Hotspot Detection Method in Large Capacity Photovoltaic (PV) Farm

P A A Pramana\textsuperscript{1,2}, R Dalimi\textsuperscript{1}

\textsuperscript{1}Universitas Indonesia, Depok 16424, Indonesia

\textsuperscript{2}putu.agus91@ui.ac.id

Abstract. The obligation to use low carbon emissions power plants encourages the increased utilization of renewable energy generation. Among the whole renewable energy plants, photovoltaic (PV) is a modular plant that is easy to implement, which the utilization reaches 100GW in the year 2017. By the increasing use of PV globally, the health of PV modules needs to be a concern because, during the operation, PV modules can experience various faults. Almost 50\% of the overall fault is the hotspot which is very hard to detect in a wide area PV farm. For example, a 30 MW PV generation with an area of 60 hectares and composed of 126000 modules (consists of millions of cell), the existing hotspot detection methods takes up to 210 days. The long time and not continuous detection lets the hotspot to degrade and burn the modules. To prevent the catastrophic failure due to hotspot, a detection method which can detect the fault quickly is needed. The proposed method, thermal imaging using a fish-eye lens could be used in this case as it has a very wide angle of view, which allows monitoring all of the PV modules in one detection period.

1. Introduction
The obligation to use power plants that produce low carbon emissions encourages the increased use of renewable energy generation such as geothermal, photovoltaic (PV), biomass, tidal, and wind. Among the other renewable energy plants, PV is a modular plant that is easy to implement for various power generation ranges, starting from tens of kilowatts of power to the utility-scale plants with power reaching tens of megawatts. Until the year of 2017, the global utilization of PV reaches 100GW[1].

With the increasing use of PV, the health of PV modules needs to be a concern because, during its operation, PV modules can experience various faults. Almost 50\% of the overall fault is the hotspot that is very hard to detect in a wide area PV farm. For example, a 30 MW PV generation with an area of 60 hectares and composed of 126000 modules (consists of millions of cell), the existing hotspot detection methods takes up to 210 days. These methods are unable to detect the fault quickly and continuously so that the hotspot fault can degrade and burn the module.

One case that has been found in Indonesia, the degradation of PV modules can cause a decrease in peak PV power to 94\% of its installed capacity after a five-year operating period. On the other hand, faults that cause the burning of the PV module is shown in [2] and [3]. Reference [2] describes an increase in the number of fires that occur in PV installations for various power capacities. This increase experienced a peak with the emergence of more than 700 fire cases. Meanwhile, reference [3] explained the large fires on the PV system in California that was started by the arcing failure.
Considering the importance of the health of the PV module especially in avoiding degradation and fires, this paper provides a review of the faults that can create a hotspot, review of its existing detection methods, and the proposed method to detect hotspot fault quickly.

2. Hotspot Fault

Classification of faults in PV modules that potentially create hotspots can be divided into two parts, namely faults that occur due to physical problems in the module as well as a fault caused by environmental factors where the PV module operates. According to [4], hotspots faults events have a percentage of 49% compared to all fault events in the PV modules. The percentage of hotspot fault due to physical problems in the module is 25% and hotspot fault due to diode damage by 24%.

The physical problem that occurs in the PV module can be in the form of encapsulation material damage, delamination, cracking, interconnection failure, corrosion, bypass diode failure, mismatch fault, and arc fault. Besides, physical faults in PV modules can trigger a short circuit, such as ground fault, phase fault, and open circuit fault. On the other hand, fault in PV modules caused by environmental factors is the shading and soiling. Shading and soiling are the PV module covering by the shadow of an object that is located around the PV. Shading can be temporary or permanent and both can cause hotspots on the PV module. Explanations of these faults are given as follows.

2.1. Encapsulation material damage

In general, the arrangement of PV modules from the top (facing the sun) to the bottom sequence is the glass layer, encapsulation material, PV cells, encapsulation material, and the back sheet. Damage to encapsulation material can be in the form encapsulant broken so that the glass material can be in contact with the active PV cells. This event can occur by various factors such as the defect due to excessive pressure during production, the ambient temperature and humidity that are too high (so that it can cause melting in the encapsulation material), as well as the entry of salt particles between the encapsulation material and PV cells. The presence of salt material coverings and the entry of water vapor in the encapsulation gap can trigger the hotspot and increase the reflection of light to the PV module so that it can reduce the output power generated by the PV. To detect this fault, a thermographic method can be used because the fault will produce a hotspot [5-7].

2.2. Delamination

Delamination is the loss of adhesion between the materials that construct the PV module, especially in the back sheet and encapsulation materials. The delamination process can also occur due to production defects and the use of PV operations in very hot weather. Loose of adhesion between layers in the PV module can trigger the penetration of water (in the form of water favor in high humidity area or in the form of liquid water when the rain happen), this potentially creates fault with the cell hotspot. Besides, gaps arising from the loss of bond between layers can cause bubbles due to chemical reactions and expansion of water favor which are trapped in the gap [8-13].

2.3. Cracking

Cracked PV material generally occurs in the protective glass layer but it also probably occurs in the active PV cell layer. This damage can occur in the installation process or before the installation process such as during the manufacturing process, packaging, or during the module transportation process. In the installation process, cracks can occur due to mismatch of the location of the bolt in the frame so that the module experiences excessive bending and results in cracking. After the installation process or when the PV is operating, cracks can occur due to the hit of other objects on the PV module such as birds crashing and the cat that runs on the module. Crack that occurs in the module can induce water penetration, create shading, and triggering hotspots [2] [9] [14-16].
2.4. Interconnection failure
PV modules are series and parallel circuits of many cells so that many conductor connections between cells are potentially damaged. Besides, this interconnection damage can also occur in the connecting conductors between modules. This interconnection problem can occur due to imperfections in the soldering process during manufacturing, errors in the transportation process, as well as repeated mechanical stress. Interconnection problems can cause an increase in resistance of a conductor junction so that it can potentially cause hotspot fault [8][17-20].

2.5. Corrosion
The delamination, cracks, and encapsulation events allow water penetration into the module through the edge of the module frame. The influx of water causes an increase in humidity of the PV module, which potentially causes corrosion and affects the conductivity of the material in the module layer, especially in the metallic material which constructs the module. Corrosion can cause leakage currents that can reduce the power production of PV modules and can increase the resistance value of the cell conductor which potentially produce hotspots [18-19][21-27].

2.6. Bypass diode failure
PV modules are composed of parallel circuits of PV cell series arrangement (string). At the same irradiation conditions, the output voltage between the strings will have the same value. However, if one string is covered by the shadow of an object, the output voltage of the string will be lower than the other one. Because each string is arranged in parallel, when the shading happened, there will be a current flow from the healthy string to the string that experiences shading (reverse bias). To prevent reverse bias, a bypass diode is installed. In a healthy condition, the diode will block the reverse bias current flow so that there is no heating in the PV module. Failure at the bypass diode will cause a hotspot on the PV module which will degrade the module [6][28-33].

2.7. Mismatch fault
Mismatch fault can be divided into two conditions, namely mismatch in the electrical parameters of the module and mismatch that occurs in the conductor junction of the PV module. This electrical parameter mismatch occurs due to differences in voltage, current, or power generated by cells contained in the module. The difference in electrical parameters can be caused by several factors such as the degradation of the PV module due to delamination, encapsulation damage, and corrosion. Meanwhile, mismatch in the soldering process (conductor junction) can occur due to production defects in the module. This mismatch disturbance can produce hotspot because it potentially creates reverse bias current flow and increases the resistance of module conductor material [8][34-37].

2.8. Arc fault
An arc fault is an electric arc event between two separate metal ends at a certain distance in the PV module. This arc fault can occur because the potential difference that occurs between the two metals has a value greater than the breakdown voltage of the insulating material between the two ends of the metal. In the PV module, an arc can occur between the conductor connections on the module as well as between the conductor to the body of the PV module. This fault can produce very high temperatures up to hundreds of degrees Celsius so that it can burn PV modules [38-44].

2.9. Shading and soiling
In addition to fault that occurs in the PV module physically (internal), hotspot fault can also occur due to environmental influences such as shading and soiling in the PV module. Shading in the PV module can be divided into two conditions, namely dark shading and transparent shading. Dark shading is shading that blocks 100% of the sunlight that going towards the module like the shadow of trees, while transparent shading is shading that transmits a small portion of sunlight to the PV module, such as smoke or fog covering around the PV module. Besides, transparent shading can occur due to the
presence of liquid that dries up on the surface of the PV modules such as liquid due to bird droppings. On the other hand, soiling is the sticking of dust particles/soil which has a small size that can stick to and cover the PV module. Soiling will block the sunlight received by the PV module and in humid conditions can trigger the growth of moss on the PV surface.

Shading and soiling that occur in cells in the PV module will cause these cells to have increased resistance when compared to other cells that do not experience shading. Increasing the value of resistance in a small number of cells in a PV module will result in differences in current and voltage characteristics of the PV string. A string that experiences shading will produce a lower total voltage value compared to a healthy string so that there will be a reverse bias current flowing from the healthy string to the shading one [33] [45-47].

The reverse bias process will cause heating on the shaded cell so that it can produce hotspots on the cell. As described in the previous section, the reverse bias process is generally prevented by using a bypass diode on each string. However, the addition of a bypass diode still has the probability to fail if the voltage difference between the healthy string and the shading string exceeds the limit of the voltage capability of the diode (breakdown voltage), or if the bypass diode is damaged [48-49].

3. PV Hotspot Detection Method

3.1. Existing method

The technology used to detect the faults that cause hotspots on PV is the thermal imaging method. Thermal imaging is a non-destructive measurement technique, which provides the temperature distribution features of the PV module. This method can be used as a contactless method to diagnose some fault that generates heat on the PV module when the PV operates in normal condition.

Thermal imaging technology utilizes infrared cameras (with electromagnetic wavelengths about 8 to 14μm) to detect the phenomenon of hotspots that occur in the PV module. PV cells that experience hotspots will have a higher temperature increase compared to the normal cells around them so that when it is observed with an infrared camera, color differences will appear between hot spotted cells and normal cells.

In Indonesia, hotspot fault detection methods for PV modules currently use manual thermal imaging techniques that utilize infrared cameras, which are carried by the operator that walking around the PV farm. The operator observes the PV module one by one with an infrared camera to see the occurrence of hotspots on the PV.

In other countries, hotspot detection methods are using thermal imaging through a drone that has been equipped with infrared cameras. Drones are flown at certain times (not operated continuously) to monitor the occurrence of hotspots on the PV module[26].

The method of detecting hotspots using infrared both manually and using drones can only work at certain times and requires a long time to detect a fault on a large PV area. At present, to detect the fault in a 30 MW PV generation with an area of 60 hectares and composed of 126000 modules, the manual detection method takes about 210 days and the detection method with drones will take about 30 days. These methods cannot detect the fault quickly and continuously because these methods need a movement from one location to the other. Hotspot fault can occur intermittently influenced by environmental conditions. Therefore, fault detection equipment is needed to be able to work quickly and continuously.

3.2. Proposed concept

The current hotspot fault detection technology takes more time to detect the hotspot fault. To complete the gap of the existing detection technology, a hotspot detection method using a fisheye lens equipped with infrared sensors is proposed. The fisheye lens has a wide area detection characteristic, which can have a field of view (FOV) of 180°. Therefore all objects in front of the lens will be observable. The illustration of the detection method is given in figure 1.
Zed, Yed, and Xed is the z, y, x coordinate position of the fisheye lens relative to the PV module row. PV module row 1 is the nearest PV module row to the fisheye lens and the PV module row 10 is the farthest one. Based on the preliminary study, with the special configuration (the value of Zed=0, Yed=10m, xed=0, 100m length of PV module row, and 10mm fisheye lens focal length) the proposed method is possible to detect whole of PV module. The view of the whole PV module row as the fisheye lens perspective view is given in figure 2.

In figure 2, (both x and y-axis are in mm) all PV module rows can be monitored using a single fisheye lens. If this model is implemented to the infrared material lens, when a hotspot occurs in one module, the proposed method will utilize the image processing to localize the hotspot. After the hotspot location is definite, the algorithm will calculate the exact module position in the PV farm. Thus, the hotspot location that occurs in a single module could be detected. Finally, it is expected, the process of detecting hotspot faults will be faster.

4. Conclusion
An explanation of the faults types that produce hotspots on the PV module has been carried out, from these results it can be seen that hotspots can occur due to the module physical fault as well as environmental influences such as shading and soiling. Hotspot fault occurs of almost 50% of all fault types in the PV system. The current hotspot fault detection methods utilize manual thermal imaging or drones thermal imaging, where these methods cannot detect the fault quickly and continuously. A fisheye lens has been modeled to monitor all of the PV modules. The result shows that the fisheye lens could simultaneously monitor all of the PV modules rows which has a length of 100m each. Future research will try to find the accuracy of the monitoring system which is affected by the infrared lens material, hotspot temperature, and the lens position relative to the PV module rows.
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