Integrated micro tesla magnetic sensor for detecting photovoltaic cells failure

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Abstract. Recently more attention on the failure of PV systems has been paid and more reports have been found in PV related papers. Various methods to detect failure of PV module have been developed; They are visual method, I-V characteristic method, electroluminescence (EL) method, UV fluorescence method, signal transmission method, IR thermography method, photoluminescence (PL) method. However, each method has some limitations. Developing a new alternative diagnostic method of PV cells will be required for efficient operation of PV system. The proposed method uses μ-tesla magnetic sensor (MI-CB-1DM) to detect failure in a PV cell. The experimental design carried out in this study covered two stages. In the first stage, we developed a method for detecting faults in PV cells using the μ-tesla magnetic sensor method. In this second stage a calculation will be made to determine the current level due to the failure of the PV cell. The results show that $B_x$ at the lower busbar in the degraded module has smaller magnetic density than the upper busbar. No obvious difference can be seen in the $B_x$ and $B_y$ profiles between the normal and degraded cells.

1. Introduction
Increasing demand for renewable energy photovoltaic (PV) power plants has become an important and a promising research topic from year to year. This is evidenced by the increasing production of PV modules with a variety of specifications and models installed. On a large-scale production of PV modules often found a lot of failures after being distributed to consumers or users. This possibility motivates researcher to focus their research on PV failure issues and many studies have discussed how PV systems work. All components of this system are strongly influenced by environmental conditions such as temperature and humidity, which requires a long-term level of reliability and stability that is very important for security and return on investment [1]. In a PV module, failure of the module can be caused by PV module manufacturer which produce the module with less perfect process and the effect of mechanical process also considered as factors that cause a PV module fault.

Since PV modules are usually mass produced and consist of many PV cells, this condition may cause a product defect which can be found on the newly produced PV cells from the manufacturer and the defects in these cells may not be detected. Defects in PV cells can also occur due to transportation factors, mechanical effects and distortion of duration use. Fault detection technique, then will be an essential feature in providing protection against damage to equipment and reducing maintenance costs. Referring literature on PV research modules, some methods have been developed to analyze and examine this interesting topic.

Several types of PV module failure detection methods have been developed, including the visual method [2], the characteristic method to estimate the equivalent I-V parameter using least-squares fitting...
and the electroluminescence photography method [4] these methods have been used to analyse the length of the diffusion, distribution of minor cell carriers from cells or modules made. For example, the Electroluminescence (EL) photographic method (hereinafter referred to as the EL method) has proven to be a fast and accurate detection tool. Detection is carried out not only related to the material properties of PV modules but also the process of induction deficiency in silicon in solar cells [5]. Another method of detecting failure in digital image processing and resonance ultrasonic vibrations (RUV) [6]. Testing of solar cells using IR thermography has been used for more than a decade and has become a standard method [7]. IR analysis can be used for large-scale PV modules. The use of IR methods to evaluate PV modules has several advantages, including being able to detect many failures in developing PV modules, such as hot spots until installation failure. This method can be used for non-destructive testing and is used for scanning PV modules during normal operation. Another advantage that this method offer is that IR thermography provide a reliable and accurate tool for the diagnosis of degradation defects, both optical and electrical, in PV cells and, furthermore, for the identification of the precise location and the severity of these faults [8]. However, similar to other methods, the IR method also has obvious shortcomings. IR cameras not only receive radiation from objects, but also reflections from the surrounding environment, so the measurement results will be greatly influenced by emissivity, reflection and atmospheric absorption [7].

In summary, various methods have been used to analyse and detect PV failure in PV failure detection research. Even though those methods provide different advantages that can be addressed in every study, the drawbacks of these methods also must be considered. This condition offers an opportunity to develop another method that can be used to overcome shortcomings from previous method as well as contributed to PV failure detection literature. Our research aims to develop alternative methods to capture failure on PV module by using integrated micro tesla magnetic sensor. Furthermore, our study also wants to examine the level of current which can be produced when the failure of PV cells occurs. By knowing this level, we can decide whether PV cells can run efficiently or vice versa.

2. Experimental Design

This study employs two stages of experimental design. On the first stage, we developed a method for detecting faults in PV cells using the μ-tesla magnetic sensor method. Output will be analysed in the form of graphs or curves which will be examined more further to produce information which can be used to determine the current that will be used in the second stage, namely measurement the electric current on PV cell. On the second stage, a calculation will be made to determine the current level due to the failure of the PV cell. The details of the two stages will be explained in the next section.

2.1. Measurement of magnetic flux density around the busbars

The photocurrent generated by the solar cell depends on the intensity of sunlight. Since the sunlight is constant and steady with no sudden time-based change, the photo current generated by the solar cell receiving this steady sunlight can be counted as a direct current. The absorbed light energy (photon) by the solar cell excites the electrons in silicon and mobile electron-hole pairs generated within the PV cell. Then these excited electrons are collected in the finger electrodes on the cell surface and transferred into the bus bar electrodes which cause a steady current to flow in the busbars.

The measurement devices used in this study have mounted magnetic sensors, which measure the magnetic flux density generated around the busbars by the current flowing through busbars. The peripheral magnetic field near the busbar is shown in fig.1. Since most PV cells have 3 or 4 busbars, the magnetic field of each busbars can be affected by the magnetic field of the adjacent busbar as shown in fig 1. The correlation between the magnetic flux density and current can be seen by following equations:

\[ B[\mu T] = \frac{2 \times 10^2 I[A]}{r[mm]} \]  

\[ B = \mu_0 H = \frac{\mu_0 I}{2\pi r} \]  

[1] and [2].
where $B$ magnetic field, $I$ is current, $\mu_0$ is vacuum permeability and $r$ is the distance from the conductor.

\[ B_x(x) = B_{x1}(x) + B_{x2}(x) + B_{x3}(x) + B_{xg} \]

\[ R_n(x) = \sqrt{(x - (n-1)d - x_1)^2 + H^2} \]

\[ \sin \theta_n = \frac{H}{R_n(x)} \]

\[ B_{xg}(x) = ax + b \]

**Figure 1.** Current flow through a busbar and peripheral magnetic field

In the fig.1, the current flows in the direction of $By$, and generates a magnetic field around the busbar shown $By$ black dashed circles. The strength of the magnetic flux based on the equation (1) is directly related to the distance $r$ of the magnetic field from the busbar and the current flowing through the busbar. For instance, when a 3 A current flows through busbar at $r = 5$ mm, the magnetic flux density around the busbar is $B = 120 \mu T$, however, at $r = 30$ mm, the magnetic flux density around the busbar reduces to $B = 20 \mu T$ based on the equation (4). Where $n:1,2,3$ busbar number, $x_1$: coordinated of the busbar.

Based on equation (1), the magnetic flux density $B$ is proportional to the current $I$ and the magnetic permeability $\mu$. Since the crystalline silicon and the PV module protective glass is not made of ferromagnetic materials, $\mu$ the magnetic permeability can be considered as $\mu_0$. So, the magnetic flux density produced by the current $I$ depend only on the distance $r$. Therefore, when measuring the magnetic flux density, it is necessary to determine a constant distance from the PV cell to get accurate results. Magnetic sensors has function to detect changes and disturbances in a magnetic field flux distribution, strength and direction. By measuring magnetic field and its changes and alterations, factors such as rotation, angles, direction and presence electrical current can be revealed and extracted.

2.2. Development of integrated $\mu$-tesla magnetic sensor method

Basically, in this section the interpretation of the most important and conventional measurement methods is described. Generally, there are several fault diagnosis methods, but each has its advantages and limitations. Therefore, in order to locate and diagnose the faults, combinations of these methods are applied. However, the $\mu$-tesla sensor device is an integrated system which consisting of multiple sensor devices, microcontrollers, Bluetooth devices, sync signal boards (smith triggers) and several other components as shown in Figure 2. Complete components needed in developing integrated $\mu$-tesla magnetic sensors can be seen in table 1.
Figure 2. Principle of μ-tesla magnetic sensor.

This integrated system will be used for examining detection and analyzing the damage to PV cells. Failure detection in PV cells can be done by looking at changes in the distribution of the magnetic field flux density, which situated on the surface of the PV cells. To find out whether there are changes that occur on the surface of the PV cell, it can be done by scanning, carried out μ-tesla by magnetic sensors and equipped with an optical sensor position on the surface of the PV cell. Scanning will produce a signal as an output that will be used to measure the density of the magnetic field distribution. The signal achieved by the μ-tesla sensor device will sync with the smith-trigger circuit and a smooth and readable signal on the display. In this experiment we used LabVIEW programming, which will be tasked to process signals into digital data through Bluetooth transmission to a PC. This program processes the data to draw profiles of each component of magnetic flux density and module temperature as a line graph. Magnetic flux density measurement will produce three magnetic field components profile, namely $B_x$, $B_y$ and $B_z$. However, in micro tesla this sensor only captures $B_x$ and $B_y$ profile component variables because there is no significant difference in the $B_z$ profile's magnetic field density distribution component. The process of this experiment can be seen in figure 2.

After getting the results of the component profile of magnet, it will then be analyzed using LabVIEW programming to find out how much the value of the magnetic field density of each component profile of the magnetic field can ultimately be used to determine the current flow of each busbar. If the current flow value for each busbar is not the same, then it can be said that PV cells experience abnormal magnetic field density distribution or faults occur. This is the development of third generation magnetic sensors developed by our laboratory by having the advantages and accuracy for error detection in PV cells and PV modules. Result from μ-tesla sensor device will be transferred to a PC that equipped with a LabVIEW program by Bluetooth connection, which is used for data acquisition and analysis.
Figure 3. Front and back view of the Integrated μ-tesla sensor measurement device.

The μ-tesla magnetic sensor measurement device used in this research was measured using multiple sensors such as a magnetic compass, μ-tesla magnetic sensor (MI-CB-1DM), IR temperature sensor, laser optical sensor, and microcontroller. The magnetic flux density is measured by using device with a system that is integrated. Here, the details of those sensors and microcontrollers are shown fig 3.

Figure 4. Top view of the μ-tesla sensor with A Type and B Type.

The μT (micro tesla) sensor is a linear output magnetic sensor with one axis. Measuring range is ± 300 μT, responding from DC to 10 kHz. There are two directions of detection: the direction of the short side (type A) and the longitudinal direction (type B) detail shown fig 4.

Table 1. Specification of the μ-tesla sensor.

| μ-tesla sensor sensitivity mV/μT | Measurement range μT | Measurement time millisecond | Operating temp °C | Origin Voltage Volt | External Dimension Mm |
|----------------------------------|----------------------|------------------------------|-------------------|---------------------|-----------------------|
| 3.0 ~ 5.0                        | ±300                 | 7.2                          | -20 ~ 80          | 2.0 ~ 3.0           | 10.4 x 31.5           |
2.3. Proposed Measurement Fault Detection Technique
In this section we will explain more practical the fault detection techniques. To find out whether there is a fault on the PV module or not, the first step is to choose the type of PV cell by type Q6LMXP3-G2 with certain specifications that can be seen in table 2 and the image of the PV cell can be seen in fig. 5.

Table 2. Specification of PV cell Q6LMXP3-G2.

| µ-tesla sensor sensitivity mV/µT | Measurement range | Measurement time milisecond | Operating temp °C | Origin Voltage Volt | External Dimension Mm |
|----------------------------------|-------------------|-----------------------------|-------------------|---------------------|----------------------|
| 3.0 ~5.0                         | ±300              | 7.2                         | -20 ~ 80          | 2.0 ~3.0            | 10.4 x 31.5          |

Figure 5. Appearance of PV cell type Q6LMXP3-G2.

To measure the density of the magnetic field distribution in a PV cell, we must ensure the direction of the scanning sensor device. The lower direction along the busbar of the PV module is x-axis, the left direction along the bus bar is y-axis, the vertically upward direction is z-axis, and the magnetic flux density components are in each direction are profile magnetic component $B_x$, $B_y$. A circuit image of the experimental setup is shown in fig. 6.

Figure 6. The direction of measurement of the sensor device.

PV cell is simulated with three status measurement conditions, namely disconnect (A), crack (B) and normal (C) where in each condition, a measurement of magnetic field distribution density will be made. The three conditions which previously mentioned were determined by taking electroluminescence photos (EL method). In this experiment, the PV cell was opened as a beginning of the simulation and
the background of magnetic field at the measurement location was measured without illumination. This is to remove the influence of the background magnetic field by subtracting the result of the background magnetic field from the result measured in the forward bias state and the power generation (on the sun) state. This procedure is illustrated in fig. 7.

![Measurement conditions](image)

**Figure 7.** Status measurement condition.

Measuring the magnetic field distribution, we use two different conditions, namely forward bias (non-irradiated) and Power generation status (during irradiation). Either in the forward bias condition, nor power generation status, three status measurement conditions cells was performed. On power generation condition (during irradiation), PV cell measurements will be carried out each magnetic flux component profile $B_x$, $B_y$, and $B_z$ in the busbar cell. Component of magnetic profile will be taken on each busbar 1, busbar 2 and busbar 3. In addition, there are also the currents- $I_1$, $I_2$ and $I_3$ respectively- that pass through each busbar.

### 3. Result and Discussion

Each component of magnetic flux density, $B_x$ and $B_z$, are dominant among the magnetic flux density components which generated by the busbars current. $B_x$ is the largest on the busbar, while $B_z$ follows the right-handed screw law. The direction of the current is observed, with the negative maximum value on the right side of the busbar and the positive maximum value on the left side. The unobserved $B_y$ is the magnetic flux density component which generated by the finger current. The finger current is very small compared to the busbar current, and since the $+B_y$ component profile and the $-B_y$ component cancel each other, some components are usually not observed in the cell surface name.

In fig. 8 shows the condition of PV cells given two different conditions, namely disconnect PV cell and non-irradiation currents of 6A. It can be seen from the figure that there is a difference in the busbar experiencing instability of magnetic fields $53 \times 10^7$ on busbar 3, so there is an imbalance from magnet flux density distribution from a measurement distance of 150mm because there is a leakage current of 2.6 Amperes in a PV cell based on the equation (5).
Figure 8. By, Bx and temperature profiles along the disconnect condition.

To analyse the magnetic field generated around test of the busbars of a three condition of the PV cells is measured. The measurement results under forward bias and illuminated short circuit (0.88 kW/m² power sun irradiance) conditions are presented in fig.8, fig.9 and fig. 10 respectively. In Fig. 8 based on the calculation, the electric current obtained for the experiment using a forward bias condition of 6 Amperes, will get a magnetic field of an average of $115 \times 10^7$ Tesla with an observation length of 150 mm conductive wire. Furthermore, when using conditions with magnetic fields the average is the same, for each busbar it is stable or it can be said that each busbar is normal.

Figure 9. Bx By and temperature profile along normal condition.

In the measurement graphs, each 150 mm show the data for one cell, since each cell has 3 busbars the Bx component of the magnetic shows 3 peaks in each 150 mm. The peaks with negative sign show that the current is flowing in the opposite direction of the Y axis. Since the first busbar has is located in a 25 mm distance from the edges of the cell, the data in the measured graphs starts with a 245 mm gap from the 0 μT base line. In fig. 9, where the forward condition is 6 Ampere bias, the magnetic field is obtained at an average of $27 \times 10^7$ Tesla with an observation length of 150 mm conductive wire. By applying this condition, this field occurs the condition of damage to the cell PV which occurs imperfect crack on the surface, so the current obtained is around 0.34 Ampere.
Figure 10. $B_x$ $B_y$ and temperature profile along crack condition.

The magnetic flux density profiles of $B_x$ and $B_y$ of a normal condition PV cell in both short circuit and biased modes show regular patterns. Peak values of $B_x$ on each busbar are around $\pm 60 \mu T$ and they show that currents among three busbars are almost balanced. $B_z$ is similarly homogenous and biased by the currents in the adjacent rows. So, for $B_z$ component profile dominant towards $B_x$, we will ignore categorical bias. The temperature on the surface is almost uniform and has a sudden increase or decrease.

4. Conclusion
Provisioning protection against damage to PV equipment and reducing maintenance costs, fault detection technique of PV cells will be an important feature in the PV model literature. Some methods have been developed to analyze and examine this interesting topic. However, the drawbacks of these methods must be considered in order to provide a better performance of PV cells. This condition offers an opportunity to develop another method that can be used to overcome shortcomings from previous method as well as contributed to PV failure detection literature. We develop alternative methods to capture failure on PV module by using integrated micro tesla magnetic sensor. Specifically, we use $\mu$-tesla magnetic sensor (MI-CB-IDM) to detect failure in a PV cell. Furthermore, our study also wants to examine the level of current which can be produced when the failure of PV cells occurs. By knowing this level, we can decide whether PV cells can run efficiently or vice versa.

After we conducted our experiments, our result suggests some main conclusions. There is a difference in the busbar experiencing instability of magnetic fields $53 \times 10^7$ on busbar 3, so there is an imbalance of the magnet flux density distribution from a measurement distance of 150mm because there is a leakage current of 2.6 Amperes in a PV cell. Module measurement also conducted by knowing surface temperature. The measurement results under forward bias and illuminated short circuit shows that the electric current obtained from the experiment using a forward bias condition of 6 Amperes, will get a magnetic field by an average of $115 \times 10^7$ Tesla with an observation length of 150 mm conductive wire. Furthermore, when using conditions with magnetic fields the average is the same, for each busbar it is stable, or it can be said that each busbar is normal. Furthermore, where the forward condition is 6 Ampere bias, the magnetic field is obtained at an average of $27 \times 10^7$ Tesla with an observation length of 150 mm conductive wires. $B_y$ applying this condition, this field occurs the condition of damage to the cell PV which occurs imperfect crack on the surface, so the current obtained is around 0.34Ampere.

Finally, our last result suggests that $B_x$ at the lower busbar in the degraded module has smaller magnetic density than the upper busbar. No obvious difference can be seen in the $B_x$ and $B_y$ profiles between the normal and degraded cells.
5. References

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