Impact study on indirect lightning strikes on photovoltaic systems near transmission lines

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ABSTRACT

Grid-integrated photovoltaic (PV) systems are currently undergoing explosive growth in Malaysia. However, as more PV systems are installed close to transmission lines, there are concerns about the impact of electromagnetic (EM) properties affecting the performance and operation of the PV systems if they are exposed to lightning strikes, particularly indirect ones. Therefore, this study aims to model the impact of indirect lightning strikes on PV systems installed in proximity to transmission lines. The model involves developing a 3D model of the PV system together with a sample transmission line and creating an artificial lightning event to study the EM activity within the area. The results are compared to the IEC 61000 standard to determine its level of r\hazard. From the simulation results, it was found that the current intensity, H, of the disturbance, can reach up to 63% more than the standard limit stipulated in the standards. The significance of the study ensures that PV systems installed within the vicinity of power lines or substations have adequate lightning protection systems (LPS) as well as proper earthing systems.

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1. INTRODUCTION

In this modern era, solar photovoltaic (PV) systems have undergone explosive demand as people shift towards a more sustainable and replenishable energy source [1]. As the energy generation for PV comes from the sun, the system depends heavily on the weather conditions for the solar panel to generate substantial electricity [2], [3]. The implementation of solar PV encounters some difficulty caused by cloudy weather, rainy season, and lightning conditions that need to be overcome. This study is more significant to pursue as Malaysia has an annual monsoon season where a large number of lightning events will occur [4].

Solar panels are particularly susceptible to lightning strikes due to the large surface area and placement of exposed areas, such as roofs or open ground. There is still no case of the lightning strike to the solar panel officially reported, however, lightning can still be destructive even if it is not a direct hit and can damage many systems [5]. Induced effects due to indirect lightning strikes may also damage alternating current (AC) and direct current (DC) power conductors and data lines [6], [7]. According to the records, Malaysia experiences an average of 180 to 260 thunderstorm days a year, behind only Indonesia (322) and Columbia (275 to 320), making Malaysia the third-highest country with lightning activity in the world based on the US National Lightning Safety Institute records [5]. With the growth of PV systems installation, many systems are located near substations and transmission lines to enable them to be connected to the grid more seamlessly [8]. Therefore, a study on lightning effects on PV systems especially in the Malaysian context is particularly relevant and important. This study is also beneficial for other locations that experience a high occurrence of lightning strikes [9].

The transient problems caused by lightning that generally occur for PV systems are the electromagnetic interference (EMI) that disrupts the operation of electronic equipment or other items [7]. A high EMI will increase energy loss and may lead to PV system equipment malfunctions [10]. EMI can come from multiple sources, but it can be divided into two categories which are continuous interference and impulse interference [10], [11]. Continuous interference often comes in the form of constant radiation from an electronic device, communication system, or internet connection that can be either man-made or the result of natural occurrence, while impulse interference consists of a high burst of intense disturbance happening in a short period of time. It can be caused by events such as lightning, electrostatic discharge (ESD), or switching [12].

In this research work, the modeling of magnetic properties, namely current density, J while current intensity H and flux B is done to see the concentration of electromagnetic (EM) disturbance that exist at the PV system, particularly at the PV module [13]. This information is important to identify the parts which are most prone to EM waves, which may result in reduced performance or even operation failure. In Malaysia, it is required for grid-connected photovoltaic (GCPV) systems to be installed within a lightning protection system (LPS) that follows the International Electrotechnical Commission (IEC 62505) lightning protection standard. In the event the PV system is installed where there are no existing LPS, then such a system should be installed together with the system [13].

2. BACKGROUND THEORY

2.1. Electromagnetic compatibility and interference

Electromagnetic compatibility (EMC) is the ability of an electronic product to operate efficiently in an EM environment by limiting any potential disturbance that can affect the performance of the devices. EMI is the unwanted radiation interference from the electronic equipment itself to other electronic equipment that leads to vulnerability issues [2]. The PV system can be sensitive to EMI if the levels of EM energy in its environment exceed the EM immunity that was designed and tested for the product [14]. EMC can also occur from unexpected weather conditions like lightning, which will produce a high level of EMC that can damage the PV system. In extreme conditions, a direct or indirect lightning strike can damage the PV panels, generator, inverter, DC lines, underline cables, and other equipment of the solar power plants [9].

IEC 61000 is the golden standard in the immunity requirement testing and the range of recommended test levels for the equipment to be tested with magnetic disturbances that is mainly encountered in industrial, power plants, railways installation, medium voltage, and high voltage sub-stations [15], [16]. The focus in this IEC standard is to establish the reference to evaluate the immunity of the electrical and electronic devices to impulse the magnetic fields [7]. The test had been done with a consistent method to obtain the immunity of the devices or the system against the specific phenomenon. The reaction of the equipment under specific test operating conditions is the description task to observe the equipment to impulse magnetic fields caused by switching and lightning effects. The range of the pulse magnetic field strength test level toward the equipment is from the levels 3 to 5 with the peak pulse magnitude field strength of 100 A/m, 300 A/m, and 1,000 A/m [17]. The magnetic field strength test is expressed with 1 A/m corresponding to the free space magnetic flux density of 1.26 µT. This standard is used in creating the simulation model environment.

2.2. Current density

According to Lenz’s law, the energy force that creates a magnetic field against the magnetic field that is created is called eddy currents, and the eddy currents react back on the source of the magnetic field. The eddy currents are the AC energy losses in the AC machinery items like generators, transformers, and electric motors. Eddy currents are also used for detecting cracks and flaws in the metal parts using specific testing instruments and use for detecting object heat.

Based on Faraday’s law of induction stated that eddy currents are electrical currents induced within conductors by a changing magnetic field in the conductor. Current is defined as the rate at which the charge passes through a specified surface area. Therefore, due to that case, the surface area will be the cross-section of a conductor as in (1):

$$I = \frac{\Delta Q}{\Delta t} \tag{1}$$

The fact that current can vary from point to point, and current density can vary from point to point. If the current density is constant across a surface, the current density can be obtained with just the total of current divided by the total surface area as in (2):

$$J = \frac{I}{A} \tag{2}$$

If the current density changes across the surface area being considered, the formula of surface integral to determine the total current as in (3):

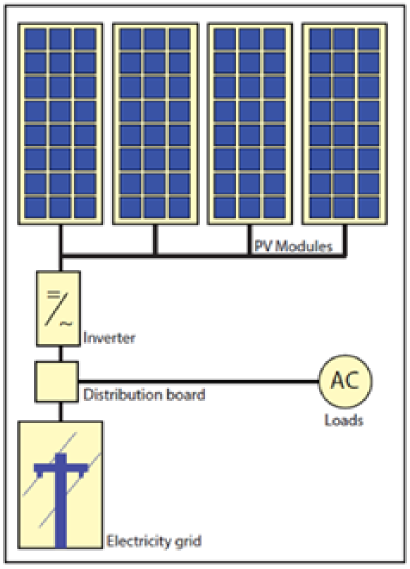
$$I = \int_{\Delta A} J.ds \tag{3}$$

2.3. Lightning faults

Lightning creates a strong EM field and induces extremely high voltage for a moment that can damage the PV panels, DC lines, inverter, underline cables, and other equipment [18], [19]. The previous analysis and recommendations would help determine the fundamental requirements and design considerations of an appropriate LPS for a big-scale solar power plant [20]. The solar power plant can be affected by direct and indirect lightning strikes. In the lightning EMI studies, the induced voltage on the DC cable can damage the underground DC lines. The studies also showed that the induced voltage depends on the depth of the pipeline, strike location, soil resistivity, and permittivity [20]. According to the previous research, a strong magnetic field is being created around the lightning strike. Moreover, a large voltage induces in the PV frame and DC line leading to the inverter. There are also some parameters such as the rising rate of lightning current, earth resistance, and lightning location that are affected by the induced voltage result [21].

3. RESEARCH METHOD

The fundamental building blocks of a GCPV system are depicted in Figure 1(a) [22], [23]. Essentially, the system comprises the PV modules that generate DC power and an inverter that converts the generated power into AC [24]. The distribution board serves as an intermediary that divides the power usage into supplying local loads first before exporting the rest of the energy to the grid. In order to model the EM profile of this system, a 3-D model has been developed, as shown in Figure 1(b).



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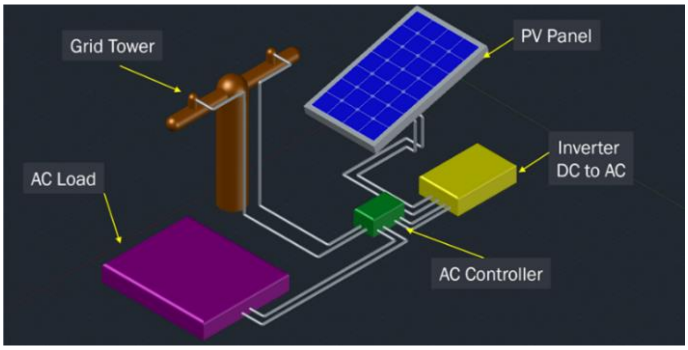


(b)

Figure 1. Building blocks of a; (a) basic GCPV system and (b) 3-D model for GCPV system

Meanwhile, to simulate the indirect lightning, a simple magnetic core was constructed within the simulation region. The model is based on a cylindrical iron core with a torus shape of the copper coil [10]. A current excitation of 100 A is assigned to the torus and positioned at the origin point. This produces a magnetic field, as shown in Figure 2.

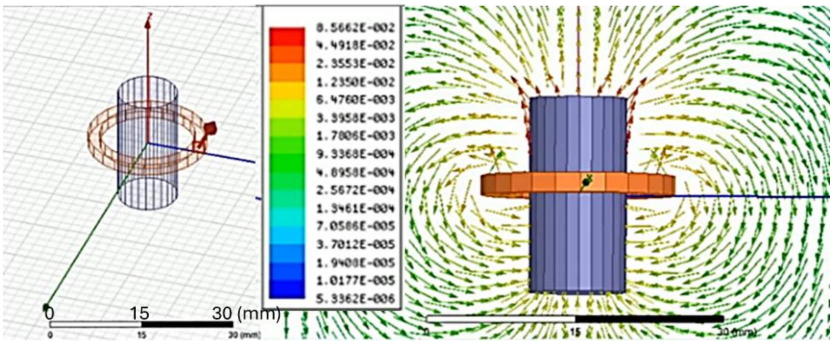
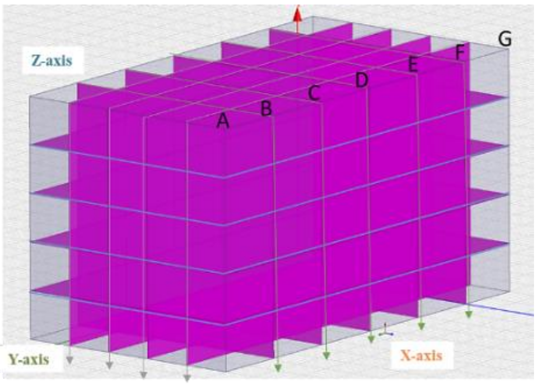


Figure 2. Indirect lightning simulation model

The key modeling concept is by treating the environment evaluated as a rectangular 3-D bounded region as shown in Figure 3(a), where it is located at the first octant of the Cartesian coordinate system, and one edge is positioned at the origin point, the same point as the artificial source of the indirect lightning. To obtain the magnetic field results, there were two tests performed in the simulation. The first test was to create a subject that has metal elements react with a uniform magnetic H field surrounding it. The second test is to create a similar environment of a lightning phenomenon in the simulation and collect data of EMC with the PV system in the simulation [6]. Figure 3(a) shows the boundary region sub-divided into smaller sections (A to G) so that the analysis of the magnetic field produced from indirect lightning can be observed with more detail. Meanwhile, Figure 3(b) shows the intensity of lightning strike EM distribution within the region after the lightning event. The range for the current density for this bounded region is set to be within the range of 100 to 1000 A/m^2. Thus, a fair comparison before and after the lightning event can be made and both are in steady-state condition and presented in a time-domain analysis.



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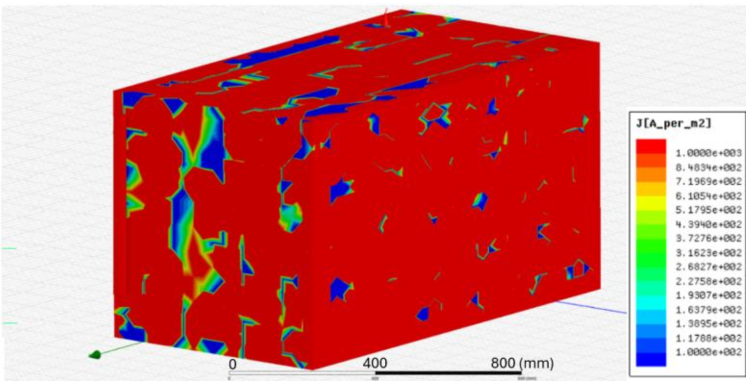


(b)

Figure 3. Boundary; (a) region subdivision and (b) after lightning event

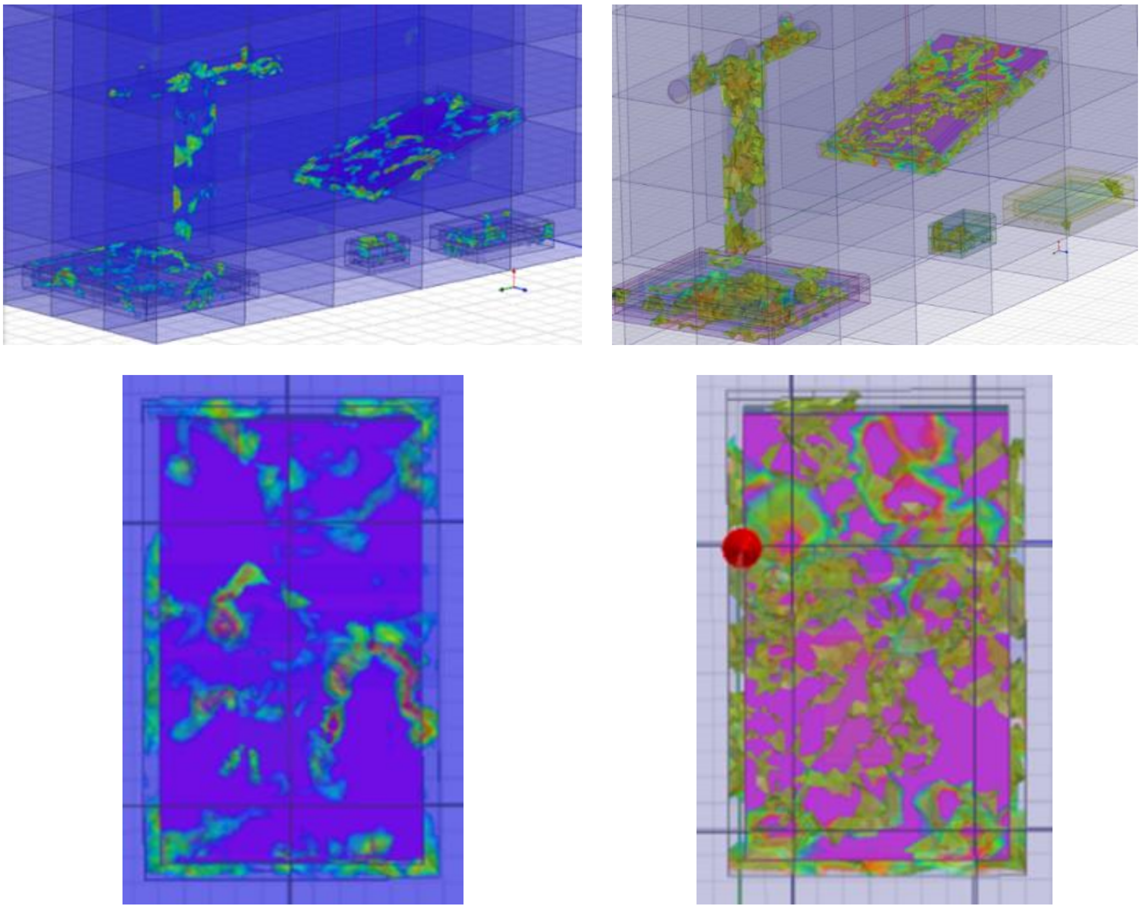
4. RESULTS AND ANALYSIS

The current intensity (H) value before and after the lightning event is recorded in Table 1. It can be observed that the magnetic intensity is low during normal operation, and the EM profile does not affect any equipment operation. However, the value increased substantially after the lightning event, which is sensible since indirect lightning increases EM waves within the bounded region. In addition, substantially high values are observed for the z-axis, indicating that there may be some interaction between the PV systems and the nearby transmission lines.

Table 1. Maximum calculated H inserted to each region boundary

Plane	x-axis (A/m)		y-axis (A/m)		z-axis (A/m)	
	Normal	Lightning	Normal	Lightning	Normal	Lightning
A	0.07	247.19	0.38	318.66	0.20	753.34
B	0.07	252.10	0.39	324.31	0.21	769.34
C	0.06	256.85	0.40	329.80	0.22	785.16
D	0.06	261.85	0.41	334.80	0.23	801.16
E	0.06	266.85	0.42	339.80	0.24	817.16
F	0.05	271.85	0.43	344.80	0.25	833.16
G	0.05	276.85	0.44	349.80	0.26	849.16

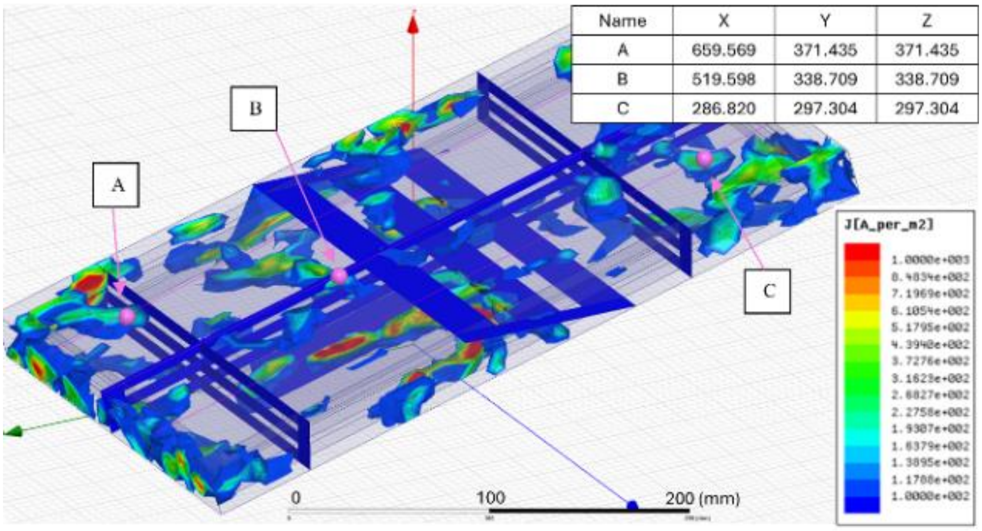
Figures 4(a) and (b) shows the visual simulation of EM activity before and after lightning for the overall system while and then specifically at the PV module. It can be observed through visual simulation that high EM activity occurs, particularly around the middle part of the PV module. This may imply that after lightning events, this zone is the most susceptible to failure or unexpected degradation.



(a) (b)

Figure 4. Magnetic J field simulation; (a) under normal operation and (b) after lightning event

To investigate the impact of indirect lightning on the PV module, the peak value of J is investigated at the module area, where three of the highest values are recorded and labelled. Under normal conditions, the three points are rather dispersed over the PV module, occurring at the top, middle, and bottom part of the module, as shown in Figures 5(a) and (b). However, after a lightning event, the three highest values occur in the module's middle part. Again, this highlights that electrical stress occurs at the central zone of the PV modules.



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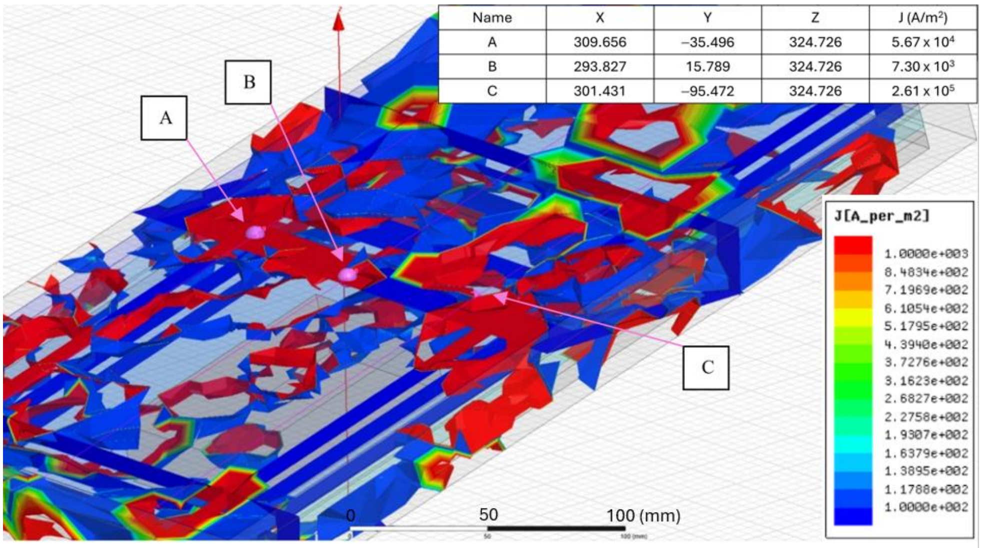
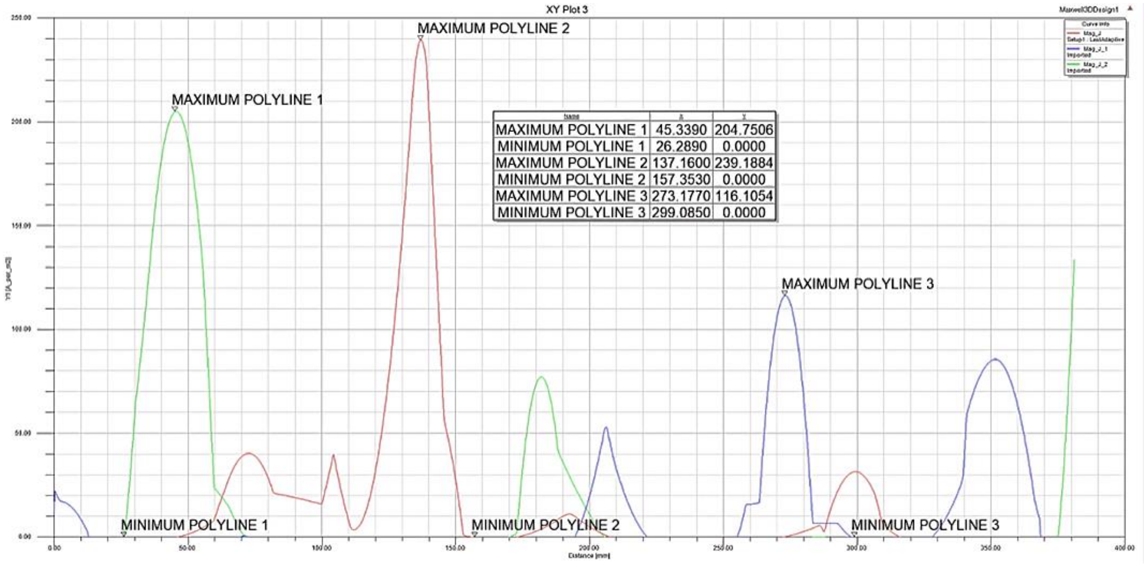


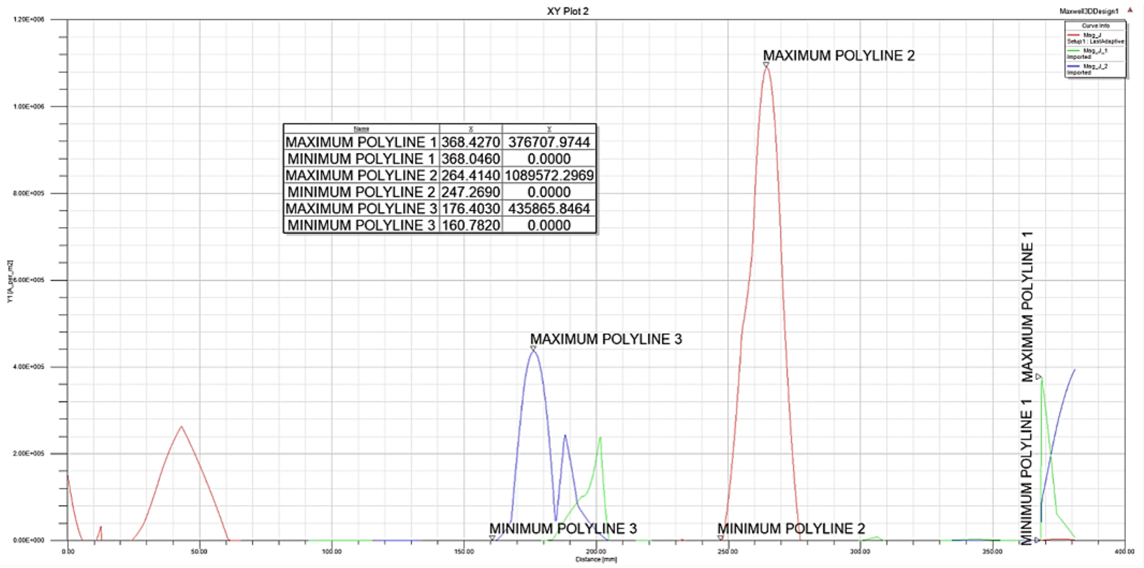
(b)

Figure 5. The profile for the J field at the 3 maximum points modules; (a) under normal operation and (b) after the lightning event

The results show that the larger the area of the components, the higher the possibility of the components exposing to the high magnetic J field, as shown in Figures 6(a) and (b). Moreover, the lowest of the magnetic field reading results that is obtained in the lightning condition still show alarmingly high values, implying that the component of the PV system is at high risk when located near transmission lines and may affect the performance of the components. The result also showed that even the non-metal components are affected by the high magnetic J field. This may indicate that even non-metal components cannot guarantee isolation from EM issues [25]. Proper earthing connection and protection systems must be in place to ensure that there is a pathway for the surge to travel safely and efficiently to the ground [26].



(a)



(b)

Figure 6. Data plot for maximum J value for three different points at the solar panel; (a) under normal operation and (b) after the lightning event

Table 2 records the values of J and H before and after a lightning event. All the values are well below the maximum limit defined by the IEC 61000 standard during normal operation. However, after the lightning event, the H and J values exceed the upper limit significantly, with the maximum H value recorded at 2.74 kA/m or 63% more than the allowable limit. The maximum current density value is even more dangerous, reaching over 1000 kA/m^2, posing a potential risk of equipment failure. From the perspective of health and safety, the result from Table 2 is recommended so that each country should revise and set their own national standards range based their own limitations instead of following the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [27].

Table 2. Result for H and J during normal and after lightning condition

Polygon line	Before lightning		After lightning	
	H_std_limit (kA/m)	J_max (kA/m^2)	H_max (kA/m)	J_max (kA/m^2)
J_1	1.0	0.21	1.23	376.71
J_2		0.24	2.74	1089.57
J_3		0.12	1.95	435.87

5. CONCLUSION

Through this simulation process, the key finding is that an intense EM field is produced around the middle area of a PV module during lightning events compared to the fringe areas. Therefore, it is likely that any indication of damage incurred by the module will be seen at the centre of the modules first. Furthermore, the intensity of the disturbance can reach up to 1.74 times or 63% more than the standard limit stipulated in the standards. This highlights the importance of ensuring any PV system installed within the vicinity of power lines or substations has proper and adequate LPS and proper earthing protection systems to ensure that the integrity of the PV system is not compromised. In this study, it can be concluded the information of the number of the high occurrence of lightning strikes are beneficial for other locations that experience a high occurrence of lightning strikes.

Future research work intends to model the PV system in greater detail for multiple series and parallel configuration to investigate the potential issues related to indirect lightning strikes. The application for measuring the variation of the EM test in this paper has also been simplified, and a more detailed color font simulation is essential to further refine the potential impact on PV systems. More research needs to be continued in the future, such as the calculation of the current that obtained during the lightning event occur, more variety measurement on a selected component of the PV system, and more data analysis in the limitation of the magnetic field on each component of the PV system.

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