Solar Photovoltaic Panels Failures Causing Power Losses: A Review

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***Abstract*— During its operation time, a photovoltaic (PV) array can be influenced by many factors that can reduce its performance. Consequently, the global yield of the array decreases, induced by photovoltaic faults and failures. It is then an essential matter for manufacturers and consumers, to know and apprehend these factors. In this paper, we investigate different faults affecting a photovoltaic system, from those detectable by visual inspection to those barely noticeable with an eye. To detect such faults, an overview of methodologies commonly used and new existing ones like the synchronized thermography is done.**

***Keywords*— Defects, Degradation, Environmental effect, PV failure, Solar cells efficiencies**

I. Introduction

These latest years, significant growth of renewable energies is observed in electrical production around the world especially with photovoltaic (PV) technology. In 2016, it was reported that, around 315 GW of PV were installed globally and the forecasts are between 385 GW and 500 GW during 2017 and 2022 [1-3]. The PV technology is supposed to be less demanding in terms of maintenance because producers give a 20 years warranty or larger. Unfortunately, PV plants are in power loss which impacts the global yield; the climatic conditions ease the development of PV failures.

There are ongoing research and initiatives, such as the International PV Quality Assurance Task Force (PVQAT) formed in 2011, with the aim to identify the causes of the power losses, diagnose PV faults, find the means to avoid them, but also to organize and share results toward testing for different climatic conditions (desert, tropical, temperate) and mounting configurations (rack-mount and roof-mount) [4-9].

Defects include failures which can result in a degradation mechanism, but, do not originate from its production structure [12]. The rated power loss of the PV system starts while it is in a condition which is not expected. The gradual degradation of the performance is defined as the inability of the PV generator to produce its nominal power, due to exposure to extrinsic factors [13]. These are climatic ones: temperature, humidity, precipitation, dust, snow and solar irradiation.

Some previous works are focused on monitoring of PV failures [10, 12-15]. Note that some defects on PV module degrade the power performance and even a normal operating cannot reverse it. In Sahelian region, facts show that after a few years, a major part of the PV installations is not efficiently working anymore. Lack of maintenance is generally mentioned as the cause of these losses. It is interesting to report the possible defects that can occur during the operating time of a PV system. That allows organizing PV plants maintenance around performing protocols with less human intervention.

The aim of this paper is to present a review of problems occurring with crystallin silicon technology in photovoltaic field. Though for the thin-films modules the available information is not enough a Pareto chart by the authors of [7] shows the dominant faults for this technology. A diagnostic methods classification for the crystalline-silicon is proposed and a detailed study of different faults and failures is done.

II. Failures on a Photovoltaic Generator

To properly investigate the failures and miscellaneous mismatches of a photovoltaic generator, it must be studied from its smallest part to its largest as illustrated:

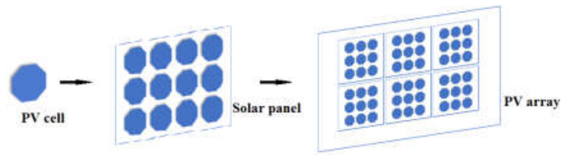

Fig. 1. Cells association forming a PV array

According to literature, those failure problems depend on facilities/ PV systems (DC or AC sides) and can occur from the design, the installation, the operation or the maintenance [15, 16]. This paper is deepening only those on the DC side.

The faults cannot be accurately distinguished from one to another in terms of characteristic values so, in order to well analyze and model them, it was proposed in [15] a five main groups classification; another fault group which also impacts the PV array at all levels (Cf. Table I) has been added. The given table intends to show that a failure which impacts a level of component, can also impact the next level (up to down). Performance degradation i.e. power loss appears at different levels (cell, group of cells, module, strings and PV array) with various factors and degradation mechanisms apparent at each point. Among all those families' faults mentioned (Cf. Table I), there is one most

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known than others because of its influence: it is the mismatch and shading defect.

A. *Mismatch and Shading faults*

Mismatch losses can come from permanent or temporary sources. The first ones are about manufacturing tolerance, performance degradation, and also module cracking while temporary sources are linked to the variation of irradiance received on the panel surface. According to [19], field experience highlighted the incapacity of solar cells forming the arrays to completely extract the available irradiance. Those losses called mismatch losses lead to a reduction in the power produced. They are mainly caused by a non-uniformity illumination on cells in the array and by the dispersion of electrical properties. Indeed, electrical properties may vary due to manufacturing tolerances or degradation processes [20]; furthermore, the modules composing the same array usually have different characteristics even if they are manufactured with the same power rating [21].

TABLE I. FAULTS CLASSIFICATION BY LEVEL

Generator's component	PV Fault	Origins and Nature
Cell	Mismatch and Shading	Scratched or broken module, cell damage, Crack, penetration of moisture, Towers, chimney, sand, snow, Heated cells, degrading of cell, Corrosion of connections between cells Modules of different types
Group of cells	Bypass diodes	Destruction of diodes, lack of diodes, inversely connected diodes, Ill connected diode, short-circuit or shunt of diode
Solar panel	Module	Short-circuit or shunt of modules, inversely connected modules
Strings	Connector	Disconnection of electrical circuit, destruction of connector, corrosion of junction or contacts, disconnected module Short-circuit of the electrical circuit
PV array	Blocking diodes	Destruction or absence of diodes, Ill and inversely connected diodes, short-circuit of diode
-	Arc	Heat, Humidity, Voltage stress loose connection, bent or crimped cables, Brittle or aged cables, Vermin chewing through wiring
	PID	Humidity, temperature and heat, in combination with a negative applied voltage

Mismatch faults such as antireflection coating degradation, encapsulant material discoloration, light-induced degradation, overheating inducting hot-spots [22], participate in the transformation of solar cells' electrical properties. These ones are the photocurrent, the cell's temperature, the series resistance and the parallel resistance. Soiling through the accumulation of dust deposition and pollution affects also those properties by creating a shade [23-25]. It can lead to an annual energy loss of up to 6% [10] or even more in extreme cases [11]. Apart from the power loss, localized front glass soiling and shading lead also to the reverse biasing of the affected solar cells and cause irreversible hot-spot damage and even module failure [24, 10-11].

These mismatches have an impact on the I-V characteristic which is not identical for all [15]. So, a better assessment of such mismatches should be done by analyzing the behavior of each module of a PV plant [26].

Actually, a PV array consists of a number Np of strings in parallel and each of these strings having a number Ns of modules in series, the nominal power of the array should be:

$$P_{array} = \Sigma P_i \tag{1}$$

Where P_i is the output power of each module and i varies from 1 to Np*Ns [21].

Mismatch is found when this nominal power is not anymore, a sum of P_i. Hence, we have:

$$P_{array} = \Sigma P_i - mismatchlosses \tag{2}$$

A previous experimental study conducted by [18] on each cell of a module proved that through that mismatchlosses the power can be calculated or evaluated, regarding specific conditions, using this formula:

$$\mathrm{ML}_{\mathrm{Pmax}} = 100\left(1 - \frac{Pmax(module)}{\sum Pmax(cell)}\right) \tag{3}$$

With $\mathrm{ML}_{\mathrm{Pmax}}$ = mismatchlosses in %, where the fraction numerator $P_{max(module)}$ is the maximum power point of the PV module and the fraction denominator $\Sigma P_{max(cell)}$ is the sum of the maximum power point of all the cells of the module.

Being a specific case of the mismatch fault, *shading* has the same effect: it brings a reduction of the insolation on the cells resulting in power losses [15]. Remember that shading occurs when an external object lays between the sunlight and the cells meaning irregular lighting [28].

Generally, *partial shading* is considered among the most severe faults because of the harmful effect that it can produce on the PV modules. Various methods have been investigated for the detection of this fault, these methods are often based on the analysis of electrical and non-electrical parameters [29]. Limits in the total current, as well as a reduction in the output voltage of the PV system, are fixed by the shaded module of the string. Both effects, current and voltage reductions, can be observed at the same time or separately depending on the shadow profile and the configuration of the PV array [30].

B. *Other kinds of faults*

Even though they are not well known, the remaining groups of faults impact in the same way the PV system by reducing the power output. In a module, *bypass diodes* protect a limited number of cells (generally 18-24). To prevent this group of cells from hot-spot development, the panels are provided with these diodes. They are connected antiparallel to the PV panels and provide alternate paths for the current flow when activated. Of course, being aware that these diodes only work when faults occur. If faulted, *bypass diodes* can be short-circuited, disconnected, inversely wired (wrong connected) or behave as an impedance. However, *bypass diodes* introduce multiple peaks in the I-V and V–P characteristics curves and make the maximum power point tracking difficult as conventional MPPT algorithms cannot differentiate between global and local maxima [30-32].

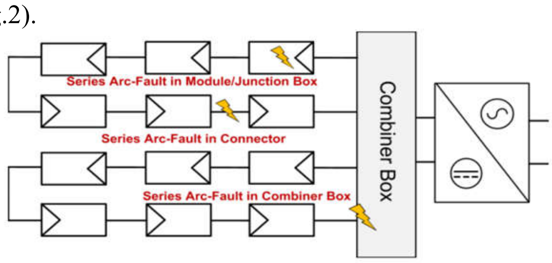
A *module* being groups of cells put in series has the same faults. Nevertheless, effects on a module are not like effects on a group of cells. An entire detection of these defects' effects has been proposed and experimentally tested by [33]. There could be short-circuited module, inverse polarity module or an impedance connected in parallel with the module.

The *connector* failure appears when there is an increasing impedance between modules. This impedance increase can cause voltage risings as shown in [32], and the amount of the voltage change depends on the amount of the impedance increase. Not only does this one occur on connectors or junction boxes, but also observed failure modes include melted contacts and plastic walls in the junction boxes, separated external connectors and broken latches [36]. Causes are numerous: pin misalignments, dirt or dust ingress etc.

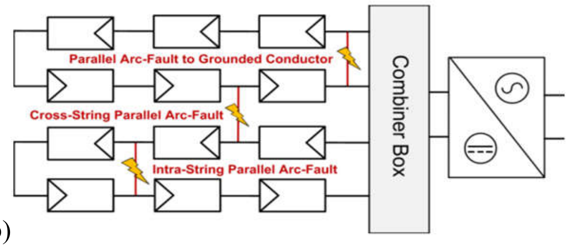
As for *bypass diodes*, *blocking diodes* faults have the same consequences; so, the diode can be short-circuited, disconnected, inversely wired or behave as an impedance.

Apart from the categorized failures aforementioned, there are *arc* and *PID* faults. An *arc* fault is an unintended arc mechanism in a PV array created by a current flowing in an unplanned path, and that can lead to a fire. In most cases, *arc* fault occurs when components are aging. Detecting and preventing *arc* faults eliminates a known hazard to the safe operation of the PV system [16].

There are two possible types of *arcs* in the DC wiring of a PV system: *Series arc* which is the result of the failure of the intended continuity (discontinuity) of a conductor or connector in an electrical circuit and *Parallel arc* which occurs due to an unintended current path between conductors (electrical discharge) i.e. it is created when an *arc* is established between conductors at different potentials [36-37]. As shown in Fig. 2, different *series* and *parallel* arc-faults exist; three generic types of each are illustrated (Cf.fig.2).



(a)



(b)

Fig. 2. (a) series and (b) parallel arcs faults [35]

The difference between *series arc*-faults and *parallel arc*-faults lies in the fact that the string current and voltage only change slightly from normal operation and the location of the *arc*-fault also does not modify the string current or voltage [37].

A *PID* for *Potential Induced Degradation* fault is a recent and new kind of PV system's defect, which has brought renewed interest in 2010 [38] since manufacturer SOLON first reported it. *PID* fault mainly affects the c-Si (crystalline silicon) module and, as the designation implies, it occurs when the module's voltage potential (difference of a few hundred volts) and leakage current drive ion mobility within the module between the semiconductor material and other elements of the module (e.g. glass, mount and frame). Then this ion mobility accelerates when finding favorable conditions such as humidity, temperature and voltage potential. If the modules/cells are not resistant to *PID*, the degradation mechanism can affect power output capacity and finally result in yield losses of 20% or more [39-40].

The factors like voltage, heat and humidity, that enable *PID* exist on all PV modules, but the effect does not occur on all. However, when it occurs, first thing noticeable will be the loss of power confirming the change that can be seen on the electroluminescence spectrum, then comes an irreversible degradation of silicon cells, followed by the aging of the polymeric encapsulant and finally the delamination and destruction of the module.

III. VISUAL DEGRADATION

Different types of degradation can be visually seen on the modules when at a specific state (long term consequence). Authors of [41] define the degradation as an alteration or a stopping of components ability to give the expected work according to technical specifications. The visual consequences or effects or simply the degradation come mainly from weather parameters intensity on the PV system.

A standard crystalline-Si solar panel has multiple layers as:

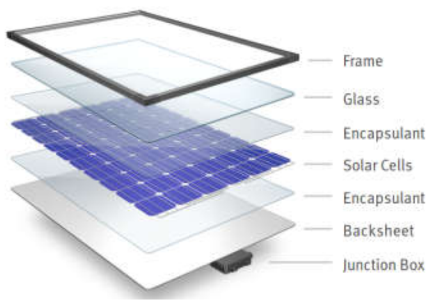


Fig. 3. Layers of a PV module

So, the degradation can be seen on each element pictured above. Note that the "Glass" is for cells protection, the

“Encapsulant” is a polymeric EVA (Ethylene Vinyl Acetate) and the “Back sheet” is generally in Tedlar (commercial name for the Poly Vinyl Fluoride (PVF)).

The first degradation of PV modules is *Corrosion* [38]. *Corrosion* is the deterioration of materials by an electrochemical interaction with the surrounding environment. This electrochemical interaction is caused by the humidity and the diffusion of moisture through the breathable back sheet and the EVA sheet [41]. The higher the humidity under the glass, the higher the conductivity of the material [38]. Hence, it can weaken the interfacial adhesive bonds, resulting in the corrosion state. Its effect can also be seen on elements like junction boxes (Cf.Fig.4).

Fig. 4. Corrosion on junction boxes and solar panel

The environmental humidity going in through the frame or the back-sheet foil condenses in water. Thus, the UV radiation combined with this water at an exposure temperature of above 50°C affects the chemical structure of the encapsulant (EVA) in a way that the color of the cells changes. The phenomenon of the cells yellowing or browning as shown next is called *discoloration* [42]. It can happen that the color of the *discoloration* is neither yellow nor brown but black: such *discoloration* is called *snail trail* or *snail trace* [43-44].

The definite causes of *snail trails* are not clearly known but two of the recent studies on the topic have presented hypotheses [43-44]. Their conclusion is that *snail trails* come from silver nanoparticles dissolved from grid fingers and migrated into the encapsulation foil on top of the grid fingers. The dissolution of nanoparticles is due to a moisture penetration. Only the cell edges or microcracks are areas where water may diffuse into the cells’ surface. That is why *snail trails* are located at the cell edges or along microcracks which can be easily detected.

The second most frequent degradation of the PV modules is *delamination* [38]. It consists of the loss of adherence between different layers of the PV module and the subsequent detachment of these layers (Cf.fig.5). *Delamination* appears between polymeric encapsulant and cells or between cells and the front glass. In general, this can lead to two effects: a light decoupling where reflection increases as well as water penetration inside the module structure [42].

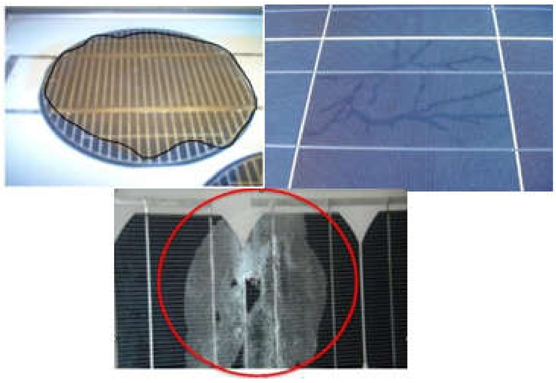


Fig. 5. Discoloration (browning cell) [38] - Snail trails – Delamination (loss of adherence)

Bubbles appear as consequences of chemical reactions after outdoor exposure that releases gasses. These are held captive under the back sheet or the encapsulant at the specific area where the adhesion has been lost. *Bubbles* make the heat dissipation of the cells more difficult, overheating them because of poor insolation, subsequently reducing the cells life and affecting the anti-reflective coating [38,42].

Lately manufacturers, for economic reasons, have reduced the thickness of the cells from 300µm to 200µm or even less; and on the opposite, the area has increased from 155mm x 155mm to a standard size of 158mm x 158mm. Those changes weakened the PV cells and made then sensitive during installations operations. Consequently, those called *micro-cracks* need different methods to be diagnosed but some *cracks* can be visible by eyesight and it is more obvious for *broken glasses* on PV modules. The *broken glasses* can be caused by installation manipulations, during transportation or maintenance or by vandalism, hailstorm. Causes related to weather can hardly be avoided even when we know their approach.

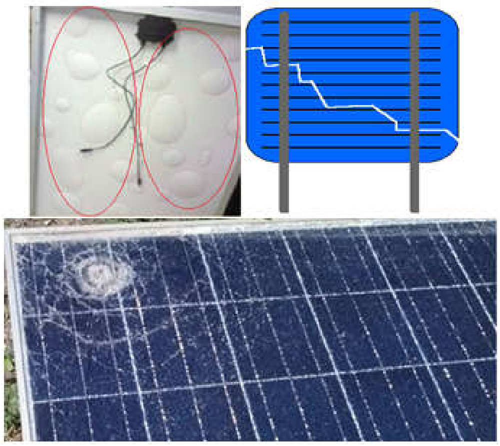


Fig. 6. Bubbles on the PV back sheet - Crack across a cell held by 2 busbars – Broken glass

IV. DIAGNOSTICS OF THE DEFECTS

There are two kinds of *Diagnostic* methods: the *classical methods* group and the *Intelligent methods* one. Some research works [45-47] made possible to summarize the *diagnostic* like shown in Fig.7, but it is not exhaustive.

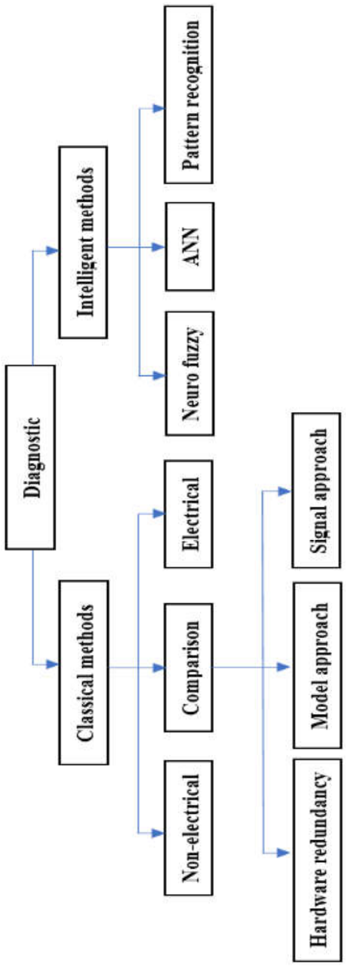


Fig. 7. Diagnostic methods flowchart

The first group of *diagnostic* methods is the *classical methods* in which we identify three sub-categories. One sub-category consists of the n*on-electrical methods*. These methods analyze *non-electrical* parameters hence neither I, V nor P in order to make a *diagnostic* about the PV array. However, most of the detected faults are cells cracks-related [15]. Here, energy emission is used.

The author of [48] states that the information needed depends on the energy emitted. It can be *electroluminescence* which is a form of luminescence in which electrons are excited into the conduction band through the use of an electric current commonly under the forward bias of the cell's PN junction. In principle, *electroluminescence* inspection of PV modules can indicate the presence and location of cell cracks and shunts, potential induced degradation (PID) and inactive submodules/strings (due to shunted bypass diodes or open-circuits), with great accuracy [49]. For example, failures like cracks, have a local current proportional to electroluminescence intensity; which means that defects on cells' images shall be seen as well, as shown in the following image:

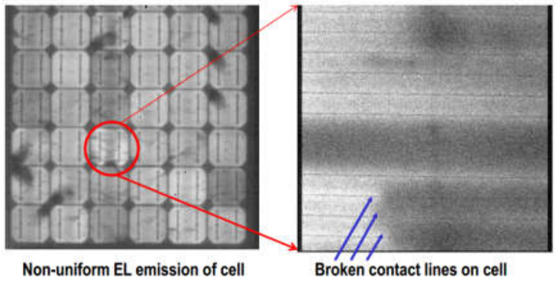


Fig. 8. Cracks detection [18]

There is also the *thermal imaging* or *infrared thermography* method which uses the infrared rays emitted by materials in a wave length range depending on their temperature [16,50]. The images are caught with a thermal camera which gives information about the thermal signature and the exact physical location of an occurring fault, indicates the defective cell, group of cells or module (qualitative diagnosis). In turn, such thermal signature can be used for quantitative diagnosis, by identifying the electrical output power losses of the impacted module, in the form of dissipated heat [49].

Infrared thermography has been used as shown by [51], to investigate the output performance of a 3-PV cells sample with the help of synchronized thermography [52].

The following image illustrates the detection of the defect, a hairline crack, on the 3-cells sample; it is noticeable thanks to the temperature color on the image:

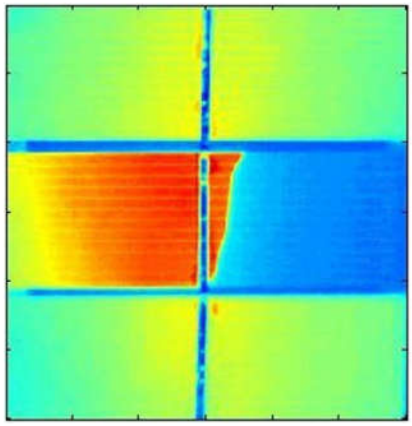


Fig. 9. Hairline crack detection [51]

The resolution of images when using infrared can only be limited by the thickness of PV glass [48, 51]. So, with these methods, faults are detected even on a module and an array; their use on connectors, junction boxes, blocking diodes or others components is also possible [15,53].

The authors of [54-55] also presented a *RUV* method. The *RUV* (*resonance ultrasonic vibrations*) technique is adapted for non-destructive cracks detection in full-size silicon wafers for solar cells. Using an external piezoelectric (frequency from 20 to 90kHz) transducer combined with a high sensitivity ultrasonic probe and computer-controlled data acquisition system, this methodology relies on the analysis of deviation of the real-time frequency response curve of a wafer ultrasonically stimulated via vacuum. Then the bandwidth increases and the frequency shift serves as reliable indicators of the crack appearance in silicon wafers because both characteristics are found to increase with the length of the crack [55].

Besides *non-electrical* methods, there are *comparison* methods which extract values from the system to diagnose and compare them to those measured at the same time from a reference or those resulting from a model or a simulation.

One of these methods is *hardware redundancy*. It consists in the use of many of the same hardware components (e.g. sensors) to play the same role. The diagnostic is made by comparing the same devices' outputs: when a difference occurs in the measured values, it is possible to directly locate the failure but not to identify its nature [15,47]. This method is exclusively used for systems where there is a need of continuity of operation.

Another *comparison* method is the *model approach* method. In this case, the author of this paper classifies the a*nalytical redundancy,* the *failure mode and effect analysis (FMEA)* and the *fault tree analysis (FTA)*; the list is not exhaustive. *Analytical redundancy* is based on a mathematical model of the supervised system. The method also uses the measured values (inputs and outputs) of the system and compare them with those collected from the model working in real time, in order to determine the state of the system itself. The values used are not only the up-to-date ones but also those previously taken. Nonetheless, for a PV system composed of many parts, having a mathematical state model of it, can be exhausting or even impossible for the diagnosis [15]; but a partial use could give good results. The *failure mode and effect analysis (FMEA)* is generally related with the *criticism analysis (CA)*. It is a complete risk evaluation of the faults including their gravity effects on the system. The assessment criteria are severity, the frequency of appearance and probability of non-detection. The *fault tree analysis (FTA)* is an arborescence structured in levels and used to identify and prevent the failures before their appearance. Each possibility is analyzed by combination; and the results construct bonds with other possibilities. The tree continues to spread until all the events are considered [45].

The last *comparison* method considered in this work, is the *signal approach.* In this case, the failure symptoms are investigated from the measured values forming of course a temporal output signal. One known *signal approach* is the *knowledge-based* approach. The system's behavior in normal and in abnormal operations must be known; this is essential before using this method. Thus, we know the effects of each fault on the output signal; once a failure occurs, it could be identified but also located by analyzing its effects on the values [46]. We can even more forecast defects for a better efficiency thanks to the *knowledge based* [47]. Here a state model of the PV system is not needed. The *Signal processing* method is like a *knowledge-based* approach except that data needed on failure are extracted by demodulation, filtering, FFT etc. Nevertheless, *signal processing* is much more fit for periodical signals [15].

The third sub-category of *classical* method is the *electrical* methods. These methods use I, V and/or P measurements to diagnose a defect. One of them is the *reflectometry* method which uses a signal sent in the system (or a part of it) in order to determine the state of wirings and connectors [53]. The emitted signal is then propagated through the system; when an obstacle occurs meaning a possibility of failure, a part of the signal is resent back to the source. Once this reflected signal is analyzed i.e. temporal delay and amplitude are extracted [45], faults like open-circuit, short-circuit and increasing impedance, can be diagnosed or detected and located in a string [18]. The following image pictures the principle:

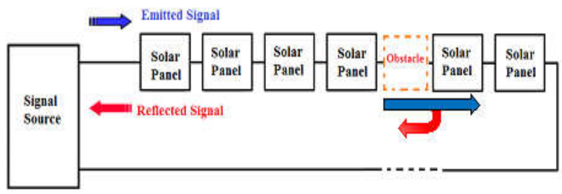


Fig. 10. Reflectometry principle

Another *electrical* method is the *analysis of the power* or the *energy* produced by the PV array. In their experimental work, though the current and the voltage have been measured, the proposed methodology of [33] used the amplitude of the decrease of the power related to the environmental conditions (temperature and insolation), to diagnose the module and string faults on a PV array. Authors of [56] uses a new automatic supervision and fault detection procedure for PV systems based also on the power losses analysis. The faults detected were: capture loss, system loss, thermal capture loss and miscellaneous capture loss.

The authors in [28] used the measured energy of a PV system in a performance model, to identify four classes of faults causing losses: Sustained zero efficiency, brief zero efficiency, shading and non-zero efficiency non-shading. In [57], a different way of detection is used, though it also implies energy production: the *failure detection routine (FDR)* analyses the pattern of the energy loss in order to create an actual failure profile which will be compared to predefined failures profiles. Hence, the *FDR* analysis concludes which faults occurred. The method proved good results but if a failure profile is not in the predefined ones, the *FDR* cannot detect it.

The use of the *maximum power point (MPP) value* obtained by simulation and compared to the real value measured, can also give more information on the state of a PV system. The faults that could be found are the module fault, the string fault and a group of non-discriminable faults like shading, MPPT error, aging. In last studies on detection of faults, researchers began to *analyze* the *I-V characteristic*. Data given by the pattern of the *I-V characteristic*, associated in some case with *dI/dV*, allow to detect shading fault and also aging when extracting standard test conditions (STC) parameters [15].

As already stated earlier, complex systems, composed of many different parts, are not easy to model accurately. To overcome such difficulty, the second group of *diagnostic* method, *intelligent* group, has been developed with the use of *artificial intelligence (AI)* methods [45]. They have been used to solve complicated practical problems in various areas and are becoming more popular nowadays. They can learn from examples, are fault tolerant meaning that they are able to handle noisy and incomplete data, are able to deal with nonlinear problems and once trained can perform prediction and generalization at high speed. Their role is to make the diagnosis of the faults simpler and quicker.

Among the *intelligent* group, *neuro-fuzzy systems* (*NFS*) refer to combinations of *artificial neural network* and *fuzzy logic* in the field of *artificial intelligence*. The basic idea behind this *NFS* is that it combines human-like reasoning style of *fuzzy* systems with the learning and connectionist structure of *neural networks* [58] to join the advantages and to cure the individual illnesses.

Artificial neural networks (ANN) are also one of the many *AI* methods. A *neural network* is composed of three layers: an input layer, an intermediate layer called the hidden layer and an output layer. Each layer can have one or many neurons/nodes. Each neuron is linked to those on the next layer by weighted connections.

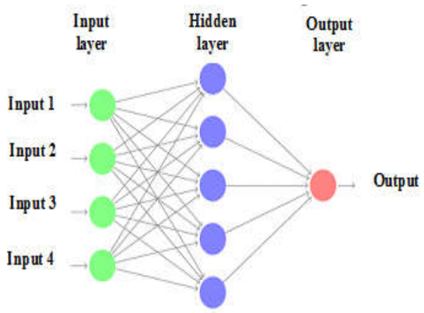


Fig. 11. Illustration of an artificial neural network

To detect the failures of the PV array, four tasks have to be fulfilled: build the *ANN*, set a data acquisition (knowledge base), classify the faults and test the network [59]. What makes *ANN* interesting for diagnosis is that first of all, they can use non-linear functions and afterward they are quite good for patterns recognition tasks; more, they do not use mathematical models [45].

The third method considered in the *intelligent* group is *pattern recognition.* The objective will be the study of methods and algorithms for an automatic classification in categories (classes) of data objects, according to similarities with a reference in order to identify distinguishing attributes, extract features for the defining attributes and compare them with known patterns to determine a match or a mismatch [60]. Fig. 12 gives a resume of all the aforementioned diagnostic methods.

V. CONCLUSION

This paper brings to light that PV systems are facing many faults when on operation and yet maybe new failures are still to come as PV plants and domestic individual productions are globally spreading everywhere. With the attempt of the manufacturers to root out some failures and the researches on the topic growing worldwide, some faults are better understood and then a little more avoidable. One outcome of this paper is that environmental conditions have an important impact on these faults, by creating favorable conditions to them. Climates variations cannot be mastered so it is up to manufacturers to propose good alternatives in the making of PV modules. The upshot of this review also is that there is no specific method that can detect all or at least most of the failures. The known detection techniques are generally complementary and for a better monitoring of the PV systems, supervisors are combining many. It is what we will do in a next work: combine classical methods that proved good results with some intelligent methods, to improve the detection. Hence, the main challenge will be to propose a diagnosis system that can handle all the PV failures at the same time and give accurate results.

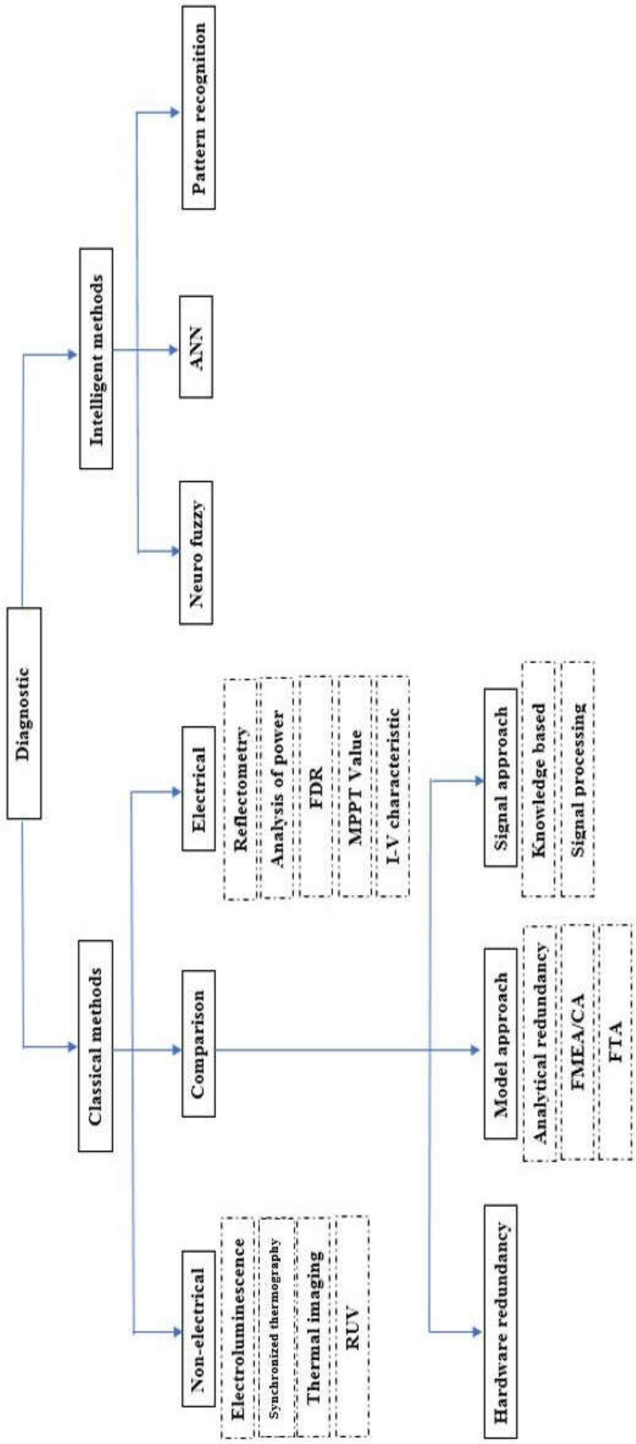


Fig. 12. Summarize of diagnostic methods

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