Active Grounding of the Photovoltaic Power PlantSafeguarded by Lightning Rods

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Abstract - *The performance of a grounding grid for photovoltaic (PV) systems protected by independent lightning rods is discussed in this article. Several grounding grid configurations are investigated, and the finite difference time domain (FDTD) method is used to evaluate the transferred voltages between the dc cables and supporting structures at various points in the PV system. The transferred voltage is very high in a PV system without a dedicated grounding grid for supporting structures, and it is even worse if the soil resistivity is high. Installing a dedicated grounding grid, which is very expensive in a large PV power plant, can effectively reduce the amplitude of the transferred voltage and eliminate residual voltage. It has been discovered that the arrangement utilizing a bonding network outperforms other grounding improvement approaches in lightning protection. More importantly, the proposed strategy is simple to implement and inexpensive. The soil with high soil resistivity will not cause severe overvoltage in the system with the bonding network. It is strongly advised to use it in a PV power plant protected by independent lightning rods.*

***Key Words*: Lightning, Protection, Photo-voltaic, Grounding, PV Power plant, Soil Resitivity**

1.INTRODUCTION

Grounding is a critical component of lightning protectionfor power systems. Several studies have been conducted to reveal the characteristics of grounding systems during lightning strikes. Soil stratification, resistivity, and ionization have been found to influence the characteristics of a grounding system under lightning. They should be taken into account when designing the grounding system. Furthermore, the grid arrangement of a grounding system influences grounding performance. It should be noted that specific grounding techniques have been developed for various parts of power systems, such as substations, towers, overhead lines, underground cables, wind turbines, and so on. The grounding system differs from one to the next. Despite significant efforts and accomplishments in designing proper grounding systems for traditional power systems, research related to the grounding of photovoltaic (PV) systems has not made significant progress. Due to the lack of a unified standard, different grounding practices have been discovered in practical installations. Grounding design solutions are frequently debated in terms of balancing cost and efficiency.The grounding system of a PV plant is similar to that of a substation in most installation guidelines and can be designed in accordance with IEEE Standard[1]. These standards, however, do not specifically mention PV plants. Nonetheless, several studies on these topics have been published. [2] presents challenges and recommendations for the safe and cost-effective design of grounding grids for PV plants. [3] describes procedures for calculating touch voltage in a PV plant during a single-line-to-ground fault on the high voltage side of a step-up transformer.

This recommends using the PV supporting structure as auxiliary ground electrode and horizontal ground conductorsfor the interconnections of all the PV supporting structure toreduce the cost of grounding system installation as well as the touch voltage[4]. A meshed earth termination grid ranging in size from 20 m to 40 m[5]. This type of groundinggrid has been shown in practice to be effective at reducing overvoltage and is recommended for use in PV plants. There is also literature on mesh size design [6, 7], current sharing inthe electrodes of the grounding grid [8, common-mode and differential-mode voltage evaluation [9, 10], and potential distribution in the plant [11].

However, because of the large occupied area of the PV plant (a large PV plant can cover an area much larger than that of the substation), installing such a grounding grid is expensive, especially when a PV plant is built in a hilly area or in an area where labor costs are high. Many PV plants use a single grounding electrode at the PV inverter instead of a large grounding grid to increase the return on investment. It is important to note that the PV supporting structure (e.g., metal brackets) is built on the ground, with one part buried in the soil. Section IV presents the simulation results for the system without a dedicated grounding grid.

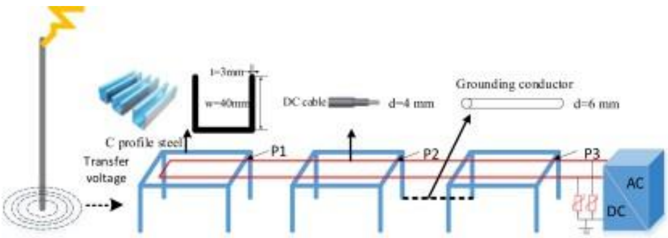

Fig -1: System configuration for the components and PV string under investigation.

2. SUMMARY OF THE PV SYSTEM UNDEREXAMINATION

The system is made up of many arrays (rectangular boxes). Eight PV strings, each with three sets of panels, are connected in parallel to form one array. Each string's panels are interconnected in series. A parallel connection between the strings' outputs and an inverter is used to protect them from surges (SPDs). The inverters are then coupled in parallel on the ac side, and a distribution transformer transmits their outputs to the medium voltage distribution system. Lightning rods have been installed in the facility to safeguard the PV system from a direct lightning hit. The locations of these lightning rods are indicated by the dots in the diagram. The circles in the illustration represent the protection area for each lightning rod, which is determined by the protection angle method in accordance with an IEC standard [12].

All of the PV system's components are safeguarded by choosing the air termination rods' height, installation locations, and number. The PV modules may degrade or sustain irreparable damage as a result of the potential difference between the DC cable and the PV brackets at the supporting structures. To the best of our knowledge, there hasn't been much discussion of this damaging process in the literature. It is crucial to comprehend how the grounding configuration influences the transferred voltage. This is so that engineers may choose the best grounding design for a PV plant by comprehending the mechanism. In this regard, a PV string—a fundamental unit for power production—is in-depthly examined in the following sections.

3. MODEL AND METHOD FOR SIMULATION

One PV string and one lightning rod are modeled separately for the sake of simplicity. The arrangement of the PV system under consideration is shown in Fig. 2. Numerous PV panels are mounted on three supporting structures to form the PV string. The supporting structures are composed of C-profile steel and are 4 m long, 3 m broad, and 3 m apart from each other. The supporting structures are 3 mm tall, standing 2 m above and 1 m below the surface. The C profile steel has a width of 4 mm and a thickness of 3 mm. The supporting supports are mounted using the 4 mm-diameter DC wires of the PV string. These DC wires have SPDs protecting them and are joined to an inverter at one end. The lightning rod is 7.6 meters from the PV string closest to it. The ground-level lightning rod is a 10 m conductor that is attached to a 3 m long vertical grounding rod.

The above-mentioned issues are looked at using the three-dimensional FDTD approach, which has been widely utilized in lightning electromagnetic pulse and surge simulations [13]–[17]. The discrete second-order approximation is used by the FDTD method to solve Maxwell's equations. The repeatedly staggered updates of thediscretized electric and magnetic field components are sampled with a half-step offset in the time and space domain.As seen in Fig. 1, several wire components may be found in the PV systems, such as the wiring in the PV panels, dc cables, lightning rods, and PV supporting structures. In this study, the PV supporting structures composed of C profile steel are modeled using the noncircular thin-wire model [22],whereas the dc cables and grounding conductors with circular cross-section are studied using an extended thin-wiremodel [18]–[23]. Due to its little effect on the common mode voltage, the wiring in the PV panel is disregarded [24]. The extended thin-wire model is also used to model thecylindrical conductor that serves as the lightning rod and its earth rod.

The model described in [25] serves as a representation of the lightning channel. According to IEC 62305 [26], the channel base return stroke current should have a waveform of 0.25/100 s and a magnitude of 50 kA. A voltage-dependent resistor simulates SPDs. Fig. 3 displays the V-I characteristic of the SPDs. The working area is divided into 150 non-uniform cells with size of 210 by 210 by 150 meters in the simulation. The smallest cell size in close proximity to the investigated PV system is 0.2 0.2 m.

It gradually rises to 2 m in the y direction and 8 m in the x and z directions. In the simulation, the lightning channel's length is set to 480 meters. Seven perfectly matched layers that absorb boundary conditions are employed to block out undesirable border reflections. There are at least 28 cells in the empty region between the conductors and absorbing barriers. The Courant-Friedrichs-Lewy limit establishes what time step is being used. Fig. 4 depicts the side view of the computational domain in the FDTD. A graphics processing unit Tesla TM K40C GPU Computing Accelerator] is used to speed up numerical computing. For the simplified one string model given in Fig. 2, the computation time is 2 hoursand 52 minutes.

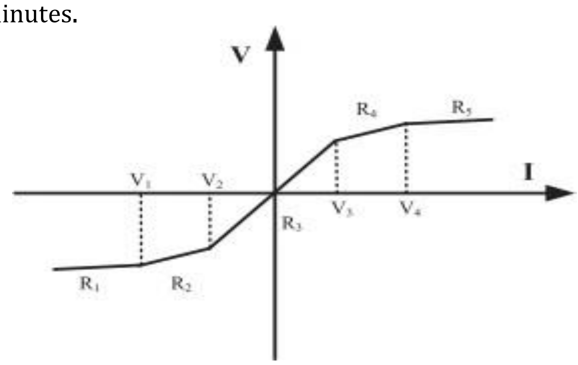

Fig - 2 V–I characteristic of the SPDs model (V1 = −1500, V2 = −1200 V, V3 = 1200 V, V4 = 1500 V; R1 = R5 = 0.001 Ω R2 = R4 = 1000Ω, R3 = 1 MΩ).

4. PV SYSTEM NOT INCLUDING A DESIGNATED GROUNDING GRID

In many PV plants, vertical grounding rods are used to ground PV systems at the PV inverters. The PV mounting structures have no separate grounding grid. Because a of the supporting structures is buried in the ground, they are thought of as the system's "grounding electrode." The following factors form the foundation of this design. First off, it would take a lot of money to create a big grounding grid because of the big covered area and remote location. The PV grounding system lacks a unified standard, which is the second issue. Furthermore, because there are independent lightning rods, lightning is no longer considereda serious risk that can seriously harm PV systems.

In this section, we looked into the lightning overvoltage at various PV system locations when an independent lightning rod was present. There is no additional or dedicated grounding grid installed; instead, three PV supporting structures are each individually grounded using brackets. As depicted in Fig. 1, the SPDs at an inverter's input port safeguard the dc wires. Using the model described in the previous section, the transmitted voltage between the supporting structures and the dc cables at various places P1, P2, and P3, as illustrated in Fig. 5, is determined. For comparison, two soil resistivity values of 100 and 2000 m are used. We assume that r = 10 for the relative permittivity and r = 1 for the relative permeability.

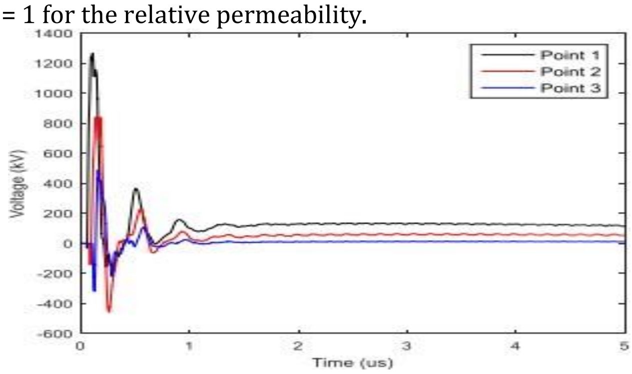

Fig -3: Overvoltages in the PV system without dedicated groundinggrid (low soil resistivity).

4.1 Low Soil Resistance: =100 m

A site with low soil resistivity is indicated by the assumption that the soil resistivity is 100 m. The voltages between the PV cables and the PV brackets at three distinct places are depicted in Fig. 6. The voltage at point 1 can peak at 1267 kV and oscillates its way down to 120 kV in less than one microsecond. The residual voltage lasts for a very long period and drops off quite gradually. This suggests that a high voltage has been placed between the PV cable and thePV bracket for a considerable amount of time. Peak and residual voltages at point 2 are 842.9 and 53.5 kV, respectively. The peak voltage and residual voltage are 489.9 and 12 kV at position 3. This indicates that when the observation point is moved to the grounding point at the inverter, both the peak voltage and the residual voltage decrease.

4.2 Extremely High Soil Resistance: = 2000 m

The system's overvoltage between the dc cable and the PVbracket is also evaluated when it is installed at a location with high soil moisture levels resistivity. The soil currently has a resistivity of 2000 m. The voltages at three different sites. It has been noted that the voltage waveform with a 2000 m soil resistivity is different from that at a 100 m soil resistivity. In this case, the voltage rises to its peak level within a limited time oscillation at first, then starts to fall. As you get closer to the system grounding rod, the time to the peak is longer and longer (4.5 s at point 1, 5.38 s at point 2, and 6.5 s at point 3), compared to when the soil resistivity is 100 m. With peak voltages of 2248 kV at point 1, 1002 kV at point 2, and 225.9 at point 3, this peak voltage is also significantly higher than the previous one. This indicates that the voltage will have a bigger amplitude and a longer duration when the PV system is put in a location with high soil resistance.

As a result, the system's lightning overvoltage issue will be more severe than it would be if it were situated somewhere with low soil resistivity. It should be emphasized that the inductive coupling from the current in the lightning rod is mostly responsible for the voltage oscillation that occurs within the first millisecond. The ground potential rise at various ground sites is what causes the gradual increase in voltage, as depicted in the figure. The soil resistivity is significantly relevant to this voltage. The voltage caused by the grounding potential rise at various sites is minor when the soil resistivity is low. Therefore, the inductive coupling effect dominates in determining the oscillation peak of the voltage. However, the voltage caused by the rise in ground potential becomes considerable when the soil resistivity reaches 2000 m.

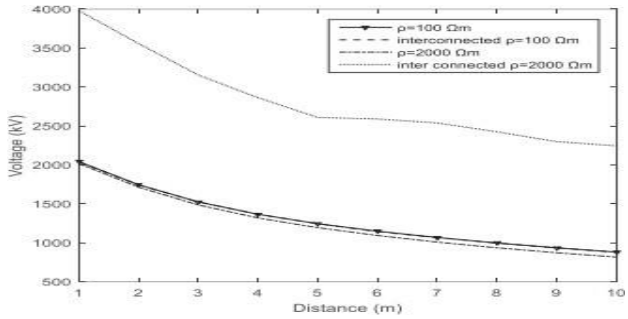

Fig -4: Influence of the distance.

5. A PV SYSTEM WITH A PERSONALIZED GROUNDING GRID

To ensure the safety of PV systems following a lightning strike, several PV plants incorporate grounding grids for the supporting structures. Different grounding grid configurations are described in the literature. The transmitted voltage between the PV cable and the PV bracket is calculated in this section using a variety of grounding grid configurations. The effect of soil resistivity is also discussed.

5.1 Grounding Conductor Horizontal

First, a simple grounding grid with several horizontal conductors buried in the soil at a depth of 1 m is used. As shown in Fig. 8, these conductors are used to connect the PV brackets and the PV inverter beneath the ground.

5.1.1 Low Soil Resistance: = 100 m

The voltage waveforms at the previously indicated three points. At point 1, the highest voltage is 1250 kV, while at point 2, it drops to 873.6 kV. The peak voltage is further reduced to 527.3 kV at point 3. Compared to systems withoutsuch a grounding grid, these voltage peaks do not change significantly. The voltage, however, degrades more quickly and approaches zero after 5 us. The system won't experiencepersistent overvoltage as a result. This is so that there is a low resistance path from the PV brackets to the inverter's grounding rod provided by the buried conductors.

5.1.2 High Soil Resistance: 2000 meters:

The simulation was also run with a 2000 m increase in soilresistivity. The voltage waveforms between the DC cable and the PV bracket are shown at three places. In comparison to the case with low soil resistivity, it is discovered that the situation is not as bad. The voltage peaks are 1229 kV at point 1, 907 kV at point 2, and 516 kV at point 3, which are nearly identical to those for 100 m soil resistivity. Keep in mind that the voltage almost reaches zero within 2 s of rapid voltage decrease. The voltage without the buried horizontal conducted is different from this. Thus, the overvoltage has a smaller impact on the PV system.

5.1.3 Using a Meshed Grid to Ground

A more complex grounding grid is chosen for comparison in order to examine the impact of the grounding grid configuration on the overvoltage in the PV system, as illustrated. A buried conductor mesh is offered in this situation. The intensity displays waveforms. Unexpectedly, the grounding mesh, which has been shown to be effective in lowering the possibility. Despite any variations within the grounding system, the between the PV wire and the PV bracket, an overvoltage Actually, when the grounding mesh is present, the voltage somewhat rises is used as opposed to buried conductors.

6. SYSTEM WITH IN THE AIR EQUIPMENT POTENTIAL BONDING

Fig - Requirement for interconnection of grounding grids in the PV plant.

It has been shown that a grounding grid with buried conductors can greatly lower the lightning overvoltage in a PV array. However, this approach can occasionally be challenging to use, particularly in areas with rocky terrain, mountains, and stiff soil. However, as the cost of PV panels and inverters continues to fall, PV power plant investors are becoming increasingly concerned about installation and construction costs.

The investment return ratio of PV power plants can be significantly increased by lowering the installation and building expenses. No matter if the grounding grid is installed as buried horizontal conductors or a mesh grid, the overall investment cost will surely increase. Therefore, a more cost-effective strategy is suggested in this section, namely the adoption of an airborne bonding network in place of buried conductors.

In this part, the system performance of the suggested technique during a lightning strike is examined. This third arrangement's configuration. The horizontal bonding conductors are used to link the inverter, three supporting structures, and the higher level of the atmosphere. These cables are closely spaced parallel conductors that run with the DC cables.

6.1 The Effect of Soil Resistance

6.1.1 Poor Soil Resistance = 100 m

The simulation was run for the bonding network case. The turned out to be a bit unexpected especially from a useful standpoint. Although there is none voltages at each of these locations are all on a distinct grounding grid. Considerably diminished in comparison to the outcomes of the other two grounding configurations.

6.1.2 High Soil Resistance: 2000 meters

This strategy exhibits a significant improvement when thePV system is put in a location with high soil resistivity the peak voltages at points 1 and 3 are further decreased when compared to the case of the low soil resistivity, falling to 964.1 and 222 kV, respectively. The peak voltage at point 2 is raised to 812.1 kV, however. When the soil resistivity is high, the depreciation of these voltages happens more quickly.

6.2 Soil stratification's impact

In this section, we assess how a stratified soil with horizontal layers affects the protective effect under various grounding configurations. Consideration is given to soil with two layers. The values h1 = 1 m and h2 = 9 m, respectively, denote the depths of the top and lower strata. The top and lower layer soil resistivities are denoted by h1 = 100 m and h2 = 500 m, respectively. The voltages at three sites for various grounding configurations. The voltages beneath a uniform soil (100 m) are also shown for better comparison. Compared to the outcomes of the other two grounding configurations.

To more thoroughly research the impact of soil structure on the suggested strategy. Different soil resistivities and soil structures are taken into consideration. The higher layer is mostly responsible for the overvoltages between the DC cable and the PV supporting structure. Only a small amount of the overvoltage is influenced by the bottom layer's soil resistivity. If the suggested strategy is used, and the top layer is deep enough, the overvoltage won't be affected by the lower layer's soil resistivity.

6.3 The Impact of Additional Configurations

By using this equipotential bonding technique, as demonstrated in earlier situations, the lightning overvoltage between the cable and the PV bracket may be significantly decreased. The outcomes are far superior to those in the system with a grounding mesh and far superior to those in the system without a specialized grounding grid. Sensitivity analysis is done in this section to see how alternative system configurations will affect the overvoltage between the PV cable and the bracket.

6.3.1 The Lightning Rod's Grounding Grid

To properly channel the lightning current into the ground, a 4 by 4 m square. The lightning rod has a grid for grounding. A 2 m by 2 m. It is buried three meters beneath the surface of the land. The mimicry was done to gauge the voltages at three different locations. It is evident in the the voltages between the wires and the brackets in the table The PV system appears to remain unchanged following a grounding grid.is used as a lightning rod.

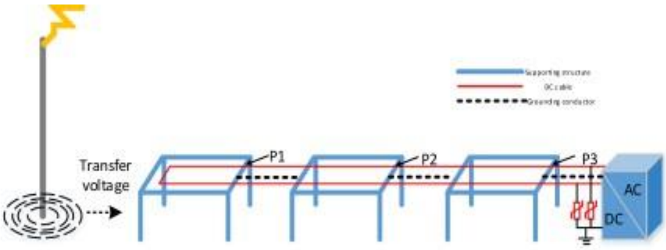

Fig - System with horizontal bonding network in the air

6.3.2 Requirement for Interconnection of Adjacent Grounding Systems for the Lightning Rod and PV System

Some standards prescribe the interconnection of adjacent grounding systems. For instance, according to, independent lightning rods should be linked to a building's grounding grid if the distance between them is less than 3 meters. The lightning protection system must be linked within within 3.6 meters of any grounded conductors that might help provide a channel for lightning currents in or on a building in order to create a common ground potential, according to NFPA 780 [28]. The two criteria mentioned above are mostly for homes. To further research how distance affects the lightning overvoltage. For comparison, several distances between the grounding grid of the PV system and the independent lightning rod are used. The peak voltage falls off more quickly in the first few meters and then gradually beyond that. No of the distance, the connector has the same impact on the transmitted voltage as previously indicated.

6.3.3 Equipotential Bonding Location

Choosing the appropriate equipotential connection position can further decrease the overvoltage. The equipotential bonding conductor is present in this instance in the midst of the two DC cables. Due to the smaller loop area between the cables and the bonding conductor, it is discovered that the voltages at all places are lower than they would be with the bonding conductors given at one side of the dc cables.

7. DISSCUSION

This section addresses the problems of adopting a condensed PV model and neglecting the neighboring PV string when assessing transmitted voltages.

7.1 The Effect of the PV Panel's Simplified Wiring Structure

Through galvanized aluminum wires, the PV cells of each panel are linked in series. Overvoltage will be created in the loop the galvanized aluminum wires make upon a lightning strike. Bypass diodes in the PV panel might fail as a result of this overvoltage. Additionally, the voltage between the positive and negative dc cables will be impacted by the overvoltage in each panel. As a result, it is impossible to simplify the wire topology when analyzing the voltage in the bypass diode. As a result, it is impossible to simplify the wire topology when analyzing the voltage in the bypass diode. Additionally, if the PV panel's wiring layout is made simpler, the assessment of the voltage between the positive and negative DC cables may be biased. However, there won't be much of a bias when analyzing over voltages caused by the ground potential rise between the grounding structure (PV brackets) and the dc cables when using a basic model. To demonstrate that it is rational to assess the overvoltage between the metal frame using a simpler wire structure and the dc cable, which is emulated with various loop regions for comparison (the +/- dc cables' spacing vary).

7.2 The Effect of EM Couples Between Adjacent Strings

There are several PV strings in a PV plant. Due to the close proximity of the neighboring strings, inductive and conductive couplings between parallel PV threads may have an impact on the computation's outcomes. In this section, the impact of the nearby strings is examined. In the simulation, it is assumed that the two strings are 3 m apart. The transferred voltage in the PV system when a nearby PV string. The voltage amplitudes under each grounding configuration with/without a nearby PV string are also displayed in the table for easier comparison. This table shows that when the nearby PV string is present, the voltage amplitude will decrease in each grounding configuration. However, the conclusion reached in earlier sections—that establishing a bonding network in the air is preferable to the other two arrangements—is unaffected by the existence of the nearby strings.

8. CONCLUSION

The PV system's grounding configuration is a problem that hasn't yet received much attention from international standards. Engineers typically increase the quantity of buried conductors, decrease the mesh size, and choose an appropriate grounding grid arrangement when creating a lightning protection system for a PV system in order to lower the resistance of the grounding grid and homogenize the potential distribution. These techniques are expensive, and it is unknown how effective they are in protecting PV plants against separate lightning strikes. The system employing a dedicated grounding grid, as advised by the majority of local standards and manufacturers, can reduce the lightning overvoltage between the dc wire and the PV bracket, according to the results of this article's research. By supplying bonding conductors running in parallel with dc cables in the air, it is possible to significantly reduce the overvoltage. By putting the bonding conductors in the midst of two suspended DC wires, the overvoltage may be further decreased.

This approach is less costly, simpler to use, and even more effective in blocking lightning than grounding mesh. The performance of lightning protection is not worsened by soil with increased resistivity thanks to the bonding network. On the other hand, when the soil resistivity is high, the PV system will experience less residual voltage. This means that when lightning protection is a problem, the site selection of a PV plant will not be constrained by the soil resistivity. Furthermore, the voltage between the dc wire and the PV bracket is little affected by the way a lightning rod is grounded. Consequently, a sophisticated grounding system for the lightning rod is not required. Some standards advocate connecting a lightning rod's ground terminal to the grounding grid of a photovoltaic system. When the soil resistivity is high, however, such connectivity may significantly increase the lightning overvoltage between the DC wire and the PV bracket. Even with low soil resistivity, the problem won't get any better. The purpose of connecting two grounding systems is to prevent electric shock during a fault situation or a lightning strike. This method is typically used in residential structures or installations of a similar kind. If the distance between the lightning rod and the PV system is too great for one person to touch both at once, then such a connection does not apply to the PV plant.

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