mist, and lightning.

The total external failure rate of a photovoltaic (PV) inverter, denoted as $\lambda_{ext}(t)$, is the sum of the failure rates from various factors that influence its performance over time.

These factors can be categorized into, Environmental $(\lambda_{env}(t))$ and Abnormal Electrical Stress $(\lambda_{Aele}(t))$. Below, is presented a formula for each factor contributing to $\lambda_{ext}(t)$, break down the elements of each formula, and provide relevant references to support the use of these models (formula 8).

$$\boldsymbol{\lambda_{ext}(t) = \lambda_{Aele}(t) + \lambda_{env}(t)} \qquad (8)$$

2.16.2. Environmental Factors

The most common environmental factors that usually can affect the possibility of fault generation on a PV inverter are the:

1. Temperature-Dependent Failure Rate (λ Temp (t))
2. Humidity-Dependent Failure Rate (λ Hum(t))
3. Salt Mist-Related Failure Rate (λ Sm (t))

2.16.3. Electrical Factors

The most vulnerable components of a PV inverter to electrical abnormities are: capacitors, power modules and relays. The Abnormal Electrical Factors is the sum of failure rate of capacitors, power modules and relays (formula 9).

$$\boldsymbol{\lambda_{Aele}(t) = \lambda_{cap}(t) + \lambda_{pwr}(t) + \lambda_{rel}(t)} \qquad (9)$$

2.16.4. Conclusions

The reliability of the solar inverters is influenced by a multifaceted set of factors, including temperature, humidity, salt mist, internal component degradation, and electrical faults. By using multifactorial mathematical models, can be better understand the complex relationships between these factors and it is possible to recalculated the inverter's operational lifespan according to the specific installation site environmental and electrical conditions.

2.17. Reliability of PV installations

A PV system consists of a structure with n the number of units. Each of the units can be (at some predetermined time t at which we consider the system) in one of two states: a) failed, not working component, «off» mode, b) functioning, working component, «on» mode

2.17.1. Serial reliability configuration

Some of the parts are crucial to be in working condition and if one of them fail entire PV installation can transition in non-productive condition that type of configuration is called serial reliability. The reliability of the serial system Rs is expressing by formula 10:

$$\boldsymbol{Rs = P(X_1)P(X_1|X_2)P(X_3|X_1X_2) \dots\dots P(X_n|X_1X_2X_{n-1})} \qquad (10)$$

Where X_i is the case when i works,

$P(X_i)$ is the probability that component i works.

2.17.2. Parallel reliability configuration

On the other hand, there are some elements on a PV installation that can fail and only one part of the system switched in non-productive condition and the rest PV installation will keep working that type of configuration is called parallel reliability. So, in a parallel system, all units must fail for the system to fail. The unreliability of the system is then given by:

$$Qs = P(X_1)P(X_2|X_1)P(X_3|X_1X_2) \dots P(X_n|X_1X_2X_{n-1}) \quad (11).$$

2.17.3. PV system reliability configuration

A typical field PV installation involves both series and parallel setups in the whole system. This type of systems examined through evaluating the reliabilities separately for series and parallel sectors and then integrating them properly.

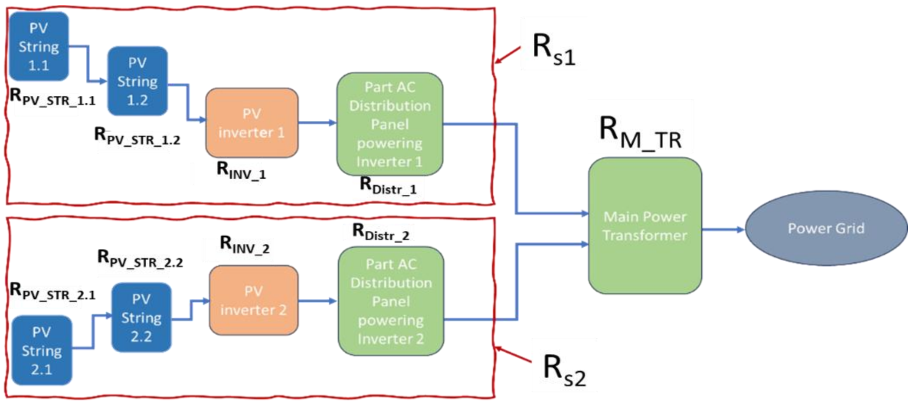

Fig. 10. Reliability block diagram configuration of a PV system

2.17.4. Conclusions

The total failure of a PV installation is usually unlikely to happen because the installations usually is separated into parallel production sectors. Usually, a failure to main power transformer can set the PV installation to non-working condition. The Inverter and panel failures usually restricted to the locally sector of the PV installation. More specific the most common PV modules failures usually led to string under-performance compare to the rests.

2.18. The most common failures that appears in commercial PV systems

2.18.1. Panel Micro-cracks

The method used for the analysis is the fishbone diagram. The statistical analysis of the research reveals that the phenomenon of microcracks appears at cells in photovoltaic panels in which support systems that have high elasticity or are not placed correctly with the result that the panels bend and oscillate due to air pressures from wind.

2.18.2. DC current leaks

DC leaks usually occur in cables and DC connectors which often go out of the manufacturer's specification design resulting in their premature aging or bad sealing.

2.18.3. Potential Induced Degradation (PID)

The primary reason for deploying of the PID is regarded to be the high voltages between the enclosed silicon solar cells and the front glass surface, which is grounded via the aluminum panel frame.

2.18.4. Damage from Wind

Most prone to damage from strong bursts of wind are photovoltaic parks that have solar trackers.

2.18.5. Catastrophic structural failures

The most common cause of catastrophic structural failures in solar trackers is the lack of a backup power source which is necessary to set the tracker to secure position the tracker when there is no power from the grid which is often the case in bad weather with strong winds.

2.19. Achievements on chapter 2

In the second chapter, the presentation of all the statistical data concerning the failures of photovoltaic systems which were collected during the research is made. These failures are categorized according to the cause of their origin. The causes of failures of photovoltaic panels and photovoltaic inverters are also studied in depth. Pareto analysis and one-way analysis of variance are performed and valuable information about the roots of failures is extracted. In photovoltaic inverters, a special analysis is made on the source of internal power losses, which are the main source of the increase in internal temperature, which has a consequence on the lifetime of the inverter. Also in this chapter, a connection is made to external abnormal situations that occur in photovoltaic installations and negatively affect the MTBF of the inverters. In the continuation of the capital, the Theoretical model of PV inverter reliability and then the overall PV system reliability configuration. The most common failures that appear in commercial PV systems are presented at the end of the chapter Fishbone Diagram analysis.

Chapter 3. Methods for increasing PV reliability

3.1. Failures cause by faulty design system

Proper design of a photovoltaic system is one of the most crucial stages that must be given special attention. A photovoltaic park is designed to produce energy for at least 25 years with as few failures as possible. For this reason, the environmental, geological and topological conditions in the area, the operating limits of the equipment and the compatibility between them should be taken into account. During the initial stages of design, it should be considered whether the site to be installed meets the following requirements: **Environmental, geological and topological conditions**

3.1.1. Sufficient inter-row spacing

A critical parameter in the design of a photovoltaic system is the calculation of the idea spacing. From the research carried out in 23 photovoltaic parks identified 4 parks which have problems of shading between the rows and this problem occurs mainly in the winter months due to the small angle that the sun has from the earth's surface and creates annual production losses from 4% to 11%.

3.1.2. Neighboring obstacles

When selecting the location where the installation is to be made, attention should be paid to neighboring obstacles that can create shadows. Nearby buildings, trees, hills and mountains can affect the performance of a photovoltaic park not only by the direct shading but also by the influence of diffuse irradiance.

3.1.3. Neighboring activities

The annual energy production of a photovoltaic system can be affected by neighboring activities. Dirt or gravel roads can be the cause of the dust formation that settles on the panels especially in the summer months where rain is rare and air humidity is low.

3.1.4. Bird droppings on solar panels

Reducing the production efficiency of photovoltaic panels is a reality that occurs in several installations. Usually, the annual reduction of energy production is between 0.5-1.5% but there are also some cases that exceeds 10%. Sometimes the areas in which photovoltaic systems are installed have some properties that can attract birds.

3.1.5. Places that retain rainwater and floods

Photovoltaic parks should be avoided from being constructed in places that hold water or flood because this condition can damage the equipment or even cause the total destruction of the park. Research of existing parks reveals that 82% of parks that have been stagnant at some area water for more than two weeks.

3.2. Multiple layers of safety and protection

3.2.1. Surge Protection

A study of photovoltaic parks found that most of them lacked or no surge protection devices and this resulted in equipment damage. The 47.1% of the parks participating in the survey have suffered equipment damage from lightning/surge at least once within 12 years of their operation.

3.2.2. Earthing

In order for the SPDs to work properly you will need to connect to a ground which a built in with the right specifications in accordance with national regulations and installation's characteristics. The main purpose of earthing in electrical circuits is to boost the safety of the electrical installation by decreasing the threat posed by fault currents usually originating from leaks due to bad insulation. 87% of the parks surveyed did not have the photovoltaic panels properly earthed.

3.2.3. Back-up power

The statistics collected from the research show that a lot of damage done to photovoltaic plants with trackers was due to the interruption of the power supply from the grid during extreme weather events. 82% of parks with trackers did not have or had insufficient backup power system.

3.2.4. Fireproofing

All electrical installations, by their nature, will carry some degree of fire risk which is usually very low. Although fires caused by PV panels are rare. 17.4% of parks had a small fires issue during their operation. Small fires are usually created during electric arcs and most often occur in switchboards, junction boxes and DC connectors.

3.2.5. Incompatibility between the equipment

From the analysis of the statistical data from the photovoltaic parks that were surveyed shows that 91% have incompatibility problems of DC connectors. These failures, some of which lead to arcing and fires but also in secondary equipment faults

3.3. Failures caused by errors and omissions during construction

This subchapter analyzes the errors and omissions that occur during the installation-construction of photovoltaic parks this type of errors has been associated with failures in parks that appears in the near and medium term. 78% of the parks surveyed had construction errors that led to premature equipment failures but also reduced annual production.

3.3.1. First stage

In the first stage of the construction includes the marking of the area by a topographer and then the smoothing of the small soil anomalies with heavy earthmoving machines and then the construction of the fence and the entrance door of the construction site.

3.3.2. Second stage

At this stage the excavation of the cable routes is done, the excavation for the foundation of the substation but also the foundation of the support system of the photovoltaic panels and the metal earthing strip and the earthing poles were placed.

3.3.3. Third stage

This stage includes the foundation and assembly of the photovoltaic panel mounting system, the placement of the panels on it, the placement of the inverters and the placement of the substation and the termination of the cables on the above systems.

3.3.4. Final stage

In this stage the test operation of the photovoltaic system is performed, which includes the tests such as: 1) Performance check of each string separately relative to the solar irradiation and the temperature of the panel and calculation of the performance ratio of the photovoltaic park. 2)Test of good operation of the substation grid monitor. 3)Checking the inverters for indications or recording errors. 4)Leakage currents measurement. 5)Comparison of the performance between the inverters of the installation. 6)Measurement of AC and DC operating voltages and currents. 7)Check with a thermal camera on AC and DC switchboards for detection.

3.4. Conclusions

The survey reveals that the 26.1% of the field PV installations had reduced annual yields due to omissions ta initial plan design. Many solar systems were construct at the area close to the coastline, corrosion led to faults associated salt mist have been recognized. Salt mist vapors can degrade many elements of a PV system the most vulnerable usually are the insulation of the cabling lines, junction boxes cover on the back of the PV modules, improper termination at aluminum cables and lightly galvanized iron on mounting support system can corrode at an accelerated degree. At the first stage of planning and design if have taken into account the risks of salt mist corrosion may have been used components which are suitable for salt-mist applications for example the usage of polystyrene box boards, anodized aluminum or hot galvanizing coating iron (at least 50μm) solar mount systems and inox fittings with certification that can withstand the salt corrosion. These key point changes elevate the construction expenses up to 3-5% but decreases the yield losses but also decrease the risk of unexpected PV hardware failures in entire PV system. In many cases the recover costs can easily reach 15% to 25% of initial cost of PV installation because in some cases appears secondaries damage and that situation increases the repair costs but also the payback time. Another omission is the miscalculation of interrow spacing resulting that during the winter months the sun trajectory is low in the horizon there is shading between the rows. Repositioning of the rows in order to reduce the yield losses is often expensive and many times is not suggested unless the yearly yield losses it is over 10%. The survey also recorded some PV installations to working with wrong and asymmetrical string dimensioning. Such string sizing lapses usually has an annual yield loss of 3-5%. However, in numerous instances, they are simple and affordable to fix and recover, with a return on investment within a few months. Also, the area of installation should be study for dynamic neighboring obstacles such as growing trees or building under construction that possibly in the future can create shadows areas at PV installation. Neighboring activities that possibly can create dust clouds should take in account to performance of PV installations.

3.5. Achievements of chapter 3

In chapter three are presenting the methods that can lead to increment the reliability and performance of PV parks. This chapter reveals the most common omission that made during design-construction of the PV systems also provide methods to reverse with minimum cost the underperformance and unprotected installations. At the end of this chapter some key parameters concern the construction phase that is critical for longevity of a PV installation.

Chapter 4. Methods for increase PV energy efficiency

4.1. Main problem

In many places of the world there is a large local concentration of photovoltaic installations. As a result, new photovoltaic installations cannot be installed because the old installations commit a large part of the grid energy absorption capacity based on the typical maximum output that they can achieve a few moments or never per year.

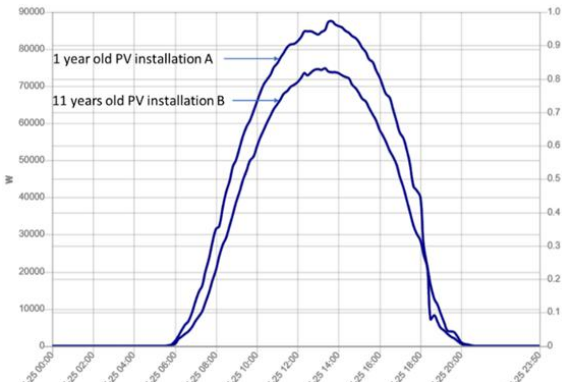

Fig. 11. Power output difference between the two PV systems 100KWp

4.2. Suggested solutions

The first step to be taken to increase the energy produced in such an old installation is the check of photovoltaic panels for defects. In such an old installation, 10 to 30% of the panels have a greater degradation in performance compared to the rest. Those panels with the largest reduction in performance are usually removed and the rest remaining in the installation are regrouped into new strings according to the characteristics measured during the performance tests. New panels are then added to independent strings. One way to optimize the power generated in the early morning and late afternoon is to install bifacial panels vertically in an east-west configuration. With an increment of 25% on the same plot panels vertically orientated it is expected at the early morning hours and late afternoon, the power output is more than duple but in the noon hours the output increment is only 8-10%. At this point it should be emphasized that appropriate measures should be taken so that the maximum power produced by the photovoltaic installation does not exceed the power agreed with the grid operator. In this way, however, it is possible that some energy is lost, so that this does not happen, it stores this energy while at the same time further reducing the maximum output power of the photovoltaic installation and expanding the energy supply of the photovoltaic system to the grid at the required hours. In this way, in saturated networks, space can be created for the addition of new photovoltaic installations. The red line shows the charging of photovoltaic system batteries The charging is scheduled to start when the output power of the photovoltaic park is above 25kw and draws 10% of the photovoltaic power of the installation. The battery capacity is 100KWh and can absorb about the 1/7 of daily summer daily production. The charging and discharging strategy of the energy storage system can be programmed according to the requirements of the grid in order to improve its grid stability.

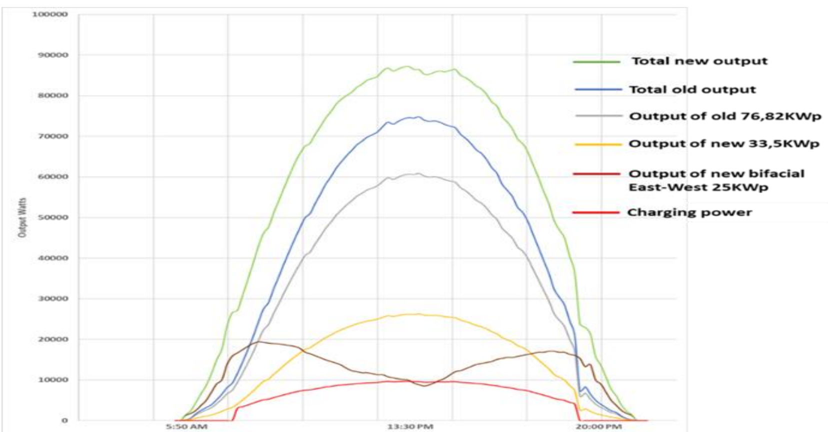

Fig. 12. Power outputs

4.3. Battery energy storage system

The last few years due to huge expansion of installed PV systems around the word the energy storage systems (ess) are becoming a key system for the stabilizing the grid, due to noon’s can storage energy and realized in when there is the need from the grid. There are two main categories of battery storage systems, the DC and AC coupling systems. AC or DC coupling relates to the method of how the power of solar modules transfer to battery device. The main topology differences between of an AC-coupled and DC-coupled battery systems is that in the first case the power of the PV modules convert from DC to AC and after from AC to DC in order to reach storage unit. On the other hand, in the second case the power of the PV modules can reach the storage unit only with the usage of DC-DC conversion.

4.3.1. Advantages and disadvantages of AC and DC coupling

Advantages of AC coupling: 1) Get to keep grid-tied inverter. 2)Easier installation, especially for retrofits
Disadvantages of AC coupling: 1) Less efficient. 2)Less system functionality
Advantages of DC coupling: 1) More efficient. 2)More regulated charging
Disadvantages of DC coupling:1) Not ideal for retrofits**. 2)**Longer installation time

4.3.2. Artificial Energy Storage of Electrical Energy

Storage systems can be categorized based on the form of energy being stored. Thus, energy storage systems are categorized as:
1. Dynamic Energy, 2. Kinetic Energy, 3. Chemical Energy, 4. Electric and magnetic energy storage

4.3.3. Energy Efficiency

The process Energy conversion is the transformation the energy from one form to another for example chemical energy to electrical energy. The efficiency of a conversion device (e) is defined as the relationship between "useful" energy output from the device to the energy consumed during the process.

4.4. Bifacial PV Panels

Bifacial PV module absorbs sunlight and converts it to DC electricity from the front but also and back surface. A bifacial PV system produces more yield in comparison with monofacial these output difference referred as bifacial gain and varies from system to system. The main factors were can influenced the bifacial gain output are the ground cover ratio (GCR), orientation (tilt and azimuth or tracking angles), and meteorological conditions such as irradiance quantity and quality (spectrum), diffuse fraction, temperature, wind speed, albedo, and dust and snow deposition.

4.4.1. Terms related to bifacial

Bifaciality Factor (BiFi) denotes the relationship between the back side power output to front side output power.

4.4.2. Bifacial Gain

Bifacial Gain extra yield and expressed by the division between the back yield energy production and total front side yield energy production.

4.4.2.1. Albedo

Albedo denotes the relationship between of reflected and diffused solar irradiance coming from a range of surfaces in relation to direct solar irradiance. Albedo Is significant including monofacial PV modules specific slope angles can amplify the reflected irradiance converted in the front faced of the solar module.

4.4.2.2. How to determine the Albedo

The initial step of planning a system aims to determinate albedo of the installation area. This is crucial because the albedo is strongly connected to the bifacial gain. Using albedo basic reference table, construction site evaluation and reflected irradiance measurements can define the value of albedo. To determine with greater precision the albedo the usage of pyranometer and multipoint sampling is required. A twin pyranometer that usually measures direct solar irradiance and reflected solar radiation is usually mentioned as Albedometer.

4.4.2.3. Ground Cover Ratio

The output yield from a bifacial PV installation is based on the standard factors as for conventional PV installations. The definition of Ground Coverage Ratio (GCR) denotes the relationship between PV panels cover surface and the overall ground covered surface. As the GCR increases, the albedo value is increasing and resulting higher value of yield.

4.4.2.4. Irradiance uniformity on the array

Irradiance uniformity also varies with the panel position in a row, even if the row has a fixed tilt. The additional bifacial gain of the row depends on the module performance with the lowest rear irradiance.

4.5. Electrical Behavior of Bifacial PV Module

When planning a PV system that utilises bifacial panels, it is important to account for the additional power that the module may produce under particular conditions of reflection, irradiance and temperature.

In many cases the boosted gain from bifacial panel can push to the limit output of the inverter.

4.6. Calculation of additional energy yield

The extra energy output can be calculated using the formula 12:

$$\textbf{Additional yield} = \textbf{Albedo} * \textbf{bifaciality} * \left[\boldsymbol{a} * \left(\mathbf{1} - \frac{\mathbf{1}}{\sqrt{\boldsymbol{A}}}\right) * \left(\mathbf{1} - \boldsymbol{e}^{-\frac{\boldsymbol{b}-\boldsymbol{H}}{\boldsymbol{A}}}\right) + \left(\mathbf{1} - \frac{\mathbf{1}}{\boldsymbol{A}^{\mathbf{4}}}\right)\right] \quad (12)$$

Where: a = a constant of 1.037 , A = interrow distance between the modules in meters (m), E = is a constant of 2.718 , b is a constant of = 8.691 ,H = distance between the lowest point on the module frame and the roof or ground in meters (m), C = is a constant of 0.125, Albedo = e.g.: 0.8 (80 percent surface reflectance), Bifaciality = e.g.: 0.7 (70 percent cell bifaciality)

4.7. Chasing the ultimate bifacial gain with minimum additional cost-case of study

The last few years solar industry promotes the benefits of bifacial modules and many engineers have concerns about the extra yield. Solar industry promises an extra yield between 5% to 25% relative to conventional monofacial PERC [92] modules. To evaluate the additional energy output from bifacial modules, a reference installation of 10.465 kWp (23 modules of 455 Wp) was construct, taking into account essential design elements for the bifacial system. The aim of system design is to enhance the bifacial gain with the lowest possible increment in overall cost. The PV system installed on a flat roof which is made of concrete. The structural configuration of the PV aims to maximize the benefits of high albedo, the clarences between the rows, the minimum height of each row relative to the ground as well as the gaps between each photovoltaic module and its neighbor were calculated. In this way, the layout configuration targeting to all panels to receive uniform irradiance from both sides. Also, in order to further increase the albedo an ultra-white epoxy weather resistance paint with a reflectivity factor of 80% was selected which was implemented not only under the PV modules as well as between the rows therefore coating a surface of ?? about 110 square meters. The total power output gain ($P_{total\ gain}$) is the sum of the PV module is the additional gain output of the front side ($P_{Front\ gain}$) plus the additional gain output of the back side $P_{Back\ gain}$ (formula 13).

$$P_{Total\ gain} = P_{Front\ gain} + P_{Back\ gain} \quad (13)$$
$$P_{Total\ gain} = 5\% + 20.75\% = 25.75\%$$

By the measurements that made on installation site revels that a total output gain by 25.75% at specific time, date and environmental conditions. Below is calculated the theoretical yearly average total output gain using the next (formula 14), where:
a = 1.037, A = 2.1m, E = 2.718, b = 8.691, H = 0.4m, C = 0.125, Albedo = 0.8, Bifaciality = 0.7

$$\textbf{Additional yield} = \mathbf{0.8} * \mathbf{0.7} * \left[\mathbf{1.037} * \left(\mathbf{1} - \frac{\mathbf{1}}{\mathbf{2,1}}\right) * \left(\mathbf{1} - \boldsymbol{e}^{-\frac{\mathbf{8,691-0.4}}{\mathbf{2,1}}}\right) + + \left(\mathbf{1} - \frac{\mathbf{1}}{\mathbf{2,1^4}}\right)\right] \quad (14)$$

$$\boldsymbol{Additional\ yield = 0.2429\ or\ \ in\ precentage\ 24.29\%}$$

A more reliable way for estimating the increase in gain is to compare it with nearby PV systems in the same region. In a close distance of six hundred meters of the reference PV system there is another PV system which is built with the identical PV modules but on a tile tilted roof. All the variations should be considered when evaluating the performance gap between the two systems. The log data between October 2023 to January 2024 shows an average yield increasement of 30%.

4.7.1. Conclusions

Bifacial panels are among the optimal solutions for repowering cases, especially in situations where the user for PV system is bound by a contract with the electricity provider for a specific maximum power of total mounted PV modules. The bifacial panels solution is a strong approach, since they can be arranged in such way to use optimum the albedo and by consequence to enhance the additional gain from the backside. In order to gain more yield from bifacial modules It is realistic with the usage of high albedo surfaces can maximize the reflected sun irradiance. The adoption of new panel technology requires approximately 40% reduced space to modules that are 13 years old. The drawback is that in many European countries' legislation will require adjustment in order to permit managers of PV systems to modify the upper limit of modules installed power without altering the system's maximum output power.

4.8. Partial repowering of 150kW PV park on fixed support structure with mixture of N and P-type Bifacial panels- case of study

The PV installation was developed on a level landscape in 2012. Starting in 2016, certain strings began to show a minor reduction in yield. The primary causes of underperformance were a drop in voltage output and current leakage due to water infiltration in the PV modules. Year by the year the low productivity of the PV system becomes the main concern. The PV installation made up of 1170 PV modules of 128Wp which are feed five inverters of 27.6kW. Each inverter has two independent MPPT inputs where in each are connected to 117 PV modules (9 parallel of 13 strings PV modules). First panel replacement [67] was made on September 2016 were replaced 117 PV panels at inverter number 1 of PV plant. The one of two MPPT was replaced with the new panels. The new 108 PV panels of 135Wp were installed with the same cell technology(tandem) compare with the olds ones but they are frameless and double glass. The second panel replacement was made on July 2018 were replaced 117 PV panels at inverter number 2 of PV plant The one of two MPPT was replaced with the new panels. The new 42 PV panels of 395Wp were installed the modules were bifacial P-Type with only frond glass and transparent back sheet. The last panel replacement was made on June 2024 were replaced 234 PV panels at inverter number 4 of PV plant The both MPPT's was replaced with the new panels. The new 52 PV panels of 575Wp were installed the modules were bifacial N-type with double glass configuration. In all panel replacement the old PV panels where was in good condition were used to replaced problematic-underperformance panels in the rest of installation.

Also, the inverter on number 3 were placed extra 18 old panel. Below there is a summarize table 4.1 of all inverter installed power.

	Type of panel				
	Monofacial Tandem 128Wp	Monofacial Tandem 135Wp	Bifacial P-Type 395Wp	Bifacial N-Type 575Wp	Total installed power per inverter (Wp)
Inv. 1 Tandem	117 pcs	108 pcs			29556
Inv. 2 bif. P-type	117 pcs		42 pcs		31566
Inv. 3 +18 old panel	252 pcs				32256
Inv. 4 bif. Type-N				52 pcs	29900
Inv. 5 Tandem	234 pcs				29952

Table 4.1. *Summarize table of all inverter installed power*

4.8.1. On field measurements for bifacial P-type PV panels

The nearest to the ground line are received the lowest amount of refracted solar irradiation of the back side the average albedo was 12,6% on the other hand the middle rows have average albedo of 19,7% and the upper lines have 25,4%.

4.8.2. On field measurements for bifacial N-type PV panels

The last panel replacement was made on June 2024 were installed 54 bifacial N-type panels of 575Wp each which mounted on modified layout existing support system in order to increase the albedo. In order to increase the albedo, the new panel was placed at two lines in the row configuration thus there is a higher ground clarence from about 50cm goes to 70cm also there is gap about 40cm between two lines of panel. The on-field measurements show that in the lowest line the albedo was 18.8% and for the upper line was 28.4%.

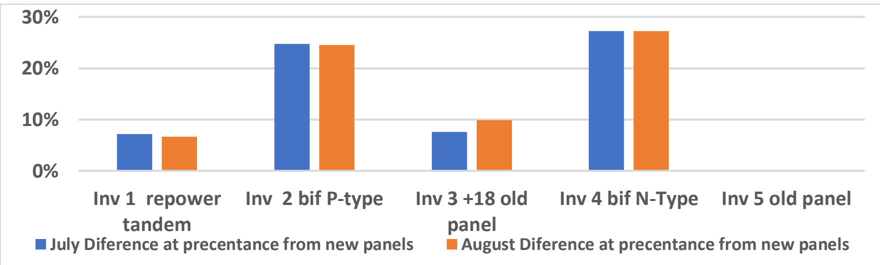

Fig. 13.Difference at yield caused only from panels during July and august 2024

4.8.3. Conclusions

Bifacial panels are among the optimal solutions for repowering cases, especially in situations where the user for PV system is bound by a contract with the electricity provider for a specific maximum power of total mounted PV modules. The bifacial panels solution is a strong approach, since they can be arranged in such way to increase the albedo and by consequence to enhance the additional gain from the backside. For instance, a 13-year-old tandem PV module had a conversion efficiency approximately 9% the last generation modules have conversion efficiency around to 23% this variance leads to the need of a less coverage surface so that a smart configuration can be done in order to leave clearances between PV modules over the old pre-existing large mounting system. This approach can enhance the annual yield by 2-6% without stressing the inverter to its full capacity. The architecture of N type bifacial panels, can achieve additional annual yields at least 4 to 7% in the fields and through the use of high albedo geotextiles the additional yield could reaches around 15%.

4.9. Fill Factor

Photovoltaic panel manufacturers put their products through strict fatigue tests and then check their condition and how much it has changed compared to the original values that were panel have before the stress tests. At electrical efficiency and performance lever there is one critical parameter which is usually subjected to test. The IV curve is tested and after can determine the fill factor PV panel and consequently the electrical healthy status of it.

4.10. Stress tests of PV module

The most common stress test which panel manufactures submit the PV modules are:

- **Thermal Cycling (TC)** test evaluates a PV module capacity to withstand temperature variations.
- **Damp Heat (DH)** test replicates the long-term wear and failure patterns of a high-temperature and high-humidity conditions, the heat and the moisture compromise material integrity of materials in the PV module.
- **Potential Induced Degradation (PID)** Testing is done according το IEC 62804-1 and evaluating the PID resistance of PV module.
- **Light-induced degradation (LID)** and the **light and elevated temperature induced degradation (LETID)** stress testing. During the LID stabilization test the module is exposure of irradiance in cycling doses which are above 5kWh/m2.
- **Hail Stress Sequence (HSS**) test. This test evaluates the results from hail impact in the PV modules.
- **Mechanical Stress test** evaluates if the solar cells in PV modules are sensitive to cracking.

Thanks to improved manufacturing processes and materials, today's solar panels are more durable, have a longer lifespan and longer warranties. The new PV panels compared to the old ones are subjected to complex and tougher fatigue tests.

Scientific and applied contributions

1. The existing failures in photovoltaic systems (PVS) are studied and the root causes for their performance reduction are analyzed. Applied is a systematic approach for failure grouping and component stress analysis for reliability assessment.

2. Suggested is a method for early failure prediction and assessment of performance degradation depending of the PV farm's operational conditions.

3. The modern PVS reliability analysis and prediction methods are analyzed and their pros and cons are compared. In the assessments a method with sub-element reliability estimation and a method with component load analysis are used.

4. Systematically formed data from a study of 23 PV parks and 34 resident systems is presented. The impact of various factors related to the ‘Installation’ and ‘Operation’ phases on the reliability, fault tolerance and yield reduction of PVS is investigated. Empirical data has been obtained using a telemetry system and PVS operational logs covering the period from PVS installation to present.

5. A research and analysis of the root causes for the sudden and unexpected sharp decrease in the performance of some PV systems is conducted. A methodology for the recovery of PV parks with degraded electricity yield is proposed. Recommendations are suggested as to which method should be used in which cases according to the desired accuracy of the assessment with MTBF calculation, sample size and type of data analyzed.

6. A methodology for estimating the economic efficiency of recovery of PV farms with reduced yield is developed. Various component configurations are researched.

7. A new approach to the operation and maintenance of PV systems has been suggested cost reduction, uptime increase, and reliability and performance improvement.

8. A model is created for an individual approach and specific factors consideration in the design of PV systems according to the geographical location and climatic characteristics of the installation site.

Articles

1. Petroglou T., Taneva, L., Common Issues Affecting PV System Performance, 13th National Conference with International Participation ELECTRONICA, Sofia, May 2022.

2. Petroglou T., Reliability and fault-tolerance of PV modules on Northern Greece, 14th National Conference with International Participation ELECTRONICA, Sofia, 2023.

3. Petroglou T., Taneva L., Reliability and fault-tolerance of string PV inverters, 15th National Conference with International Participation ELECTRONICA, Sofia, 2024.

4. Petroglou T., Taneva, L., Chasing the ultimate PV-bifacial gain with minimum additional cost on flat rooftops–Case of study, 15th National Conference with International Participation ELECTRONICA, Sofia, 2024.

5. Petroglou T., Taneva, L., Performance of bifacial PV panels on fields – case of study, XXIII international scientific conference for young scientists'2024, 3-4 October 2024, Blagoevgrad, proceedings pp. 193-202.