https://doi.org/10.1051/e3sconf/202340402003

Detailed infrared diagnostics of photovoltaic panels for higher safety and optimal energy generation

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Abstract. The Photovoltaic (PV) systems are one of the key renewable energy sources that are becoming increasingly popular, but they still have many drawbacks compared to conventional energy sources. Their main disadvantages are that they require a lot of installation space and they have low investment return ration. Both could be overcome by local installation of the PV plants as close as possible to the end consumer, and the best case is the PV panels to be installed on the buildings, but this could lead to higher fire risk for the residents. Different PV panels degrade with different speeds and work under slightly different conditions. These problems require at least periodic PV panel diagnostics and the thermal infrared (IR) inspection seems to be the best solution. The prerequisites for correct IR diagnostics are presented. One of the requirements for detailed IR inspection is the thermal camera to capture each PV cell with at least 5 by 5 pixels in horizontal and vertical directions. A methodology for pixel size calculation and IR monitoring system design is developed and presented in this work.

1 Introduction

The world is facing global environmental and climate changes, and the renewable energy sources could be a good solution. The photovoltaic (PV) systems have the potential to solve these problems, but they still have many drawbacks. They are not appropriate for every climate and different solutions for their effectiveness improvement are needed in this regard because the meteorological parameters as wind, solar radiation, air temperature, air humidity, atmospheric pressure and precipitation differ, [1]. The problem is that the I-V curve of the PV panels change together with the ambient conditions as temperature, angle of illumination, intensity and spectrum of radiation, and with the array degradation too, [2]. At the same time, the PV systems have a low investment return ratio compared to other conventional energy sources and it could be even worst because studies conclude that in certain cases there are significant amounts of unused energy, which further seriously reduces their efficiency, [3,4]. In such cases, it is important to increase the energy utilization if the PV investment is to be optimal.

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There are many ways for PV system optimization. One option is the PV system to be combined with another energy generation system. In this regard, a study investigated the optimum tilt angle of a photovoltaic-wind hybrid system which utilizes both wind and solar energy by attaching the PV modules to the blades of a vertical-axis wind turbine, [5]. Another option is to optimize the operation of a photovoltaic system by cogeneration, simultaneous production of electricity and low-temperature water heating, and increasing efficiency by achieving a balance between electricity and heat production, [6]. Most of the available optimization methods are still experimental and often not applicable, and they don't solve certain hazards related to PV system utilization.

From another point of view, the PV systems require a lot of installation space. The problem is that the human population grows and the land is needed for food production.

The mentioned drawbacks could be solved with local installation of PV infrastructure on residential buildings. PV systems with small power are an efficient and sustainable method of generating electricity. Mounted on roofs, facades, sheds or other free spaces, these systems are currently the most cost-effective option for utilizing free areas, reducing electricity costs and sustainable production of electricity, without additional losses from its transmission, [7]. One of the main drawbacks is that this solution leads to higher fire risks and requires at least periodic PV panel diagnostics. However, the rooftop solar photovoltaic potential has been estimated in many countries, such as Japan, India, Spain, and Switzerland using various methods, [8]. In this regard, the infrared (IR) cameras are becoming increasingly popular for thermal inspection of PV panels, necessary for timely discovery of defects for safety purposes and for overall system optimization. A study evaluated the mid-life degradation of PV plant and 52.5% of the 360 PV modules showed certain defects. The conclusion is that in a PV plant, the degraded defective PV modules must be replaced immediately because of mismatch losses of strings and risk of fire, [9]. At the same time, a study compared and analysed the performance and degradation differences of two photovoltaic modules from different producers after 15 years of field operation and concluded that they are with very different resulting observed changes in their operational and physical characteristics, [10]. Another investigation concluded that the load-bearing structures and the photovoltaic panels must be able to withstand mechanical loads both from their own weight and from snow and wind [11]. The more extreme weather conditions lately, as strong wind and heil, can cause sudden damage to PV panels and to increase considerably the fire risk.

The quality differences between PV panels of different producers and the chances for unexpected damage require periodic IR inspections to be done in all the phases of their life, even at the time of first installation for warranty purposes. In this regard, the creation of virtual laboratories for remote investigations of photovoltaic modules could also help a lot because they allow operating the lab independently of the weather conditions and the time of the day, [12].

The thermal IR diagnostic of PV panels is one of the most widespread non-invasive technique used nowadays. It has many advantages and could be used on spot, but in order the inspection to be reliable it must be done under certain conditions. The solar irradiance should be over 600W/m2, [13]. Another research concludes that the irradiance must be over 700 W/m2 and that the measurements are best to be done in cold winter day, [14]. The camera should be looking at the panels from a position with certain horizontal and vertical angles. The ideal horizontal angle of thermographic inspection must be the angle which minimizes the solar reflection and does not increase the reflectivity and it depends on the panel orientation, and time of the year, [15]. The vertical angle between the module plane and the camera should be between 30 and 90 degrees, [16]. For detailed IR inspection the camera must capture each solar cell with standard sizes of 16 by 16 cm with at least 5 by 5 pixels horizontally and vertically, [13]. This is the minimum required image resolution to detect certain smaller defects. More pixels means a more accurate diagnostic process, but more costly too, because it requires either more expensive higher resolution cameras, or more cameras, or more pictures to be taken with one moving one. Usually, one IR camera must capture more than one PV panels and the distance from the sensor to each separate PV cell is different. At the same time the viewing angles for each solar cell are also slightly different. This leads to different pixel sizes for each solar cell and hence to different number of capturing pixels. It is important the furthest from the camera solar cell to be captured with at least 5 by 5 pixels because it also should be diagnosed in detail. If this is achieved, it means that all other solar cells will be captured with more than the minimum required resolution.

Most of the prerequisites are matter of right camera position, time of the day and season. The one requiring over 5 pixels per solar cell in each direction poses certain requirements towards the IR camera and its installation place, but no any precise methodologies for calculating the pixel size and for choosing the right camera are found.

The aim of this work is to present developed methodology for pixel size calculation, for correct selection of camera sensor resolution and for finding the right installation distance. Such methodologies are needed for experimental PV system designs, as well as for education of installers of such systems because people working in the field usually have electrical or electronic background and no experience with imaging techniques.

2 Methodology

The sizing methodology is presented in a structured way in two main steps. The concept is visualized through comprehensible drawings. The first logical step is defining the minimum distance from certain IR camera with certain viewing angles to the PV panels because first of all it must be able to capture certain number of them. The second logical step is the calculation of the pixel size and pixel number per PV cell for certain IR sensor resolution and the selection of the right thermal camera based on this criteria.

For the monitoring system sizing, the minimum distance from certain IR camera to the PV panels should be calculated first, based on its viewing angles and the size of the monitored PV installation. The stationary camera should be as close as possible to the monitored PV panels for more precise diagnostics, but it should be able to capture all of them. If the camera is with the more expensive pan and tilt system, then this requirement is not fully valid. The viewing angles of different IR cameras are usually within the range of certain common values and the right one with the right installation distance should be found.

The second step could vary. One way is the pixel size to the most distant PV panels to be calculated for certain camera with certain standard resolution. The other more efficient way is the needed IR sensor resolution to be calculated based on the distance between the thermal camera and the furthest PV panel. The calculations depend on the thermal camera parameters, on its vertical and horizontal viewing angles, on the PV panel cell sizes and on the distance between them and the camera. They are usually done for the worst-case scenario, which means that the distance to the furthest monitored PV cells should be used for the calculations and the selection of the needed camera sensor resolution. This requirement usually comes from the fact, that even the furthest PV cells need to be monitored in certain details. If a camera with such viewing angles and sufficient resolution doesn't exist or it is too expensive, then two cameras could be installed or one with pan and tilt system. This methodology is for stationary mounted IR cameras, but it could be used and for a monitoring system design with pan and tilt ones.

3 Defining the minimum installation distance from certain IR camera with certain viewing angles to the PV panels

The minimum distance from the IR camera to the PV panels should be calculated first, based on its viewing angles and the size of the monitored PV installation. This requires the width of the closest first row of PV panels to be measured first. The worst-case scenario is when the camera is installed against the middle of the first row (centred to the first row) because then its sensor must be with the highest horizontal viewing angle. In this case the horizontal viewing plane is consisted by 2 right angle triangles, Figure 1. Usually, the horizontal viewing angle must be wider than the vertical, so it must be calculated first, and then it usually corresponds to certain comparatively standard vertical one, which is wide enough. In this case, for each right angle triangle is valid equation (1), where "w" is the width of the closest first row of PV panels, "d" is the distance between the camera and the PV panels and "α" is the horizontal IR camera viewing angle.

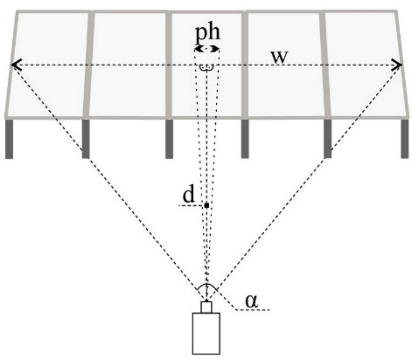

Fig. 1. Horizontal field of view of the thermal camera to the photovoltaic panels.

$$tg\left(\alpha/2\right) = \frac{\frac{w}{2}}{d} = \frac{w}{2d} \tag{1}$$

If the camera horizontal viewing angle and the width of the first PV panel row are known, then the needed installation distance could be calculated by equation (2):

$$d \geq \frac{w}{2tg\left(\alpha/2\right)} \tag{2}$$

If the installation distance and the width of the first PV panel row are known, then the minimum horizontal IR sensor viewing angle α could be calculated by equation (3):

$$\alpha \geq 2arctg\left(\frac{w}{2d}\right) \tag{3}$$

The installation distance could be either directly measured with the help of laser tape measure or calculated from the measured horizontal distance "l" and vertical installation height "h" of the camera related to the installation plane of the PV panels by (4), Figure 2:

$$d = \sqrt{h^2 + l^2} \tag{4}$$

There are IR camera sensors with 45° horizontal wide-viewing angles on the market and their vertical viewing angles are usually less than that. For example, the Mobotix thermal camera has 45° horizontal and 32° vertical image angles. Table 1 presents the results from a search for most common standard resolutions and available viewing angles (field of view) for modern IR cameras. It is visible that for the medium and professional class ones the available sensor viewing angles are about the same. For lower class IR cameras with resolution of 160 x 120 there are sensors with wider field of view, but their low resolution is usually enough for single PV panel diagnostic. In all examples the horizontal viewing angles are wider than the vertical ones because in most cases this is the need.

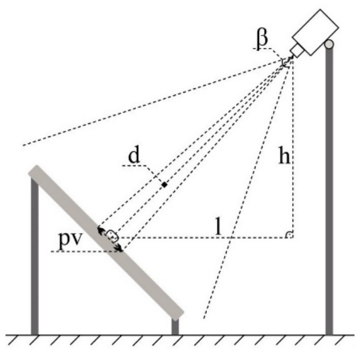

Fig. 2. Vertical field of view of the thermal camera to the photovoltaic panels.

Table 1. Standard IR camera resolutions and viewing angles.

Camera parameter	Lower class	Medium class	Professional class
Resolution	160 x 120	320 x 240	640 x 480
Available viewing angles	57° x 44° 55° x 43° 31° x 23°	45° x 34° 30° x 23° 24° x 18°	42° x 30° 34° x 24° 24° x 18°

If the PV system consists of many short PV panel rows, lined up one behind the other, then the camera must capture all of them. In such rare cases, the vertical viewing angle is also critical and its field of view also needs to be estimated in the same manner.

4 Calculation of the pixel size and pixel number per PV cell for certain camera and determining the right resolution

The current IR cameras offered on the market are most likely equipped with IR sensors with one of the following standard resolutions presented in Table 1. The higher resolution cameras cost more and the price matters. The PV systems are expensive and with comparatively low investment return ratio, which means that at least the IR diagnostic system must be with low enough price, but precise enough. Which IR camera resolution is best for certain case depends mainly on the size of the monitored object, the sensor field of view (FOV) and on the installation distance. The FOV depends on the horizontal (α) and vertical (β) viewing angles of the camera.

Once the needed camera viewing angles are determined, the next step is the right resolution of the IR sensor to be found in order each solar cell to be pictured with at least 5 pixels in each direction. The next step is the horizontal and vertical pixel sizes to be calculated for one of the 3 standard resolutions and for the chosen FOV. The best way is the first calculation to be done for the middle resolution 320 x 240. This means that the horizontal number of pixels is 320 and the vertical one is 240. First the instantaneous field of view (IFOV) of one pixel must be calculated for both horizontal (IFOVh) and vertical (IFOVv) directions, based on the horizontal α and vertical β viewing angles of the IR sensor, and based on the camera resolution, which consists of certain horizontal and vertical number of pixels. These parameters are the one pixel viewing angles.

$$IFOVh = \frac{\alpha}{horizontal\ number\ of\ pixels} \quad (5)$$

$$IFOVv = \frac{\beta}{vertical\ number\ of\ pixels} \quad (6)$$

If the camera is looking at 90° in both directions to the monitored object, the PV panels in this case, then the horizontal and vertical viewing planes consist of 2 right angle triangles, Figure 1 and Figure 2. For both of them are valid the following equations (7-10), where “ph” and “pv” are the pixel sizes in horizontal and vertical directions, and “dsc” is the distance from the IR camera to the particular solar cell for which the calculations are done.

$$tg\left(\frac{IFOVh}{2}\right) = \frac{ph/2}{dsc} \quad (7)$$

$$tg\left(\frac{IFOVv}{2}\right) = \frac{pv/2}{dsc} \quad (8)$$

$$ph = 2dsc \times tg\left(IFOVh/2\right) \quad (9)$$

$$pv = 2dsc \times tg\left(IFOVv/2\right) \quad (10)$$

If a standard solar cell with certain horizontal (sh) and vertical (sv) dimensions must be monitored, then the actual capturing number of pixels in horizontal (np_h) and vertical (np_v) directions are:

$$np_h = \frac{sh}{ph} \quad (11)$$

$$np_v = \frac{sv}{pv} \quad (12)$$

The problem with these calculations are that the horizontal and vertical viewing angles are not perpendicular to the monitored object, unless only one PV panel is monitored, in which case we could accept that at least the horizontal viewing angle is. This leads to a certain inaccuracy of the calculations, which in most practical cases is irrelevant. No ready to use tables could be presented with standard PV panel sizes and appropriate camera resolutions because the IR camera parameters depend on the number of monitored panels, and usually they are more than one, on the number of PV panel rows, on the viewing angles and installation distance. Each case is different and requires its own project to be created.

If the calculated number of pixels per direction is not enough for precise diagnostics, then the numbers for the higher IR camera resolution, but for the same viewing angles, which is twice higher, are twice higher. If the number of pixels is not enough again, then a camera with pan and tilt system might be selected.

5 Discussion and results

An example thermal image of the new PV plant located at University of Ruse is presented on Figure 3. It consists of 3 PV panel rows of 12 panels each with sizes 1 m wide and 2 m high. The thermal image proves that the PV panels do not suffer from any factory defects. The defects appear as hot spots. The only visible hot spot is on the 4th panel from right on the first row and it is caused by the shade which the IR camera casts over the first row.

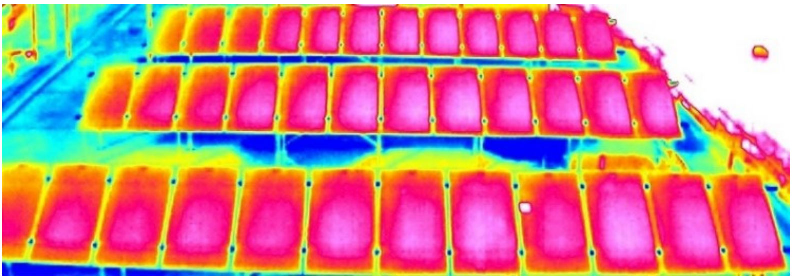

Fig. 3. IR image of a PV plant at University of Ruse.

The IR image is taken with Konika Minolta thermographic camera Mobotix Mx-M16TB-R079, with infrared sensor with resolution 336 x 252 pixels and horizontal/vertical image angles of 45°/32°. The camera looks against the middle of the rows. Its installation distance to the middle of the 1st, 2nd and 3rd rows are 14.99 m, 20.83 m and 26.87 m, respectively. The distances to either end of the 1st, 2nd and 3rd rows respectively are 16.15 m, 21.68 m and 27.53 m.

Table 2. Calculated capturing number of pixels for the best and worst-case scenario.

Place of PV panel in a row	Number of pixels in a direction	Number of pixels per solar cell		
		1st row	2nd row	3rd row
Middle	Vertical	4.82	3.47	2.69
Either end	Vertical	4.47	3.33	2.62
Middle	Horizontal	4.57	3.29	2.55
Either end	Horizontal	4.24	3.16	2.49

Table 2 presents the calculations of the capturing number of pixels for the closest and furthest PV cells from each row of the presented PV plant, based on the presented methodology. The camera has two sensors and plays a double role. It is used for continuous security surveillance as well as for rough IR diagnostic of the PV panels. Two to five capturing pixels are enough for only rough diagnostic process, which is the required purpose in this case. In case of occurring damage, it will be investigated in more detail with another modular IR camera.

If the requirements towards the camera change and more detailed continuous IR imaging is needed, then there is no need for these calculations to be done again. Twice higher IR sensor resolution with the same viewing angles will lead to twice as many pixels per solar cell. Usually, calculations are needed only for the worst-case scenario, which is for the solar cell with farthest distance from the IR camera. In the presented case, these are the cells at either end of the 3rd row. The right IR camera resolution for PV plant diagnostics depends on the requirements and parameters of the project, and on the budget. The lowest class IR camera that allows precise enough diagnostic process is the best solution.

The IR diagnostic and the needed pixel count per solar cell calculations are not conceptual, but increasingly used nowadays. There are many extensive works describing the appearance of the different PV panel defects on the thermal images and the possible optimization technics, and this is not the aim of this work. At the same time, no methodology for the needed capturing pixel count calculation is found, but it has been developed and presented.

The IR imaging is used for new PV plant check for warranty purposes. Each PV panel has its warranty period and if a defect is found it could be replaced. Most of the defects are not visible with naked eyes. If damage in an out of warranty PV panel is found the optimization depends on the case. If the PV plant is installed in an urban environment, the PV panel must be replaced because it creates risk of fire and degrades the generated energy for that particular string, which will worsen the PV plant efficiency and the return of the investment. If the PV infrastructure is located outside of urban areas and if there is not any risk an occurring fire to create serious damage, then the defective PV panels could be combined in different strings, depending on the level of degradation of their output power. In such a case, they will continue to generate useful energy without degrading, but improving the PV plant performance and hence the return of the investment. PV plants have a low investment return ratio compared to other conventional energy ones and their functional optimization is critical.

6 Conclusions

The work presents a methodology for PV plant IR monitoring system design, based on calculations of the capturing number of pixels per PV cell. The correct sizing allows detailed inspection of the PV plant needed for timely prevention of fire hazards and for PV system optimization, which can improve the investment return ratio. The fire hazard must be minimized because otherwise it could impede the widespread use of the greener PV systems in urban environments, which is the optimal case.

The presented methodology for IR camera selection is based on the resolution of the IR sensor, the installation distance and the size of the monitored object. Its main drawback is that it does not correct the calculations for different than perpendicular horizontal and vertical camera viewing angles, which is the most common case. More often the camera cannot be installed high enough for perpendicular vertical viewing angle because it creates undesirable shade over the monitored PV panels. At the same time, it could be with close to perpendicular horizontal viewing angle for one PV panel, but it will not be with such for the next one.

These calculations are sharp enough in many practical cases, but in certain situations more precise results are needed. The improvement of this methodology for different horizontal and vertical viewing angles and how much they influence the pixel sizes is aim of future work, because it requires an extensive additional analysis. The farther the angles are from 90° the wider the pixels. Which parameter influences most the pixel size is also important for the precise design process of an IR diagnostic system and will be investigated in more detail in future works.

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