Czech Technical University in Prague

Faculty of Electrical Engineering and Computer Science

Bachelor Thesis

The rate of module degradation due to PID effect and impact on the power plant

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ZADÁNÍ BAKALÁŘSKÉ PRÁCE

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Studijní program: **Electrical Engineering and Computer Science**

II. ÚDAJE K BAKALÁŘSKÉ PRÁCI

Název bakalářské práce:

Rychlost degradace fotovoltaických modulů v důsledku PID efektu a její vliv na fotovoltaickou elektrárnu

Název bakalářské práce anglicky:

The rate of module degradation due to PID effect and impact on the power plant

Pokyny pro vypracování:

1. Proveďte rešerši využití solární energie a fotovoltaických elektráren v egyptě, současný stav a výhled do budoucnosti.
2. Zaměřte se na PID degradaci modulů v prostředí Egypta, a sepište příčiny této degradace.
3. Proveďte experimenty zaměřené na degradaci PID, v podmínkách podobných Egyptu.
4. Proveďtě orientační měření degradace malé elektrárny zasažené PID.

Seznam doporučené literatury:

1) Handbook of photovoltaic science and engineering / edited by Antonio Luque and Steven Hegedus. ISBN 0-471-49196-9
2) Impedance spectroscopy :Nakladatel: John Wiley And Sons Ltd ISBN: 9780470627785 Rok vydání: 2012

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III. PŘEVZETÍ ZADÁNÍ

Student bere na vědomí, že je povinen vypracovat bakalářskou práci samostatně, bez cizí pomoci, s výjimkou poskytnutých konzultací. Seznam použité literatury, jiných pramenů a jmen konzultantů je třeba uvést v bakalářské práci.

Datum převzetí zadání	Podpis studenta

Declaration

I declare that I have wrote my Bachelor Thesis ‘The rate of module degradation due to PID effect and impact on the power plant’’ on my own and I have used only cited literature and other professional sources.

Prague 11.8. 2020 ………………………..….

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1. Abstract

Using different methods of testing to diagnose a photovoltaic module, firstly by going through degradation and then reverse it with the regeneration process. The thesis has two main parts, the theoretical and practical part. The theoretical part focuses on a general view of renewable energy and focuses on solar energy, while the practical part had two experiments, verifying the intensity of the PID in lab and measurement of PID degradation in the field at the power plant.

1. Abstrakt

Použití různých metod testování k diagnostice fotovoltaického modulu, nejprve procházením degradací a poté jeho obrácením s procesem regenerace. Práce má dvě hlavní části, teoretickou a praktickou. Teoretická část se zaměřuje na obecný pohled na obnovitelnou energii a na sluneční energii, zatímco praktická část měla dva experimenty, ověřování intenzity PID v laboratoři a měření degradace PID v poli v elektrárně.

2. Introduction

Renewable energy is a term used to describe the energy sources and technology that possesses non-depletable characteristics, or energies that naturally replenish themselves. There are numerous types of renewable energy resources which include wind energy, solar, geothermal energy, falling water, biomass (plant materials), ocean currents, waves; [1]. These sources of energy (renewable energy technology) produce power, heat or power-driven energy through the conversion of these properties either to motive power or electricity. From a political point of view, the renewable energy properties can be mostly categorized depending on the political objectives being considered by the country. For instance, one country may differentiate these sources by classifying the conventional ones and underdeveloped among others. All renewable energy sources can be treated differently for city applications than in countryside applications.

Renewable energy applications are largely divided into two, on-grid and off-grid. A grid is defined as a cohesive generation, transmission, and distribution structure serving many clienteles, it also refers to an assortment of engendering units operational under the control of a central communication centre, grids can be categorized into regional or national [2]. The renewable energies are friendly to the environment, and have slight effect on the environment. Compared to other sources of energy, the discharge of unfriendly substances into the environment is unlikely because of the renewability. Furthermore, these types of energy resources also promote energy variation because its assorted collection minimizes a country's overdependence of one particular energy source. Better still, these technologies are intended to operate on a nearly infinite or replenish able supply of natural fuels [3].

Egypt is one among the highly populated countries in Africa, located on the northern fragment of the continent. It is a home of one of the fastest resurging populations worldwide. Due to this high increase in population, a lot of strain has been put on the available energy sources even though the country had recently found natural gas on the offshore [1,4]. The 2014 heightened fuel shortages presented a struggle on the republic's electrical energy generation capacity with the rise in power requirement. To meet the ever-increasing power consumption volume, the country's government has trailed and energy variation strategy named Integrated Sustainable Energy Strategy (ISES) toward 2035, with an intention of ensuring the incessant and stable energy supply in the country [4]. Egypt enjoys richness in renewable energy resources with increase settlement potential, chiefly, these include Biomass, wind, solar, and hydro energy resources [2].

There has an initiation by the Egyptian government since the 1970s, the programs for demonstration, testing and assessment of diverse renewable energy applications and tech structures while co-operating with numerous countries like Spain, Germany, Japan, EU, and the US among others. The association led to setting up of solar that heats the water in novel cities, airstream farms and photovoltaic (PV) applied in thrusting water, solar manufacturing process heat systems, freezers, and purification plants and biomass digesters in the countryside [5].

3. Theoretical Part

3.1 Renewable Solar Energy

3.1.1 Characteristics

In 2009/10 the renewable energy resources had contributed to principal energy production at 4%, with hydro being the main source of power at 3% and wind energy at 1%, with an expectation of reaching a total of 8% coming 2021/22 and about 14% coming 2035/35, they will ultimately correspond to 23 MW in 2035 [3]. Basing on these contributions, it is expected that renewable energy will make up to 20% of current production in 2021/2022 and an equivalent 42% of power generation in 2034/2035. The regular development rate for renewable power in the main power supply reaching 7.2% [3]. It is expected that the renewable energy sources would click 19 GW by 2021/22 and a subsequent 50 GW to 63 GW in 2029/30 and 2034/35 correspondingly. See table 1. Below;

Power Station	2009/2010	2021/2022	2029/2030	2034/2035
Hydropower	2.7 GW	2.8 GW	2.9 GW	2.9 GW
Wind	o.6 GW	23.3 GW	20.6 GW	20.6 GW
PV	0.0 GW	3.0 GW	22.9 GW	31.75 GW
CSP	0.0 GW	0.1 GW	4.1 GW	8.1 GW
Total	**3.3** GW	**19.2** GW	**50.5** GW	**62.6** GW

Table 1: Progression of Renewable energy power volume in GW [4]

The table above demonstrates the growth and capacity of the installed renewable energy technologies beginning in 2009-2035 [6].

3.1.2 Solar Energy

There is a great solar radiation intensity in Egypt. The 1991 solar atlas for Egypt demonstrated that the republic relishes 2,900 to 3,200 hours of glare each year attached with the unswerving annual energy density of 1,970 to 3200 kWh per square meter [4]. From the North to the south, Egypt is well-thought-out as one of the superlative areas for manipulating solar energy both for power and thermic heating applications. See figure (1) for illustration.

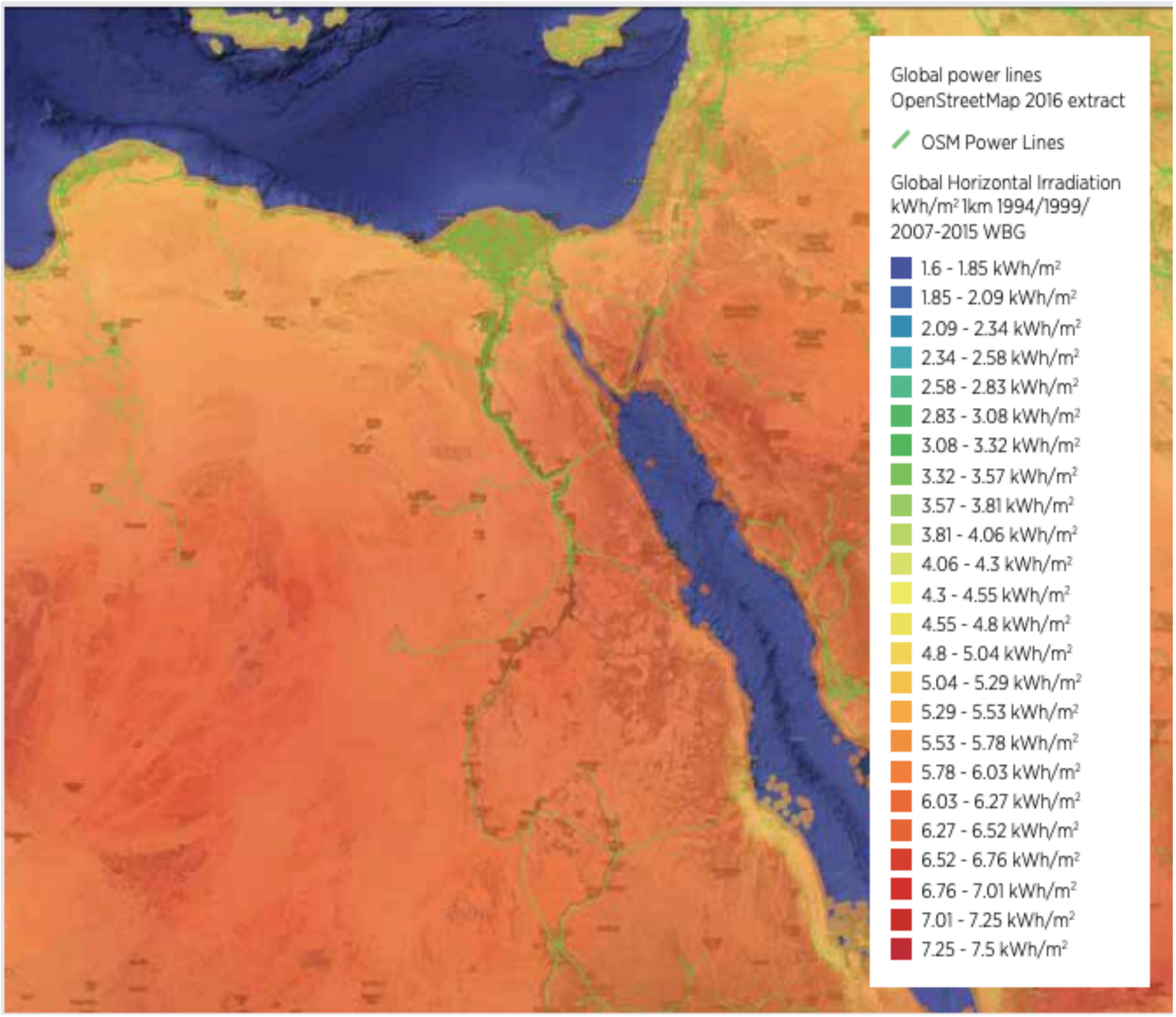


Figure 1: Solar Atlas: Information about Egypt's solar region [4]

The capacity of the overall connected small-scale PV systems reached to 7 MW in year 2013, whereas collective 31 MW of off-grid energy plants [4]. Other large capacity PV systems have been set into development mode by the Ministry of Electricity and Renewable Energy following the implementation of the' Feed in Tariff arrangement in 2014, this followed massive power shortage in the country tied with the cost reduction of PV panels the same year. Owing to cost-effectiveness, several government officials in Egypt have channelled efforts toward implementing the PV systems; especially rooftop and street lighting. This led to the planning and installation of large-scale PV installations with about 21 MW and 27 MW capacity that have been built in Hurghada and Kom Ombo which was scheduled for accomplishment in 2019 [7].

3.1.3 Distributed Solar PV

Egypt launched the FIT support system that enabled it to have a good distribution of solar power and wind projects. The distribution of these renewable energy resources through this system allowed the distribution of power in the capacity of 50 MW. Country's target is to increase this power in time. In 2017 the power plant that is located in the Benban solar complex was initiated with the capacity of 64 MW [7]. More plants were set up in 2018 that allowed up to 80MW. In July 2019, 27 more plants were initiated increasing the renewable energy sources in the country [7].

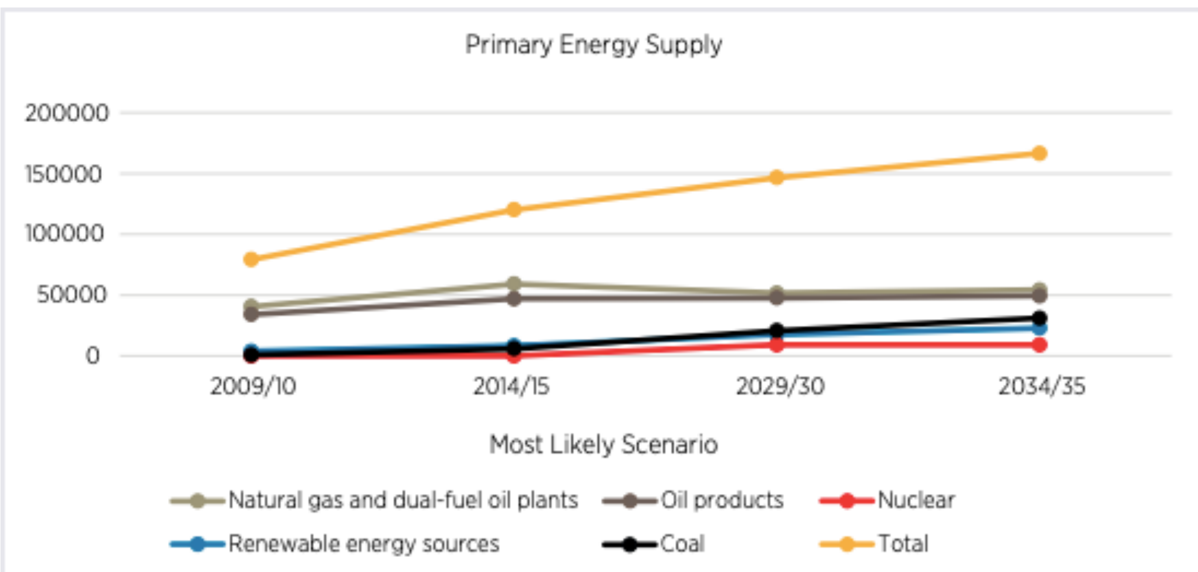
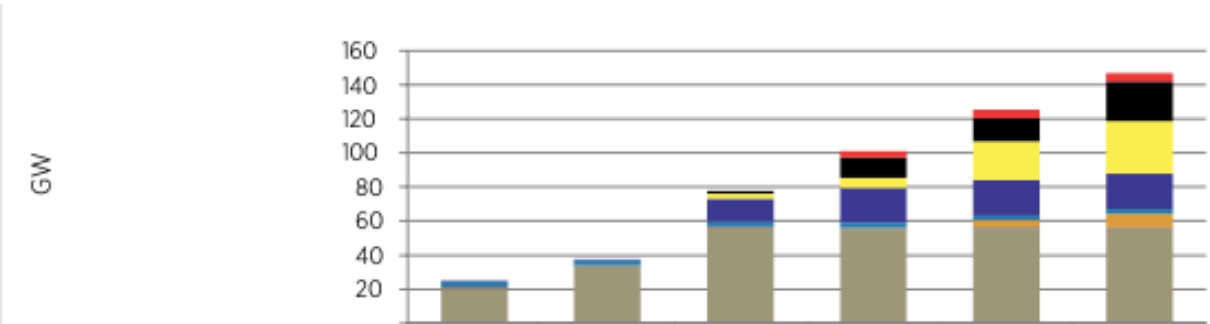


Figure 2: **Summation of installed power-generation capacity under the setting [4]**



	2009/10	2014/15	2019/20	2025/26	2029/30	2034/35
Nuclear power stations	0.0	0.0	0.0	3.6	4.8	4.8
Coal	0.0	0.0	1.6	12.0	13.6	23.2
PV	0.0	0.0	3.0	5.9	22.9	31.0
Wind	0.5	0.5	13.3	20.5	20.6	20.6
Hydroelectric	2.8	2.8	2.8	2.9	2.9	2.9
CSP	0.0	0.1	0.1	0.1	4.1	8.1
Oil products	1.4	1.3	0.9	1.0	1.3	1.3
Natural gas & dual-fuel oil plants	20.4	33.0	55.9	54.9	55.0	54.8

Figure 3: Total installed volume vs peak demand to 2035 [4]

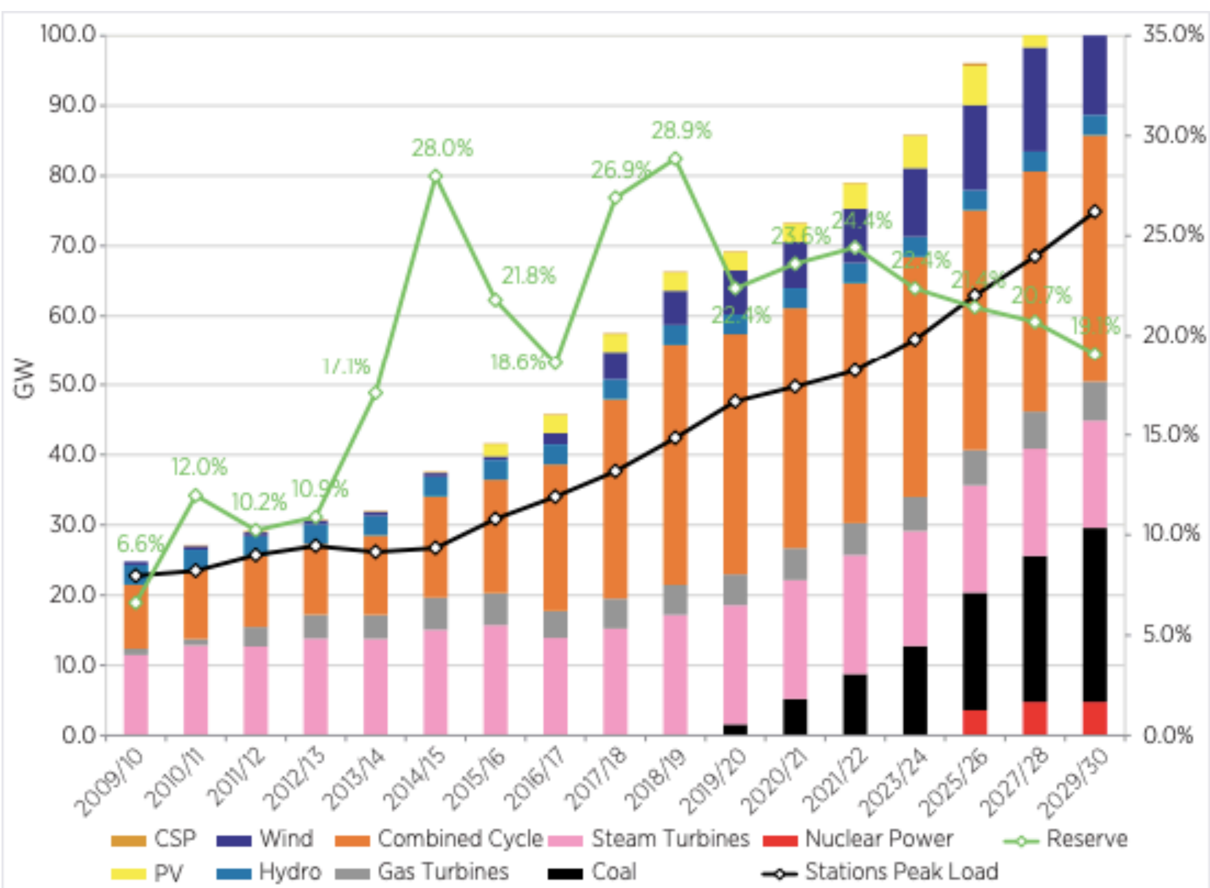


Figure 4: Total installed volume vs. peak demand to 3030 [4]

For a maximum solar energy capture, there are specific angles in which the PV systems need to be installed. This is achieved by pointing the panels in the direction that captures maximum sun rays. However, a number of various variables considered when supposing the best direction. This aspect applies to any kind of panel that captures energy from the sun rays, solar hot water and photovoltaic among others apart from the tracking panels [8]. Whether a panel is fixed or can be tilted, a seasonal adjustment can be done to ensure optimum capture of the sun rays. According to the experts, PV panels should be set facing true south in case the user is the northern hemisphere, while those who are in the southern hemisphere should install their panels facing true north. Consider the fact that true north does not mean the magnetic north. With regard to the tilt of the panels, most journals or books recommends that the tilt should be equivalent to the latitude, plus or minus of 15^0 during winter and summer season respectively [8].

3.2 PV Power Plants

It has been proven that the amount of energy striking the surface of the earth in one hour is enough to serve the entire world's energy consumption for a full year. As each hour 430 quintillion Joules of energy from the sun hits the Earth, and humans use in a year is 410 quintillion Joules [4]. The solar power systems come in numerous shapes and sizes. There is the residential solar system found on the rooftops, while on the other hand, corporations are installing large solar energy plants to provide cleaner energy for its customers. The three main types of solar energy technologies include the concentrating solar power (CSP), the photovoltaic solar energy (PV), and the solar heating and cooling systems (SHC) [4].

3.2.1 Parts of PV Systems

- **Solar Power Inverters (Grid Connected)**

The solar inverters translate DC power provided by the solar PV panels into AC power to be used by a household or for exportation to the distribution system. An inverter is designed to maximize the PV outputs from the arrays whereas minimizing an energy loss [9]. The inverters are also categorized depending on the power output of each solar panel, the operating and general voltages. Solar systems with dissimilar electrical and physical features every so often validate a different approach to the category and choice of inverters to be used [10]. An integrated design may employ several small inverters (micro-inverters) whereas 2 or 3 inverters may also be selected based on the kind of setup that can realize the optimal power production. Most inverters come with an elementary form of system monitoring and built-in DC protection disconnect.

- Solar PV Electrical Components

- **AC and DC Isolators**

In solar power generation there is usually the inverter which receives the DC which is the direct current from the strings of the solar, and output it as an AC the alternating current to the grid. It is necessary to isolate the panels from the alternating current (AC) side during installation or maintenance, so a DC isolator is installed which is an isolating switch to be put between the panels and the inverter input to provide a DC isolation between the PV panels and the rest of the system. There are two types of isolators that can be used, a single pole or a double pole. We use the single pole DC isolator when the inverter feeds the grid through an isolating transformer, but when an ungrounded array is needed to feed an inverter without a transformer, a double pole is needed. Some models has two isolators as well, a DC one and an AC one.

- **PV Junction Boxes/ PV Combiner Box**

This component is used for safe termination of multiple PV panels' strings on the DC before connecting to an inverter. This is not always essential for smaller structures. The PV combiners offer the critical function of being capable to safely separate and fuse separate PV strings and the aggregation of several smaller PV connections into fewer cables before connecting into an inverter. Additionally, the junction box provided a solution where solar panel ranges necessitate combination, where distinct string performance has to be observed or in case the inverter has an inadequate number of inputs [11].

- **Solar PV Cables and Connectors**

The cable is mainly used to connect several apparatuses and it is selected to accomplish efficiently based on several aspects like the current to be carried, the operating temperature in their areas of functionality, and installation environments. For instance, whether outside, in hot areas or even underground, high voltage among others [11]. They can be used to form the DC home-run to the inverter or connect the module to the module-level device in case the system is using DC micro inverters. Attention should be given to the kinds of connectors employed to make sure that the cables are installed in secure, safe areas where there is less likelihood of damage or interference.

- **Solar PV Generation Meters**

Meters are accessible for both single and three-phase power grids; meters are used to quantify the quantity of electricity that a solar PV system produces [10]. An OFGEM appropriate generator meter must be installed to enhance system eligibility for the Feed-in Tariff.

- **Off-Grid Solar Power Inverters**

This kind of inverter converts DC power release by storage batteries into AC power for use within a household employing conservative wiring. Specific consideration ought to be paid while choosing an off-grid inverter for ensuring progressive and smooth operation, especially when there is the likelihood of system supplying unstable loads [9].

- **Solar PV controllers**

This component helps in the protection of the batteries through the blockage of reverse current and prevention of battery overcharge. However, more unconventional charge controllers may as well monitor battery temperature through sensors, increasing the voltage to compensate and protect the batteries. For a battery base power system, it is wise to invest in and select a good charge controller [9].

- **Solar batteries**

The batteries are used to stock the DC generated power by the system, make use of the solar batteries guarantees that the power is available when PV array stops generating energy. The backup needed to be kept in the reserve and the volume of ampere-hours necessitates the kind and quantity of battery in a given system. The right size of a battery is a vital aspect in the performance of any off-grid PV system. It is the aspects of the batteries which will dictate the extent of time you will be able to work amid charges [11].

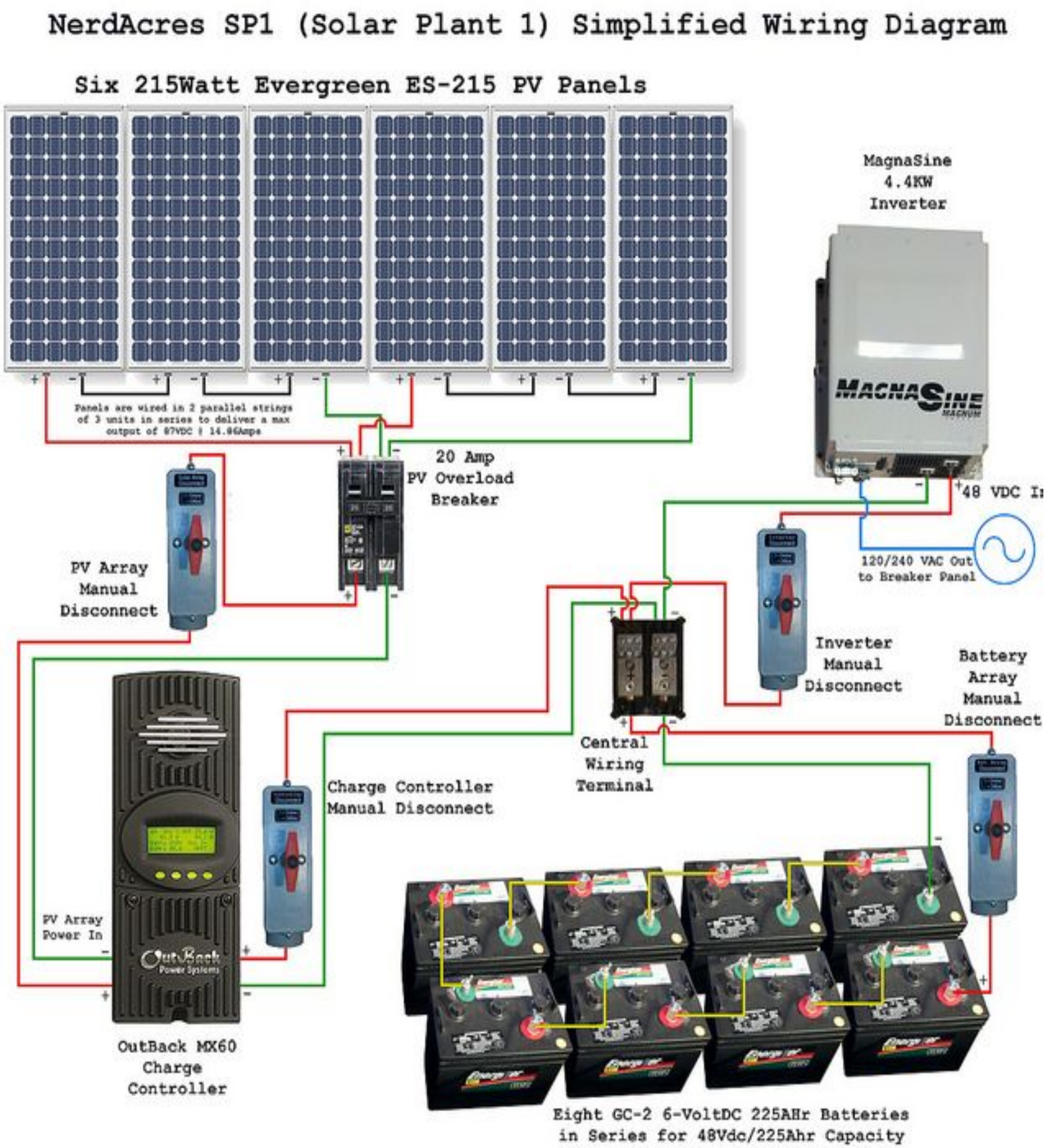
3.2.2 Phases of Power Plants

- **Single-phase system**

In the single phase system, the current flow between two wires, one neutral and one power. Depending on the system, he circular changing in the direction and the magnitude normally alter the current flow and voltage about 60 times per second.

- **Three-phase system**

In the three-phase system, there are three power wires which deliver three alternating currents, fundamentally three distinct electric services, homogeneously divided in a single face. This means that the point in time at which respective leg of alternating current attains maximum voltage are separated by 1/3 of the time in a complete cycle. This illustrates that the total power supplies by all three alternating currents remain constant.



Source: elecengworld1.blogpost.com.eg

Figure 5: Principal schemes for PV panels and inverters and connection to a network

3.3 Potential Induced Degradation (PID)

A potential Induced Degradation is a marvel that has been in existence for several years. It is occurring on several photovoltaic panels consequential to an underperformance of the solar panels. The condition was originally realized in the 1970s, since then, numerous researches have been initiated to be able to bring forth through several assessments the origin of such incidences [12,13]. Even though the aspects instigating Potential Induced Degradation like humidity, heat and a negative voltage having recognized, still there is no clarity as to why PID is not occurring on all or in a good number of Photovoltaic panels [12]. That said, it has also realized that the sudden decline in solar panel costs and quality have been found as reasons why PID transpires. In the PID affected component likely among the cells createa a polarization outcome, leading to amplified current leakage, from the surface of the cell via encapsulation and the glass, which is then cleared to the ground [13].

The PID effect can have a negative impact on the power plant, it has a degradation factor that can make it lose up to 70% of the power that is being generated by the plant. Due to the effects that are resulted by the PID effect on the power plant, there is some functionality that run faster than they should. For this reason, the power plant makes significant losses that can lead to an ultimate failure of the power plant.

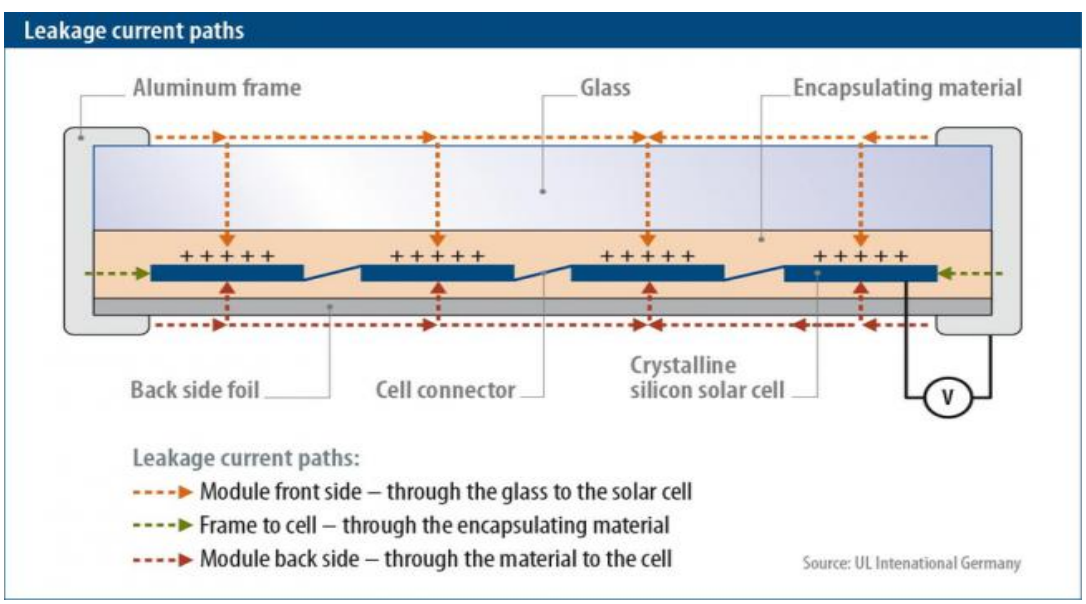
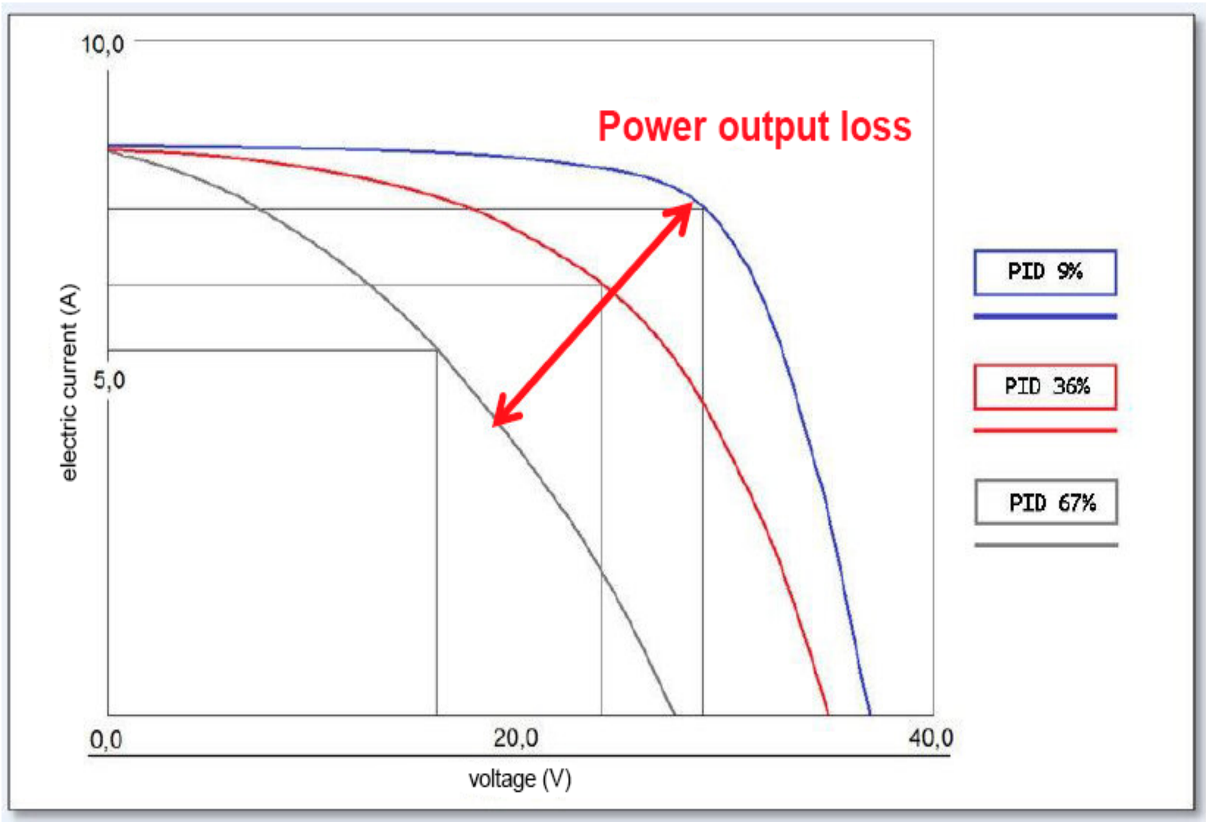


Figure 6: Leakage current path diagram [14]



Source: Eicero Intelligent Power

Figure 7: Power output loss due to different PID percentages

Studies have revealed two types of PID, the first kind is the non-reversible, which can happen in thin film technologies are caused by the electrochemical response that later result in electro-corrosion of the transparent conducting oxide [15]. The second type occurs due to superficial polarization, this occurs due to build-up of positive charges on the cells of the solar, this results in an upsurge in currents leakage. The volume of current leakage is dependent on the foundation outline of the PV arrays; the collected charge hinders the cell energy production capacity. Nonetheless, there is a possibility of controlling and reversing as well as preventing the accumulation of charges through observation of essential safety measures at the cell level, encapsulate and module levels.

3.3.1 Conditions that cause PID

- **Environmental aspects**

The environmental aspects are reliant on amount of water vapour in the atmosphere and the prevailing temperature, these two aspects act as catalyst agents as they are known to play role in increasing the quantity of current being leaked [15,16]. In case water infiltrates the panel, the current from the leakage upsurges as a result of increase in conductivity of the encapsulation material. This interaction between the encapsulation material, the foil at the back sheet, the glass, and the frame may result in particular leakage along the current pathways. Figure [8] illustrates the details of the mechanism of PID within a solar module or solar panel:

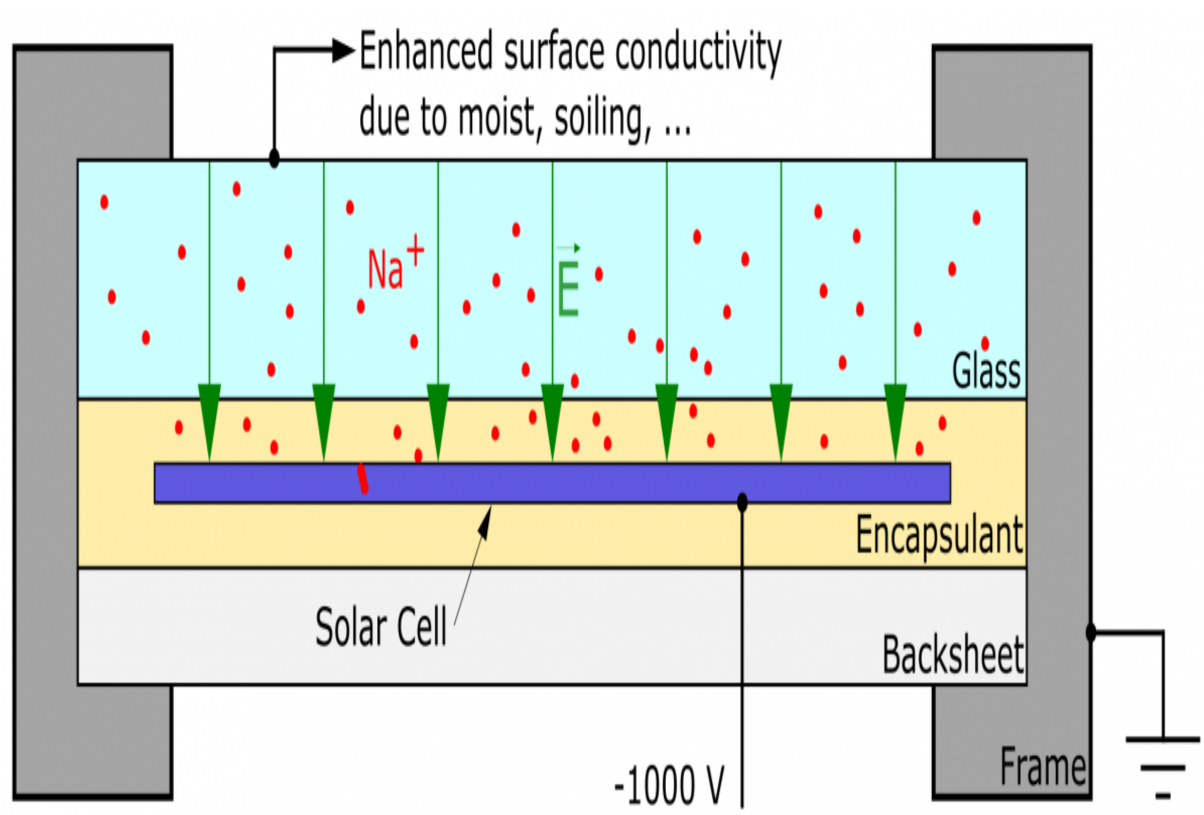


Figure 8: Alkaline metal ion drift towards the solar cell under influence of a strong field [13]

- **System aspects**

System aspects are dependent on the voltages of the system and the sign as well, which depend on the position of the module and the grounding of the system. The difference in potentiality between the mounting ground and the cell marks an imperative factor for PID [17]. The voltages of the system are dependent on the initial order as well as on the quantity of the panel in the sequence of interconnection; the second-order is dependent on the temperature of the panel. Concerning system arrangement of the ground layout, the potentiality of the cell toward the ground should be situated negative or vice versa [13]. There are three grounding possibilities, two relates to the ground while one relates to systemic poles, which is either positive or negative grounding, this means that every cell or panels become negative or positive if poles are grounded. However, if there is no pole established, then the subsequent potential remains unfixed therefore referring to floating potential.

- **Cell aspects**

This is one of the major aspects that influence PID resistance at the cell point, the structure of the cell has an influence on the PID process itself. The structure of the cell affects the density of the charge carrier of the silicon used, and the anti-reflective coating chemical composition layer.

3.3.2 Detecting PID

There are several ways through which the action of PID can be detected, first is through the open voltage circuits, if a module has been affected by PID action, the open circuits become lower than the expected voltage [15]. This is because the shunt resistivity is reduced; this becomes more and easily evident when the action of PID has reached its peak.

Next, is through conducting the distinctive test to find out whether the modules are affected PID is by measuring the panels IV characteristics using an electronic tracer, the presence of the PID can be detected when you find that the Pmax has taken a square shape rather than being flat.

Thirdly, through electroluminescence reflection, this method has the potential of detecting with ease the PID in a module, this process involves the use of CCD camera, biasing the module with a current source deprive of sunrays. Not affected module displays electroluminescence reflection with every cell displaying the same brightness, on the other hand, the affected module is characterized by dark cells that come as a result of cell shunting triggered by Na ions. Additionally, modules dilapidation along the string displays a pattern where negative sideways becomes the most affected while the positive end demonstrates fewer effects [16].

Additional method for PID detection includes a measurement of the dark and light IV curve, flash tester, which has a major advantage over incessant illumination testers which includes the provision of an intensified light with better uniformity over extended areas while minimizing the overheating that due to short pulse of light. The flash testers include a single-flash and a multi-flash with single flash more frequently employed system [15]. The method is efficient because it creates a pulse of light with a plateau of light concentration, which is constant, and it records the whole I-V curve in milliseconds. This method is a bit expensive and the peak of power yields has volumes of kilowatts, which makes it challenging to regulate the power outputs [12].

3.3.3 Prevention of PID

PID can be prevented at different levels with different mechanisms, for instance, prevention at the system level especially for transform constructed inverter, the effects of PID may be eliminated through negative string grounding, through consulting the manufacturer of the inverter to avoid additional damage on the inverter [17].

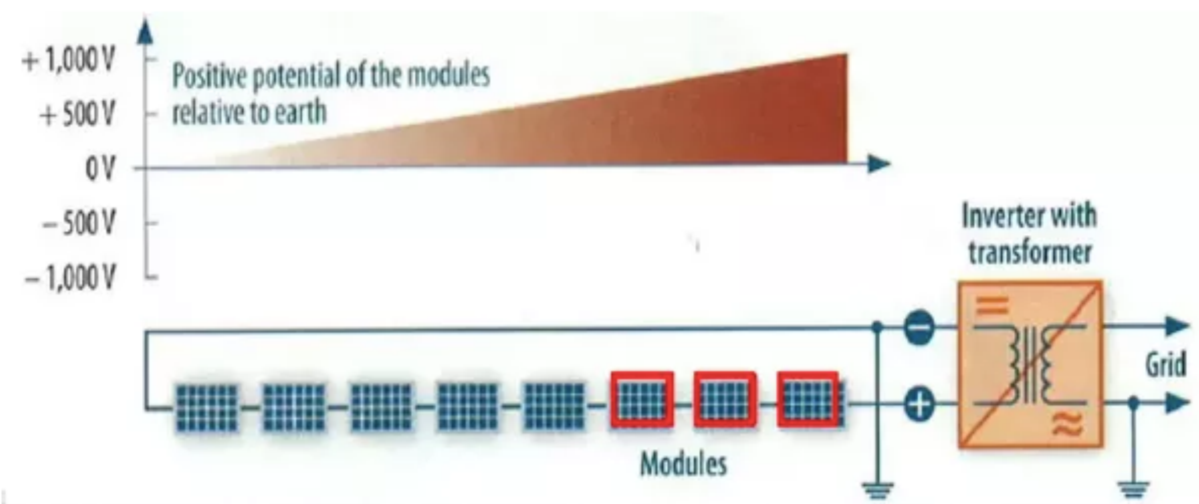


Figure 9: Positive potential of the muddles relative to Earth [18]

Otherwise, one can install the transformers that do not have the inverters, these transformers are cost-effective and well portable. However, if this kind of transformer lacks galvanic isolation between the AC and DC parts, grounding the negative DC cannot be done [19].

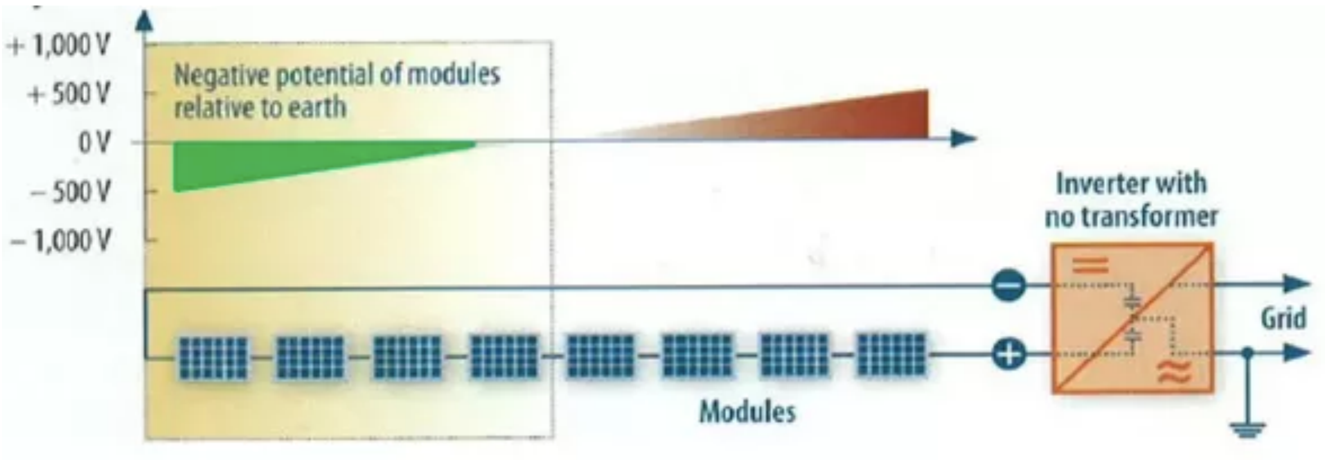


Figure 10: Negative potential of the muddles relative to Earth [18]

Prevention of PID at the module level can mainly be done through a reduction of water build-up to avert charges leakage. Additionally, novel technology in glass such as Quartz glass may be considered for exploration, the same to the exploration of Potassium-based glass. Last but not least, prevention can also be ensured from the cell level, anti- reflective cell coating has to be placed in a precise range, a conciliation must be made in the width of the ARC layer since an excessive may well increase the resistivity of the PID however how much the transitivity of the light is reduced or the opposite [20].

Consequently, heat recovery can be performed, initiating PID recovery through temperature storing PID panels at about temperature 100C in about 9 hours may result in nearly 100% recovery, however, this process highly depends on the condition of the module. As much as this presents a much faster process, the procedure of performing recovery at such intense temperatures inserts stress on the panel alongside its components thus may pose effects on its stability on the long- term basis [19].

4. Practical Part

4.1. Verifying the intensity of the PID in lab

4.1.1. Experiment

The aim of the experiment is to determine measurement methods suitable for PID diagnostics and figure out the rate of module degradation due to the PID effect. A total of four methods were used, namely volt-ampere characteristics, electroluminescence, unlit cells measurement and impedance spectroscopy. Only the first two of enumerated methods are typically used in diagnostics. The last two mentioned methods show great potential for early diagnosis of PID.

The course of degradation and later treatment was measured for the whole module. A commercially available module from OMSUN factory was used for the experiment. Specifically, it was a type OMP250-60P with a peak output of 250 Wp. The module was connected to the power plant for about 5 years and exposed to weather conditions before the experiment.

During the measurement, the emphasis was on maintaining a similar condition for all time during experiment., especially the same module temperature and humidity. The module was placed in laboratory where is temperature around 22°C, humidity has been monitored for a long time and is around 30%. The degradation was carried out by means of a high voltage source. In the case of degradation, the voltage was applied to the module so that the positive pole was connected to the frame and the negative pole to the module contacts. In the case of treatment, the polarity was only reversed. The degradation proceeded with a potential of 915V. This value was chosen with respect to the time possibilities of the experiment. To accelerate degradation or treatment, the module was covered with aluminium foil that was held on the module due to the electrostatic force. After each degradation or treatment interval, measurements were made using four the methods. Measurement of IV curves, dark IV curves, electroluminescence and impedance spectroscopy.

4.1.2. Results

- **Process of Degradation**

We started the degradation process and we tested first the electroluminescence. The electroluminescence images were always taken as the first diagnostic method after degradation. In the case of a stronger PID exposure, it is possible to observe a certain change in intensity. However, electroluminescence is not suitable for early stage diagnosis, as well as its use in the field is problematic. The quantification of electroluminescent images is also complicated.

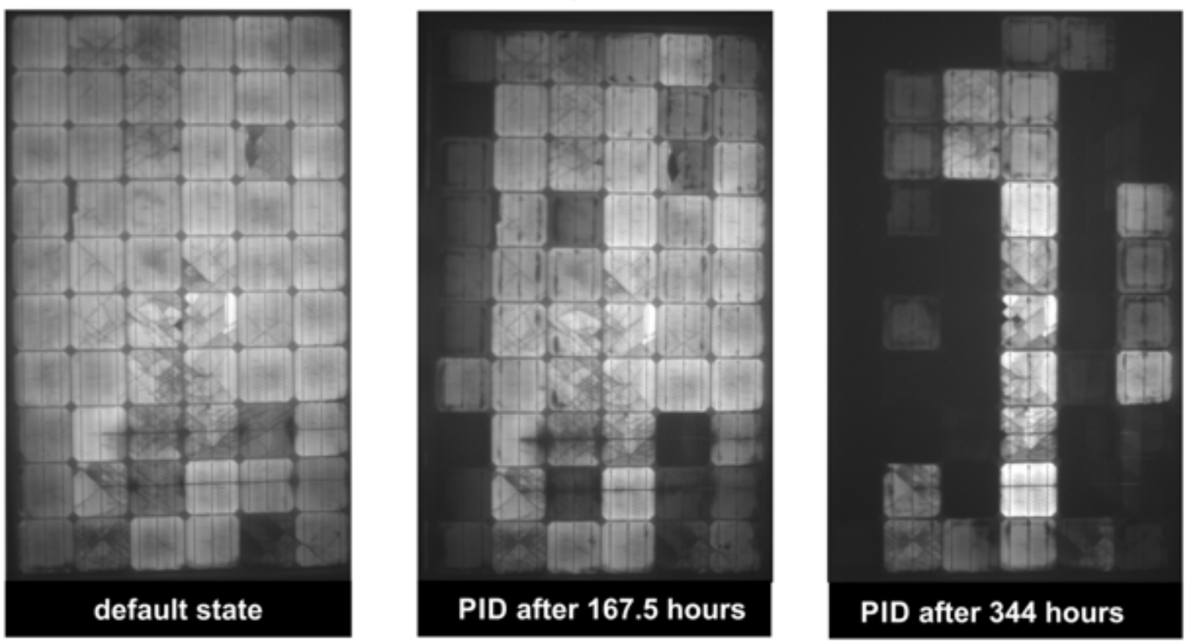
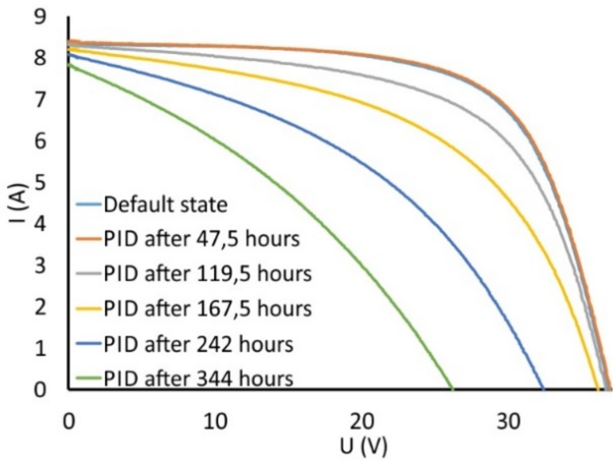


Figure 11: Electroluminescent images during degradation

For the other three remaining tests, we can see from the obtained graphs (Figure 12) that it is possible to say that the whole module is losing power during degradation, also a V_{oc} voltage decreasing everywhere. The module had a dominant decrease showed the shunt resistance R_{SH}, but also an almost double increase in the series resistance R_S is evident.



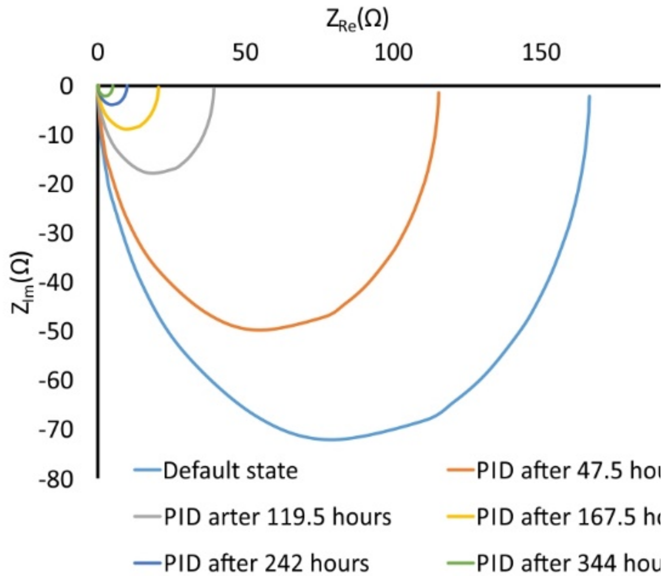


Figure 12 a). I-V curves during degradation for PV module

Figure 12 b) Cole- Cole curve during degradation for PV module

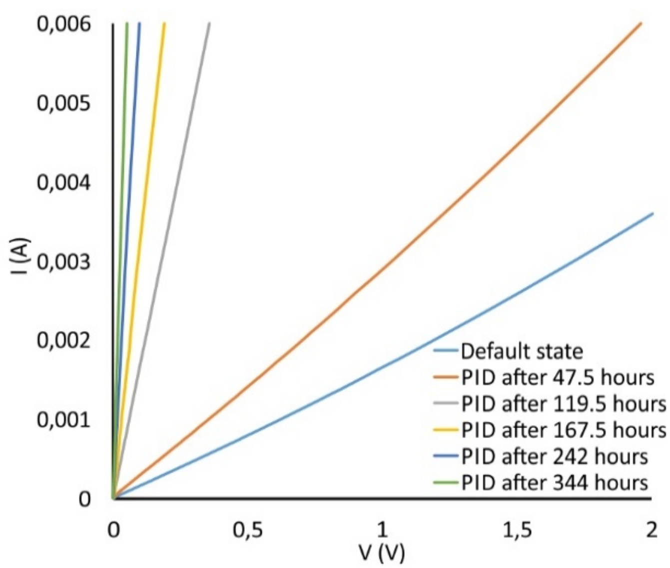


Figure 12 c) dark I – V curve during degradation for PV module

- **Process of Regeneration**

Characteristic obtained during module regeneration are shown in Figure 13. It can be seen that the PID regeneration proceeded very quickly and the last two measured characteristics overlap with the baseline characteristics. In our module, even higher performance was achieved than the module had in its original state before degradation. However, it is also important to note that some parameters did not return to their original value, especially the shunt R_{SH} resistance.

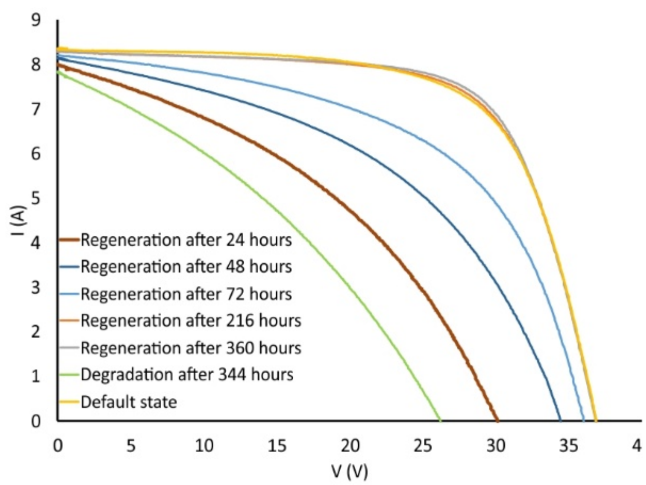


Figure 13 a) I-V curves during regeneration for PV module

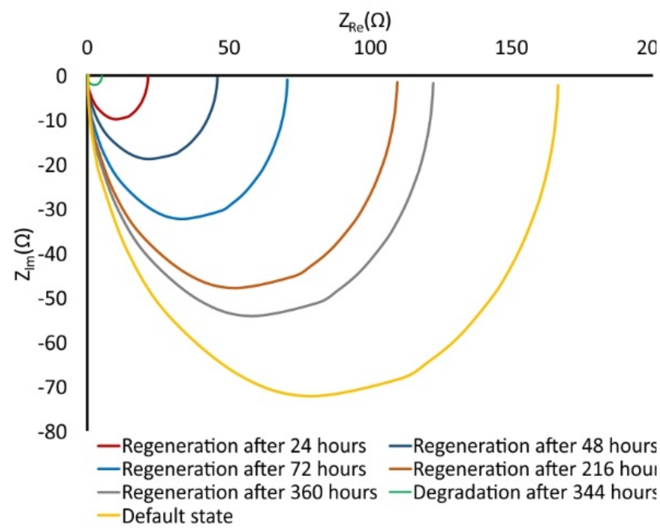


Figure 13 b). Cole- Cole curve during regeneration for PV module

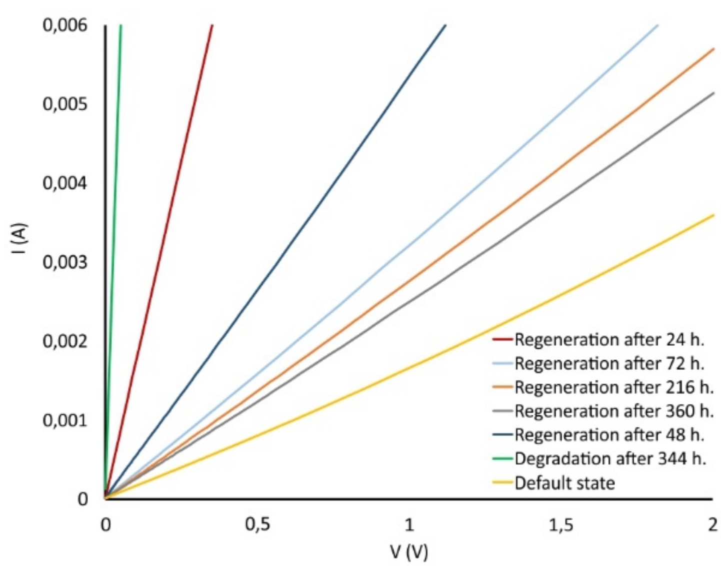


Figure 13 c) dark I – V curve during regeneration for PV module

4.1.3. Discussion

In the case of performance evaluation below one hundred hours of degradation, practically no significant change occurs, while a significant decrease in parallel resistance is observable in less than 50 hours. The course of the power decrease is shown in Figure (14). The power decreased from 200W to almost 75W in the whole course. The tested module already showed significant changes in shunt resistance after 47.5 hours of degradation. In Figure (15) it is possible to see the time change of the shunt resistance obtained from the 3 tests, from the I-V curve by deriving the extreme conditions, the shunt resistance obtained by impedance spectroscopy, and the shunt resistance obtained from the dark I-V curve.

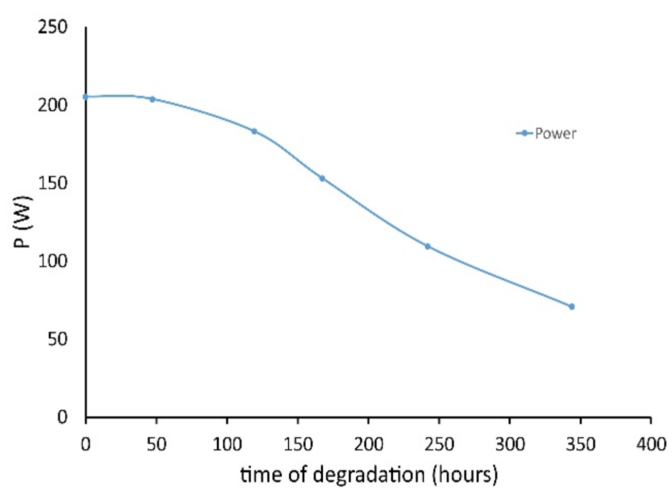
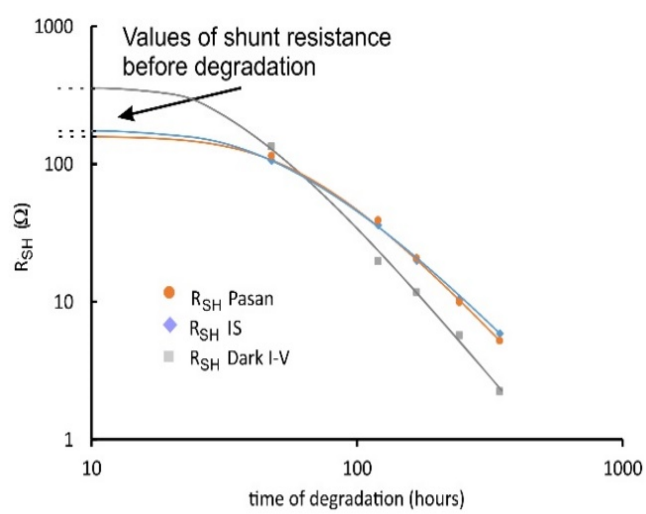
	

Figure 14) Change of power of PV module due to PID	**Figure 15) Change measured R of PV module due to PID**

All these methods can be considered as an approximation. The dark I-V curve method proved to be the most sensitive, the IS and the flash tester are comparable in terms of determining the shunt resistance. The estimated shunt resistance value when using the flash tester, decreased by 27% in the first 47.5 hours, in the case of IS by 30% and in the case of dark I-V curve, even by 57%. In the first tens of hours of degradation, the dependence of the resistance R_{SH} on the degradation time appears to be linear and gradually changes to the power function.

The course of the photovoltaic module parameters during degradation and subsequent regeneration is shown in Figure 16. Parameters such as power, Voc, Isc, R_S returned to their original values after 360 hours of regeneration. R_{SH} shows some hysteresis and it was not possible to completely regenerate it. However, this degradation of the R_{SH} value has not yet affected the performance of the module, but proves a certain irreversibility of the PID.

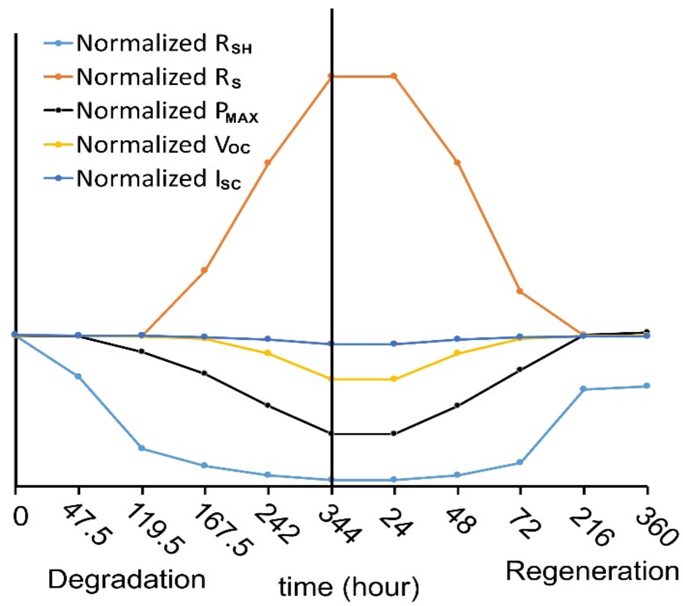


Figure 16: Photovoltaic module parameters during degradation and regeneration

Impedance spectroscopy and measurement of dark I - V curve can be used to detect the PID effect at an early stage. Both of these unconventional methods have proved that the photovoltaic modules cannot be fully regenerated after PID. For diagnostics of PV arrays, it is best to use dark I-V measurement due to the simplicity of the measuring device, it is also possible to use IS measurement.

4.2. Measurement of PID degradation in the field at the power plant

4.2.1. Experiment

We investigated the diagnosis of PID using conventional methods in the field. Thermography is most often used for field diagnostics. Virtually another diagnostic method is not possible. Continuous power measurement reveals the gradual degradation of the power plant, but it is not possible to determine which type of failure it is. We could not use unconventional methods such as IS and measurement of dark characteristics, because they can practically be considered more as comparative methods and unfortunately we lacked initial values from the time of power plant installation.

In real operation, there is usually a combination of individual PID mechanisms, especially PID-p and PID-s. While PID-p is a fully reversible mechanism, the reversibility is only partial (greater degrees can be achieved by increasing the temperature during regeneration). In the first phase, therefore, the formation of a positive charge layer first occurs in the vicinity of the antireflection layer, and only after a longer period of field action does the migration of ions into the PN junction and its local destruction (short circuits) occur.

For the existence of PID, as mentioned earlier, the key field strength between the frame-ground (in the case of frameless modules the front of the module) and the negative pole of the PV module. As the number of modules increases, the magnitude of the voltage acting on the module increases. The solution is to ground the negative pole, which shifts the voltage to the same potential as on the frame. Conversely, the worst possible situation occurs when the positive pole is grounded. If no pole is grounded, the system behaves as if it were grounded in the middle of the chain. The critical voltage value for the development of the PID effect is around 200 V. The specific value depends on the structure of the module, especially the properties of the EVA film and anti-reflection layer. At this value, the onset of PID can already be observed (Fig. 17).

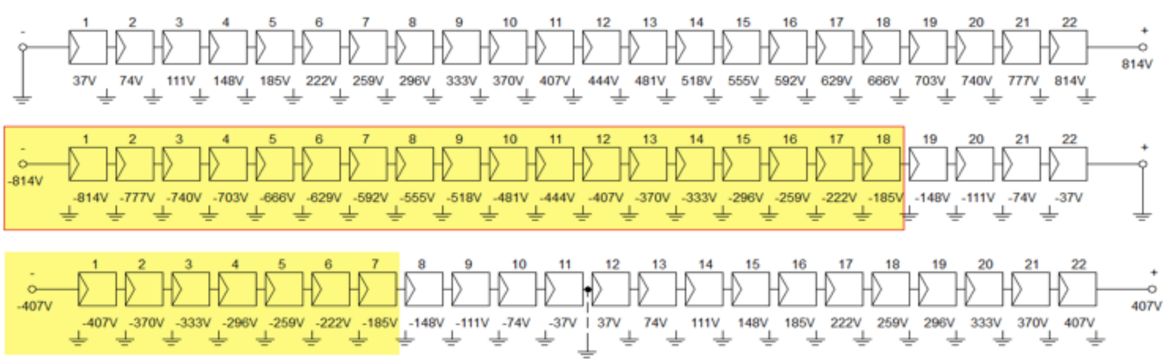


Figure 17: Dependence of PID on string size (affected areas marked in yellow)

The formation of PID is also influenced by climatic conditions, where humidity and temperature significantly worsen the effects of the PID effect. In the case of increased humidity, the conductivity of the module surface is better and thus the electric field is applied over the entire surface of the module. Temperature in turn helps the migration of sodium ions, which is accelerated. This is also used in the so-called "PID tests", when a methodology was created, which, although not enshrined in legislation, provides guidance on how to test whether the module is PID Free or PID Sensitive.

4.2.2. Used equipment

A Metrel solar analyser was used to verify the degradation of PV string detected by thermos-camera. Using this analyser, the power of the affected string and the power of the string equipped with PID free modules were measured. The measured data were automatically converted, using the measured temperature and exposure, to the parameters measured at STC. Tester Metrel MI 3108 PS Eurotest PV was used for measurement the basic parameters and V-A characteristics of the string.

Figure 19: Tester Metrel MI 3108

Function	Measuring range	Basic measuring error
Voltage	0 V DC ... 99 V DC	±(1,5 z MH + 5 D)
	V AC ... 99 V AC	±(1,5 z MH + 3 D)
	I-V m.: 2 V DC ... 99 V DC	±(2 z MH + 2 D)
Current	Modul m.: 0,0 mA ... 300 A DC	±(1,5 z MH + 5 D)
	Invert. m.: 0,0 mA ... 300 A AC	±(1,5 z MH + 3 D)
	I-V m.: 0,00 A ... 15 A DC	±(2 z MH + 3 D)
Power	Modul m.:0 ... 200 kW	±(2,5 z MH + 6 D)
	I-V m.: 0 ... 15 kW	±(3 z MH + 5 D)
Energy	0,000 –h - 1999 kWh	
I-V curve	1000 V / 15 A / 15 kW	
Irradiation	0 ... 2000 W/m	± (5 z MH + 5 D)
Temperature	-10°C ... + 85°C	± 5 D

Table 2: Technical data Metrel MI 3108

Instruments for measuring radiation intensity and temperature

Figure 20: Sensors for measuring temperature and radiation intensity

4.2.3. Discussion and Results

When diagnosing PVE affected by PID, it is necessary to systematically divide the power plant according to chains and identify the position of individual modules in a given string (the intensity of detected defects will have a strong dependence on the position in the chain). The individual cells of the modules affected by the PID will have different temperatures, while the cells of the modules that are not affected by the PID should glow with the same intensity on the thermogram. However, it is necessary to perform IR measurements in sunny weather to ensure a sufficient temperature difference between the affected and unaffected cells of the module.

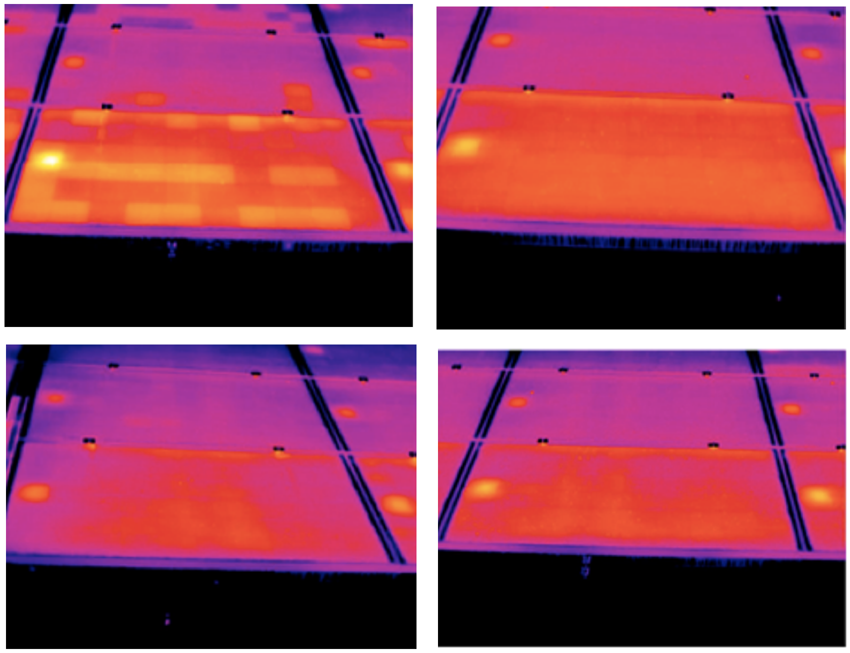


Figure 18: Dependence of PID on position in string – thermograms

The individual images are shown in Fig. 18. However, it is not possible to determine the decrease in string power due to degradation from the thermal imager measurements. The modules included in both strings were not from the same manufacturer, but the same top performance and installation date. The aim of this measurement was to identify strings affected by PID degradation at a 500kW power plant.

The results of comparison I-V curve measuremed by Metrel are shown in Fig. 21. Both strings contained 17 modules and the photovoltaic field was fed into one, 3 f inverter with a power of 15 kW. Thus, a total of 3 PV arrays, each with an output of approx. 5 kW, were connected to the inverter. In our the case which was examined, only one PV field showed PID degradation.

Measurement of characteristics using a meter and subsequent calculation of power showed a decrease of more than 50%. Such a significant change in performance was caused by PID degradation. Such a strong decrease in string performance was also due to the fact that the PID degraded modules were stacked into one string. The goal of this configuration change was to minimize the effects of PID degradation.

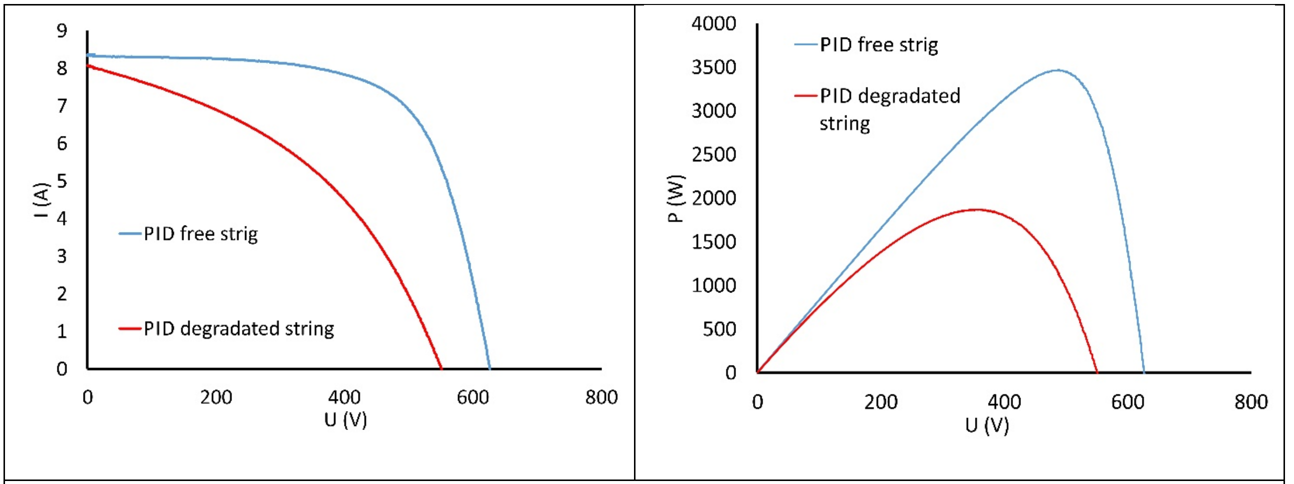


Figure 21: I-V curve and power curve not degraded and degraded string.

5. Conclusion

PID effects on the module is a changeable procedure when targeted on particular levels such as at the cell level where strict monitoring can be focused on aspects such as resistivity of the sheet, cell layers' thickness and through procurement of cells which are free from PID. About the encapsulation aspect, it is highly affected by the resistivity and absorptivity of water, EVA Polyolefin and incomers may be tested as per experience. Furthermore, the Na gas content need to be observed and to enhance resistance modules, a gradual move in the adoption of quartz glass to replace soda-lime glass should be initiated.

We used four different methods for testing for PID during our experiment, and from those four we can say that method unlit cells measurement and impedance spectroscopy show potential for early PID detection. While electroluminescence is not suitable for early stage detection, and it would be inconvenient for use in the field. The course of the photovoltaic module parameters such as power, Voc, Isc, R_S during degradation and subsequent regeneration returned to their original values after 360 hours of regeneration, while shunt resistance shows some hysteresis and it was not possible to completely regenerate it. The degradation of the shunt resistance is only to prove that some parameters can't be fully reverted from PID, so it does not have any effect on the performance of the module. As we mentioned earlier that impedance spectroscopy and measurement of dark I - V curve can be used to detect the PID effect at an early stage, so both of these unconventional methods have proved that the photovoltaic modules cannot be fully regenerated after PID. Those two methods can also be used for PV arrays for diagnostics, it is best to use dark I-V measurement due to the simplicity of the measuring device, it is also possible to use IS measurement.

For an outdoor PV field in a power plant, in order to detect PID we usually use Thermography. We could not use unconventional methods such as IS and measurement of dark characteristics, because they can practically be considered more as comparative methods and unfortunately in our case we lacked the initial values from the time of power plant installation. The IR measurements had to be taken in a sunny weather to ensure a sufficient temperature difference between the affected and unaffected cells of the module. The individual cells of the modules affected by the PID will always have different temperatures, while the cells of the modules that are not affected by the PID should have the same glow intensity on the thermogram.

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