ANALYSIS OF INDIRECT LIGHTNING PHENOMENA ON SOLAR POWER SYSTEM

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Abstract: *The threat of solar power system is lightning induced voltage, which can damage the photovoltaic generators and its ancillary equipment, has been examined in this paper. The induced voltage due to lightning strike can be reduced using lightning protection system; however there is a possibility of getting damage of system equipment from electromagnetic interference. The induced voltage on Power Condition System (PCS) of solar power system is analyzed using electromagnetic analysis approach. The effects of strike height and soil resistivity have been considered for analyzing the induced voltage on a system. We examine, with the increasing strike height and rising soil resistivity how the induced voltages of system are affected. We found that with the increasing strike height the induced voltage is also increasing except the line to ground voltage, and with the rising soil resistivity induced voltages are approximately constant excluding frame voltage. Virtual Surge Test Lab (VSTL), which utilized the finite-difference time-domain (FDTD) method for solving Maxwell's electromagnetic equations, was used to compute the induced voltages. The solar power system was modeled with thin wire structures having good representational capacity of a steel frame and power line to induced voltage.*

Key words: *Indirect lightning, solar power system, soil resistivity, strike height, induced voltage.*

1. Introduction

The growth rate of solar power generation is increasing gradually all over the world because of available supply of sun, financial benefit, environmental friendly and so on; however its vulnerable parts which are often being damaged to induced voltage due to lightning interference are being analyzed seldom. In the case of a commercial solar power system, which is uncovered on large area, indirect lightning effect can reason a high voltage induction at panel wiring, frame voltage, line to line, and between DC power line and power conditioning subsystem (PCS); which eventually damage the PCS and/or solar junction box. Lightning induced voltage causes severe damage to electrical parts and electronic components in the system and network [1]. The knowledge of induced voltage on a system gives the engineer opportunity to take the particular arrangement for protecting the system. The study of lightning interference on solar power system is very important due to maintain its accepted growth around the world.

In order to know the lightning protection system of solar panel, it is important to know the effect of inducing voltage on solar panel due to lightning effect. For this reason, direct lightning induced voltage between DC power line of PV panels and PCS was investigated by Mourad [2]. He shows that the induced voltage which is cause of a direct strike at the center of PV panel is 1000kV at resistivity of 100Ωm and recommends to use lightning arrester at the end of line toward the PCS side. The induced voltage between the power line and PCS has been also discussed by Takada [3], [4]. In Takada model, the induction mechanism is explained when resonance inside the frame affects the induced voltage between power line and PCS. In Yamamoto work, the induced voltage is explained by the theory of potential rise during a lightning hit: when the lightning hits the frame, the potential of the frame will rise depending on the ground impedance. And since part of the DC lines are surrounded by the frame, this part will be affected by the space potential and continue rising.

The most of the incident occurred in the system was due to nearby lightning strike [5], so it implies that the indirect lightning strike needs more study to design a system properly. A very close dart leaders carry most important role which is known as return strokes in the case of induced voltage [6]. The lightning induced voltage phenomena mainly depend upon the velocity of electromagnetic field of return stroke along the striking line [7]-[9]. In the case of assessment of both the line parameters and electromagnetic field, the ground conductivity has an imperative role. The computations were done using the 3-D FDTD method, and induced voltages of horizontal wire were computed by integrating the electric field from the ground plane to the conductor height.

The simulation of a solar power system was an appropriately model of the three-dimensional structure. A calculation method which directly solves the Maxwell's equations was used for analyzing the three-dimensional structures. The finite difference time domain (FDTD) method [10] can simply handle dielectrics and conductors, and is applied to surge analysis in numerous fields [11]-[14]. This paper shows the results of simulating the division of a lightning surge voltage in a solar power system. For more comprehension, this paper is divided into mainly 3 categories where 1st part describes methodology, 2nd part illustrates modeling, and simulating of solar power system and last part evaluate the results of simulation.

2. Methodology

The FDTD method for solving electromagnetic field problem is a suitable scheme to numerically solve scattering problems [15], [16]. The FDTD method can incorporate the effects of radiation and reflection that are commonly neglected by other methods. Direct time and space discretization made the FDTD method more helpful to handle three-dimensionally distributed currents in an imperfect conductive medium. Virtual Surge Test Lab (VSTL) code [17], [18], which is based on the FDTD method developed by the Central Research Institute of Electric Power Industry (CRIEPI), is a simulation software to analyze electromagnetic transient lightning surge. The VSTL code is verified with measurement results in several papers [19]-[21]. The VSTL code is capable of handling thin conductor and non-linear elements which are difficult task in the FDTD method. The results of this software depend on total space, time step, cell size and boundary condition. It represents physical and geometrical mean rather than circuit.

In FDTD method, the cell size and time step must satisfy the Courant stability condition below [22],

$$c\Delta t \leq \frac{1}{\sqrt{\frac{1}{(\Delta x)^2}+\frac{1}{(\Delta y)^2}+\frac{1}{(\Delta z)^2}}}$$

Where,

c=speed of light in free space

Δx, Δy, and Δz are cell size of x, y, and z direction respectively.

In general, length of cell size is set less than 1/10 of the wavelength of the maximum frequency and cell size should not make much smaller than the Nyquist sampling limit, $\lambda=2\Delta s$.

After the selecting space step, time step can be computed using following equation [17].

$$\Delta t = \Delta s\sqrt{\frac{\mu\epsilon}{3}}(1-\alpha)$$

Here,

α is small positive value, <1, specified by a user in order to prevent instability of the numerical integration due to rounding of error.

Thin wire conductors [23], [24], which is one of the most fundamental components in surge analysis to represent power lines, steel frames, etc. have been considered in this paper having smaller diameter than the cell size.

The Engineering model that represents a return stroke channel has been adopted for lightning. The propagation velocity of the return stroke influences emitted electromagnetic field and has significant influence on the induced voltage on the lines. This parameter should be designed perfectly to ensure proper evaluation. In this paper, propagation velocity of subsequent return stroke lightning current is set to 1/3 of the speed of light.

The current waveform injected at the channel base i(0, t) of ground-initiated lightning return stroke is adopted from the analytical expression of ref. [25].

$$i(0,t) = \frac{I_0}{\eta}\frac{(t/\tau_1)^n}{1+(t/\tau_1)^n}\exp\left(-\frac{t}{\tau_2}\right) \quad (1)$$

Where,

$$\eta = \exp\left[-\left(\frac{\tau_1}{\tau_2}\right)\left(\frac{n\tau_2}{\tau_1}\right)^{\left(\frac{1}{n}\right)}\right] \quad (2)$$

I_0 = Amplitude of the channel-base current

τ_1 = Front time constant

τ_2 = Decay time constant

η = Amplitude correction factor

n = Exponent (2 ... 10)

The sum of two functions given in Eq. (1) was chosen so as to obtain the overall wave shape of the current as observed in typical experimental results.

The current waveform used in the simulation is represented in Fig. 1. The injection current waveform uses the model of subsequent lightning waveform recommended by IEC standard [26].

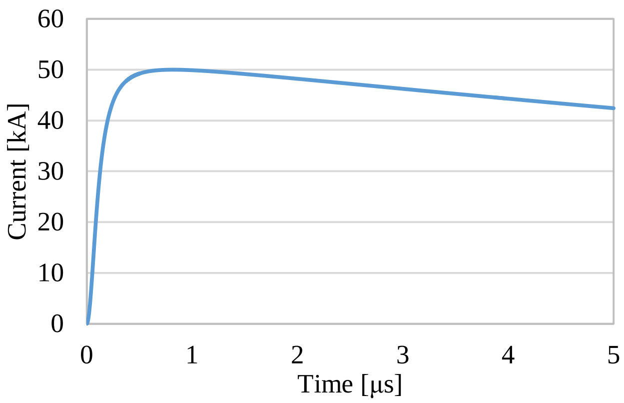


Fig. 1. Injection current waveform recommended for subsequent return stroke current, 0.25µs front time

3. Simulation modeling of solar power system

The indirect lightning induced phenomena on solar power system were performed with the modeling of its components; which is shown in Fig. 2 and 3, solar frame model had the width of 3m, height of 2.5m, length of 20m, and depth of grounding rods is 0.5m. In this model, panel wiring has been considered with an equivalent cell resistance of 2Ω connected in series. Power conditioning subsystem (PCS) is placed 13m away from the panel frame and is connected to the solar panel using the 25m DC line. DC wires are set in air with an insulation of 0.1m thickness and relative permittivity 3, at a height of 0.1m above the ground, and are separated by 0.1m distance having end open at the PCS side.

This model has been considered on the base of practically used some of the large solar power system. In this paper, the lightning striking occurrence is assumed at nearby place which is modeled with 10m away from the solar panel and 21m apart from DC line.

In analysis space of VSTL software, the dimension of X, Y, and Z are taken as 35m, 50m, and 30m respectively. The analytic space was divided into 250 (X-direction) × 150 (Y-direction) × 80 (Z-direction) cells to reduce the computational time. Grounding was changed with resistivity 100Ωm, 500Ωm, and 1000Ωm in the space between the XY plane of Z= 0m and Z=10m to observe the effect of it. Liao's second order absorbing boundary condition was set in six planes of analysis space to avoid reflection, i.e. infinite space [27]. The sizes of the cells become gradually larger as they are further away from a point of interest. The size of the cells for analysis space is 10cm; however its ranges vary from 0.1m to 1m. Soil resistivity is kept to 100Ωm with relative permittivity of 10.

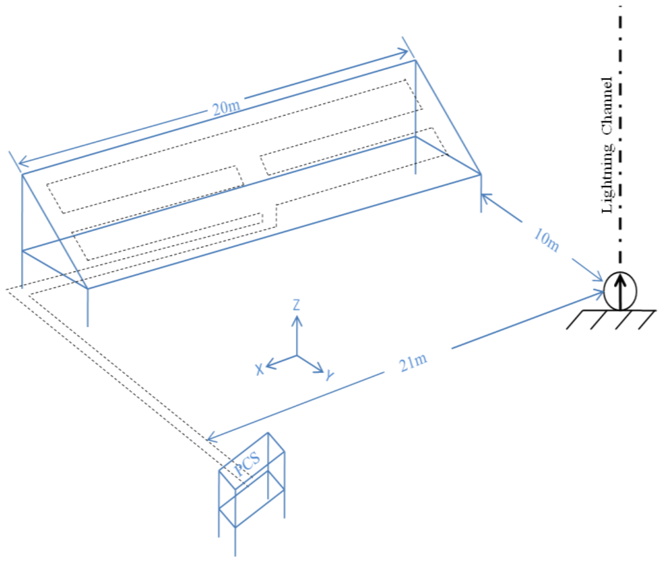


Fig. 2. Modeling of typical solar power system for simulation in VSTL

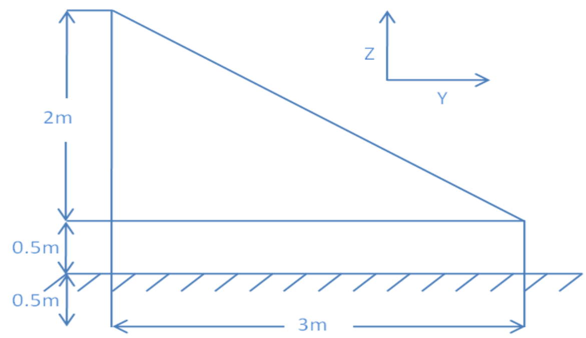
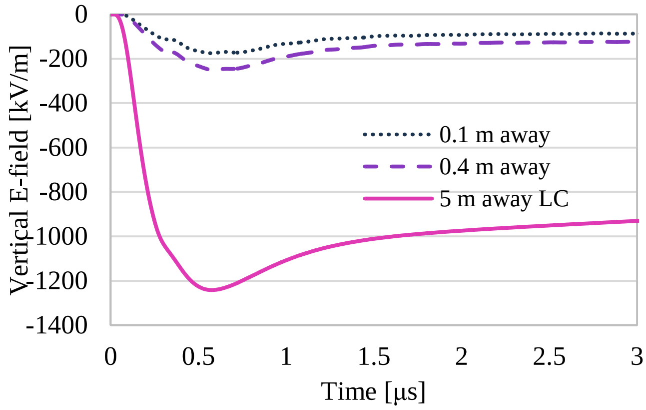


Fig. 3. Side view dimension of solar panel installation

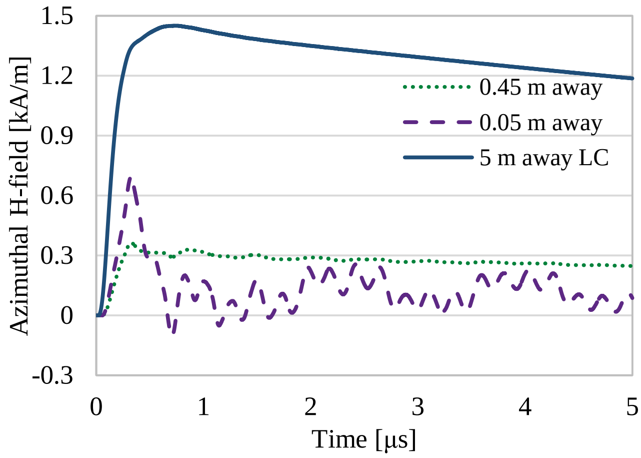
4. Result and discussion

4.1 Effect of ground conductivity

Soil is an important parameter to install the solar panel in commercial purpose, generally solar panels are placed on the ground in a large field; however to operate securely and uninterruptedly, it is necessary to investigate the effect of soil resistivity on solar systems for inducing voltage owing to lightning effect because it has great effect on the system. In our study, we have tried to show what are the effects can come into the account for considering soil parameters.



(a)

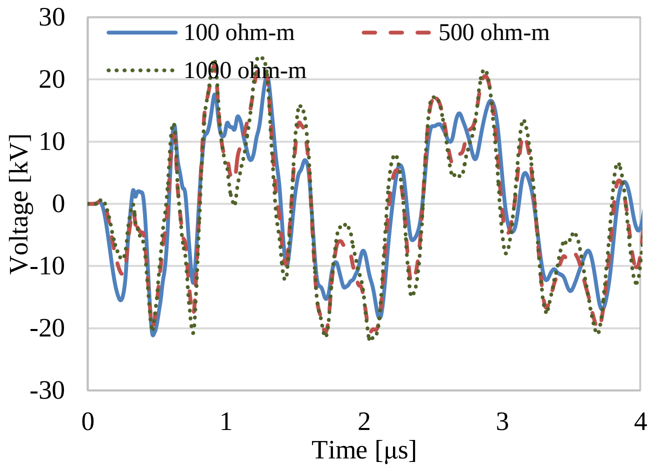


(b)

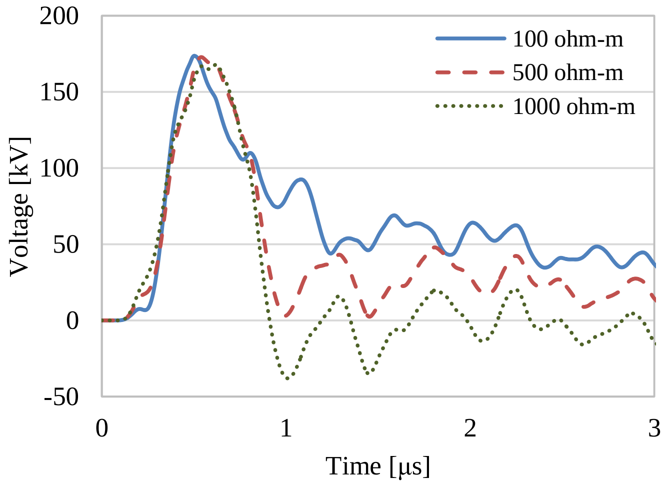
Fig. 4. (a) Vertical electric field and (b) Azimuthal magnetic field distribution along the medium at 100Ωm soil resistivity when lightning strike on ground .

Fig. 4 describes the electric field and magnetic field distribution along the air medium. Here, away and away LC are used to indicate that it is away from the junction box wire and the Lightning Channel (LC) respectively. In Fig. 4 (a) indicates a computed vertical electric field waveform having the peak magnitude 175.09kV/m at 0.58μs near the junction box (0.1m away) of solar panel; and Fig. 4 (b) demonstrations that azimuthal magnetic field, which is near the junction box (0.05m away) and has maximum value 697.48 A/m at 0.33μs, is oscillating (frequency 5MHz) with greater magnitude than the 0.45m away. It is because of interaction between original magnetic field and created magnetic field in the wire during current flow through the wire.

It is seen from Fig. 5 that the induced voltage is fluctuating over the whole range because of the inductive nature of soil parameter which helps to oscillate the signal. There is no noticeable change in magnitude to the Fig. 5 (a), (b), and (c) for different soil resistivity except frame voltage. The maximum frame voltage for 100, 500, and 1000Ωm are 67.19, 146.29, and 172.49kV respectively. The positive and negative values of induced voltage can be described as a soil reflection of electric field where the high resistivity soil provides more reflection of electric field and low resistivity soil provides less reflection of electric field that is why induced voltage in the frame is high at high resistivity and low at low resistivity.



(a)



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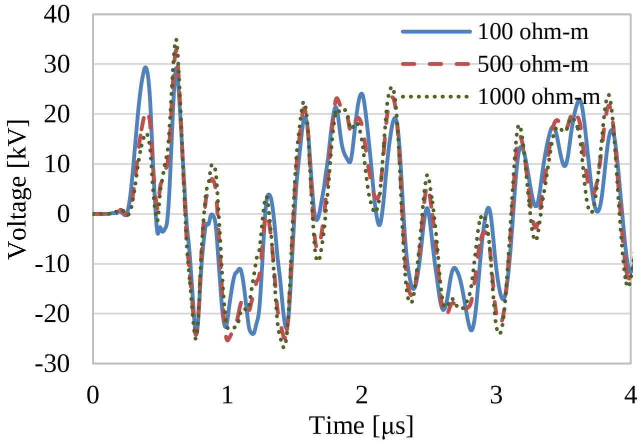
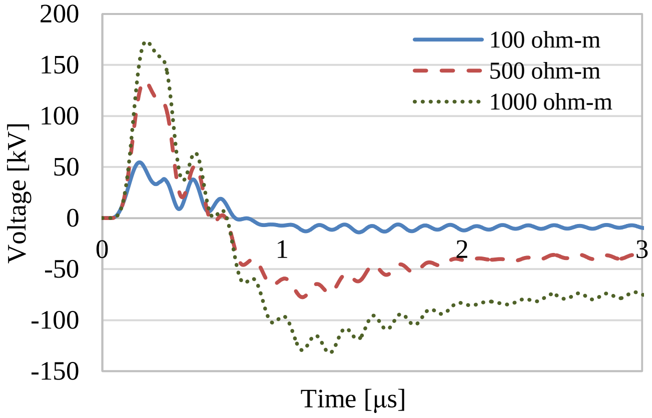


(c)



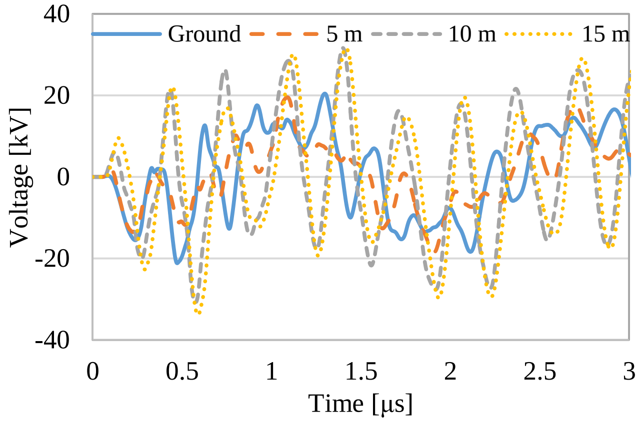
(d)

Fig. 5. The effect of soil resistivity on ground lightning strike upon (a) panel wiring voltage difference, (b) line to ground voltage at PCS side, (c) line to line voltage at PCS side, and (d) frame voltage at the lower part of the front side

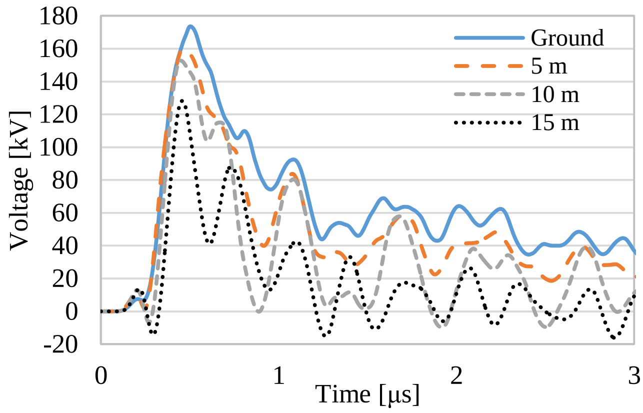
The change of induced voltage magnitude for frame suggests that lower resistivity of soil is preferable and has a less impact on the induced voltage over high resistivity soil. It means that for secure operation and less induced voltage designer should select low resistivity soil to install the solar panel on the ground.

4.2 The Effect of height

In the indirect lightning effect, height is an also important parameter to take into consideration. The knowledge of induced voltage for different height will help the designer to select an apposite place for installing solar panels. In our study, it is shown that the effect of induced voltage at different locations of panel system was studied for different strike heights setting.



(a)



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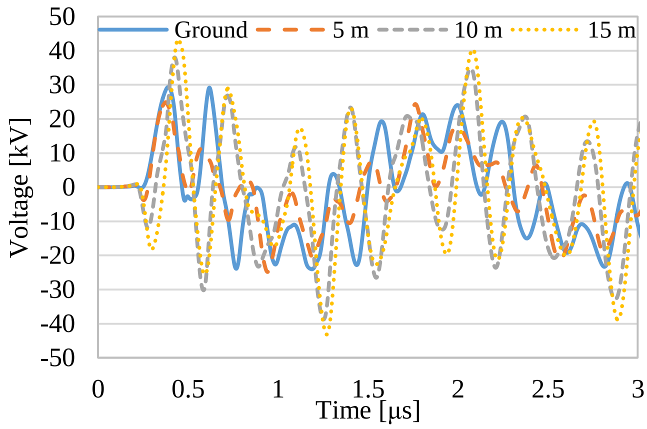

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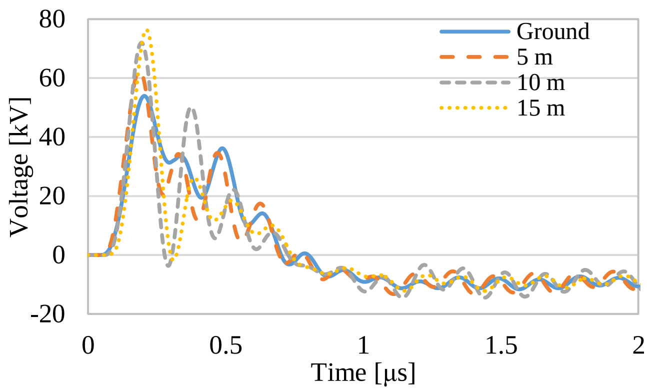

(d)

Fig. 6. The effect of striking height on an object at100Ωm, 10m away from frame upon (a) panel wiring voltage difference, (b) line to ground voltage at PCS side, (c) line to line voltage at PCS side, and (d) frame voltage at lower part of the front side

Fig. 6 (a), (c), and (d) show that with the increasing strike height on an object, induced voltage is also increasing. The maximum induced voltage magnitude for panel wiring occurred at 15m height strike object was 32.6kV at 0.6μs; and minimum induced voltage magnitude is 20.56kV at 0.48μs for ground strike. The line to line and panel wiring induced voltage are same nature except polarity change and magnitude value. The maximum induced voltage occurred at 0.45μs is 43.41kV for line to line voltage where oscillating frequency is 35.71 kHz. It is also observed that frame voltage, whose value increases with height, has a great effect on induced voltage due to rising strike height. The maximum and minimum voltages recorded at 0.2μs were 53.94 and 76.43kV for ground and 15m object height respectively. Oscillating frequency was measured for 5m height is 190 kHz. However, line to ground voltage is different from that of the previous records. It shows that with the mounting strike height its value reduces. The minimum and maximum voltages are 128.2 and 173.65kV at height 15m and ground respectively.

5. Conclusion

The knowledge of induced voltage will aid the designer for the appropriate design of solar power system as well as its set up in a proper way. In our study, we have observed the effect of grounding resistivity and effect of strike height on induced voltage of a solar power system due to nearby lightning phenomena. It is found that panel wiring, line to line voltage, and line to ground voltage have less magnitude different for resistivity variation but induced voltage is more in frame voltage in the case of high resistivity due to absorbing capability of high resistivity is less than low resistivity. We have also observed that the effect of height on induced voltage, in this case voltage is increasing with increasing strike height of the object except the line to ground voltage.

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