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Overvoltages in Photovoltaic Systems Induced by Lightning Strikes

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***Abstract*— The high number of photovoltaic systems raises questions regarding their operational security even under extremely weather conditions like thunderstorms. Therefore a simplified model of a photovoltaic system, consisting of typical arrangement of solar-panels, was investigated. The influence of lightning strike was simulated by different lightning current shapes and striking points into the solar-panels. It was found, that besides the construction size and shape of the lightning current the striking point has a main influence on the value of induced overvoltages, occurring on the connection point of the solar-panels. The simulation results were confirmed by measurement with an impulse current. The results demonstrate the dangerousness of lightning currents with very fast rise time e.g. subsequent impulse as well as the reducing of induced overvoltages by an appropriate earthing connection. This has to be considered at the design of the lightning protection system.**

Keywords-Surge protection; photovoltaic system; induction; computer simulation

I. INTRODUCTION

The increasing number of photovoltaic systems raises questions regarding their operational security and safety, particularly under extremely weather conditions like thunderstorms. A typical photovoltaic system consists of a metallic support construction, mostly Aluminium profiles, which is grounded by pillars and covered with solar panels. The solar panels are usually connected in series or parallel strings, with their ends connected to a DC/AC Inverter. It is the basic aim of a lightning protection system for PV -systems to prevent any partial lightning current flowing within the PV - system. In a system equipped with an insulted LPS only the induction effects due to lightning electromagnetic impulses (LEMP) have to be considered. If this requirements are fulfilled it is sufficient to install Class II tested SPDs, on the DC side of the PV -generator. The magnetic field H created by the lightning currents flowing in the neighboring LPS may induce considerable voltages in any conductor loop, which results in corresponding impulse currents if these conductor loops are closed [1].

If the grounded pillar construction is connected directly to the lightning protection system, such as a metallic rod, direct lightning currents flow into the grounded metallic construction. Depending on the point of strike, the maximum impulse current and the earthing resistance there is a possible risk that the voltage drop along the PV-module mounting system and the voltage rise at the earth termination system create a potential difference between the PV-modules and the DC cables which exceed the impulse voltage withstand of this equipment. In this case there is a possible risk that partial lightning currents are flowing into the DC system due to uncontrolled flashovers.

Assuming that due to the lightning current distribution in the metal construction and a low ohmic and intermeshed earth termination system the voltage between the metal parts of the PV-mounting system and the isolated electrical equipment is below the impulse voltage withstand still high induced over-voltages in the solar panels occur. For the determination of exact values resulting from such effects, a simple model was investigated. It could be shown, that under certain conditions significant values of overvoltages must be taken into account.

II. BASIC ASSUMPTIONS

The typical photovoltaic system to be investigated was modeled by a metallic pillar construction and a layer of solar panels covering the supporting construction. The construction consisted of a lattice of Aluminium profiles, grounded by pillars. Especially with PV –plants, pile-driven solar mounting systems are very common as it is often an economical solution. In this case the pile-driven supports are often also used as earth-termination electrodes for the PV -generator. The impulse earth resistance of such a pile-driven support is described in [1]. The layer of solar panels was placed with a predetermined (vertical) distance to the construction (Fig. 1).

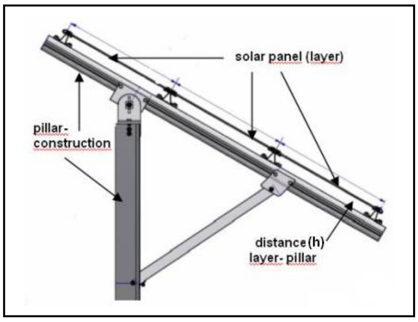


Figure 1. Principle pillar construction and panel layer

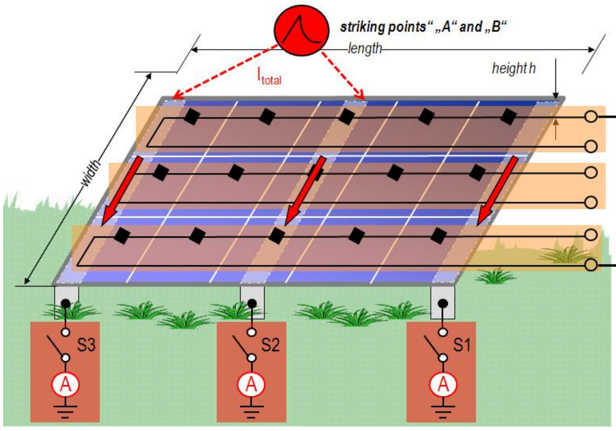


Figure 2. Basic model for simulation

It was assumed, that lightning strikes the grounded metallic pillar construction in different ways (see "striking points"). In every case the lightning current will be distributed into the lattice of Aluminium profiles according to their construction, the "striking point" and the grounded pillars. The magnetic field caused by this current effects the solar panel table, which is located a certain distance h from the Aluminium profile lattice. For the induced overvoltages two parameters are of importance: the magnetic flux and the time derivation of the current. In addition to the current profile, the value of magnetic flux is determined by the given panel structure and their inner conductive paths. For the investigation a structure of 3 parallel strings with 5 serial connected panels for each of them was assumed "Fig. 2". To simulate the lightning stroke, a current function according to [2] was assumed (values η, τ_1 a τ_2 are given in the following table).

$$i(t) = \frac{1}{\eta} \frac{\left(t\,\tau_1^{-1}\right)^{10}}{\left(1+\left(t\,\tau_1^{-1}\right)^{10}\right)} e^{-\frac{t}{\tau 2}} \quad (1)$$

τ1/τ2	(10/350)µs	(0.25/100)µs
η	0.93	0.993
τ1	19.0 µs	0.454 µs
τ2	485 µs	143 µs

The maximum values of lightning currents were taken in according with the standardized lightning protection levels of up to 200 kA for the first positive impulse 10/350 µs and 50 kA for the subsequent impulse 0.25/100 µs respectively [3].

III. Simulation Model and Procedures

For the modeling of Aluminium lattice structure an adequate topology model was assumed, whereby the different "striking points" are represented by the nodes (A, B) and the grounded pillars by (E1 – E3) (see Fig. 3).

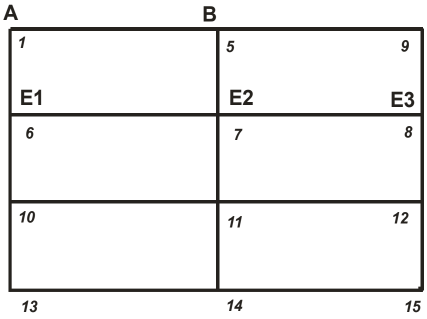


Figure 3. Topology model for Aluminium lattice

For simulation purposes, all electrical parameters of the entire system must be described as precise as possible. The electrical behavior of such a PV-frame can be described by a network of series inductance and resistance connection, taking into account the actual number and dimensions of the metallic frame [1].

For determination of induced overvoltages the following procedure steps were carried out:

- Determination of current distribution within the Aluminium lattice depending on the "striking points", grounded points and current value.
- Calculation of the magnetic field within the panel layer and evaluation of the coupled magnetic flux dependent on the panel plane arrangement.
- Calculation of the maximal value of induced over-voltages in conducting loop with regard to its position.

IV. Results

A. *Current distribution in the Aluminium lattice construction*

According to the topology model, an equivalent network was created (see Fig. 4). Based on this model the current distribution could be calculated by a commonly used network simulation program [1], [4], [5].

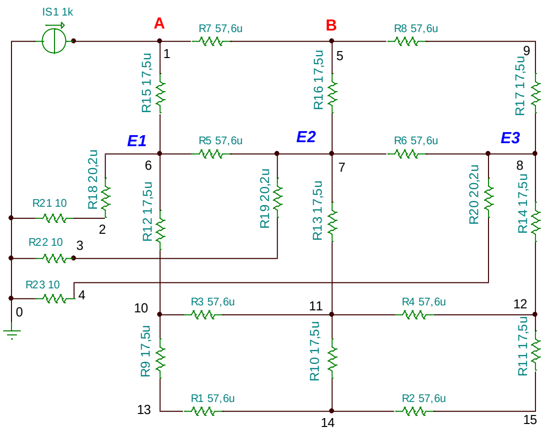


Figure 4. Equivalent resistive network of the Aluminium lattice

It was found out that the current distribution is namely depending on the branch resistance R, the position of "striking point" and the way of ground connections. The branch inductance and value of earth resistance R_E had an insignificant influence.

B. Magnetic field in the panel plane

For the evaluation of magnetic flux coupled with the panel plane at first the magnetic field on this plane has to be calculated. It was carried-out by usage of the Biot-Savart law, the magnetic strength at any point (x, y) generated by current in the *i*-th conductor is given by formula.

$$\mathbf{H}_i\,(x,y) = \frac{I_i}{4\pi}\int_{l_i}\frac{\mathbf{dl}\times\mathbf{r}}{r^3} \tag{2}$$

The result magnetic strength at this point $\mathbf{H}_0$ generated by all N construction conductors induced by striking current I_0 = 1 kA is given by the sum.

$$\mathbf{H}_0\,(x,y) = \sum_{i=1}^{N}\mathbf{H}_i(x,y) \tag{3}$$

The evaluation of eq. (2) was carried-out numerically. The current in thin conductor has been supposed in eq. (2), the calculation error caused by this assumption is insignificant outside of profile construction conductor. It can be proved by the graph on Fig. 5, where the magnetic field distribution for both, the thin conductor placed at the axis of the profile conductor and the profile conductor was compared.

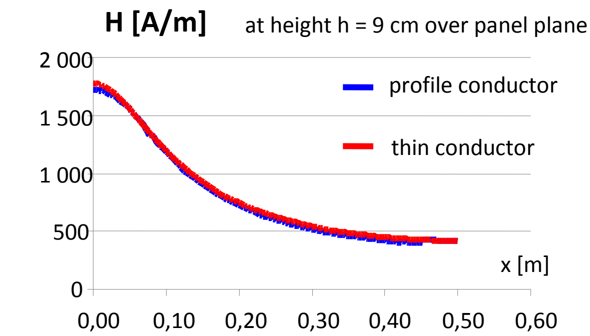


Figure 5. Comparison of magnetic field distribution

The magnetic field distribution on the panel plane placed at the height h = 0,09 m above construction axis was evaluated. On Fig. 6 is depicted the distribution for the "striking point" A, it is seen that the strongest field is near to the point A and the distribution is very asymmetric.

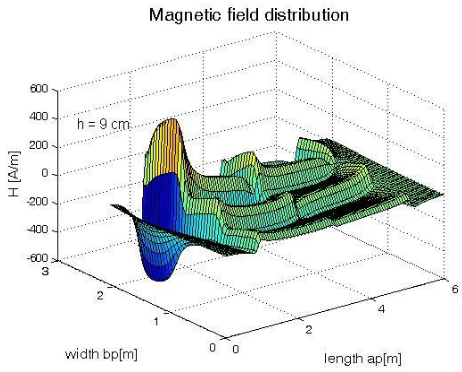


Figure 6. Magnetic field in the case of "striking point" A

The magnetic field distribution for the "striking point" B is shown on Fig. 7. In this case the distribution is more symmetric and the peak values of strength H are a little lower. This fact has a significant influence on the summarized magnetic flux and, in the same manner, on the value of the induced over-voltages as described below.

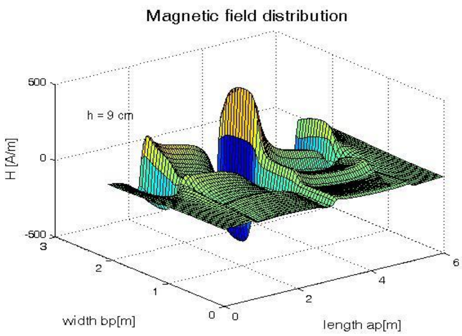


Figure 7. Magnetic field in the case of "striking point" B

To evaluate the magnetic flux coupled with conductive structure of solar panel it is necessary to determine magnetic flux density **B** at any point of the panel plane with regard to the real maximal current value $I_{\max}$ according to the standard lightning stroke peak value. It can be done by following formula.

$$\mathbf{B}\,(x,y) = \mu_0\,\mathbf{H}\,(x,y) = \mu_0\,\frac{I_{\max}}{I_0}\,\mathbf{H}_0\,(x,y) \tag{4}$$

C. Induced over-voltages in the panel plane

The induced over-voltages which can be dangerous for the invertor depends on the magnetic flux coupled with conductive loops in the panel plane. According to the structure of the panel plane (see Fig. 1) a loop area for each panel string was assumed (see Fig. 8). Various colours were used in order to distinguish each row of panels. The length a = 6 m and the width c = 0.05 resp. 0.5 m of each loop was considered.

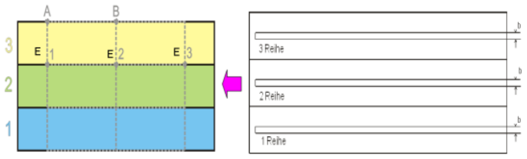


Figure 8. Assumed loop areas for determining the magnetic flux

The magnetic flux coupled with the above described areas was evaluated according to formula.

$$\Phi = \iint_S \mathbf{B}\, d\mathbf{S} \cong \sum_j \sum_k \mathbf{B}_{j,k}\, \Delta\mathbf{S} \tag{5}$$

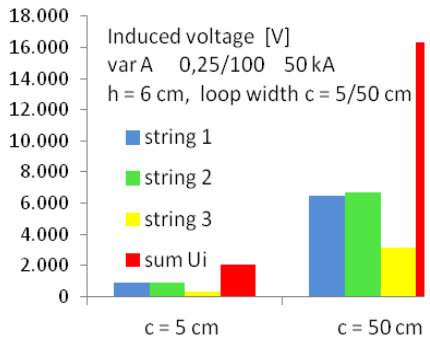
Where $\mathbf{B}_{j,k}$ is the magnetic flux density at the centre of the element j,k and ΔS is the size of this element. Using the formulas (4) and (5) the values of Φ were determined for the lightning strikes (10/350) µs and (0.25/100) µs respectively in each loop.

Following calculation of the magnetic flux, the induced voltage was evaluated by Faraday's formula.

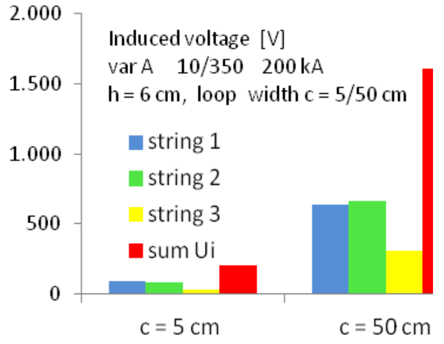
$$u_i = -\frac{d\Phi}{dt} \tag{6}$$

It was assumed, that the loop operates in an "open circuit" regime and the inner connections or components such as bypass diodes or other components were not considered. In this case the "worst case" maximum induced voltage will be obtained.

As expected, a major influence on the induced voltage is the current rise time. Despite the higher maximum value 200 kA for the first positive impulse 10/350 µs, in the case of a subsequent impulse 0.25/100 µs – 50 kA) the induced voltage is significantly higher (see Fig. 9 a,b). There is seen not only the induced voltage in each panel string but their sum as well. The evaluation was carried out for the distance panel plane h = 6 cm from conductor axis.



a) induced voltage for 0.25/100 µs



b) induced voltage for 10/350 µs

Figure 9. a,b) Induced voltage for various lightning strikes at point A

It can also be seen that in the brighter loop (c = 0.5 m comparing with c = 0.05 m) the induced voltages is much higher. In this case maximum values can reach of more than 10 kV.

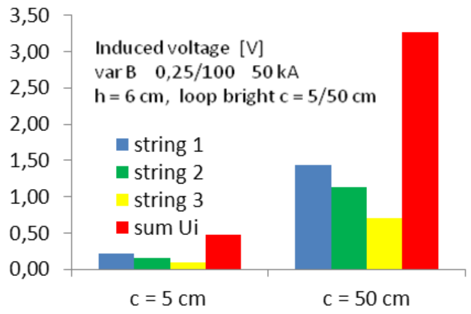


Figure 10. Induced voltage for striking point B

Very significant influence for induced voltages is given by the "striking point". Having the same conditional parameters, but another "striking point", very different results could be obtained. On Fig. 10 the results for striking point B are given. Despite of similar values of magnetic field (see Fig. 7), the magnetic flux and, in same manner the induced voltage, will be approximately compensated. This means that the induced voltage on the loops output is relatively small and could be neglected, even for the subsequent impulse 0.25/100 µs.

V. Measurement

To verify the above described algorithm for analysis of inductive coupling between support-construction and panel plane respectively conductive loop connection the output of solar panel and inverter some measurement on the simplified model was carried out. The support-construction was modeled by three horizontal and six vertical Aluminium-bars (see Fig. 11).

Figure 11. Construction model for measurement with conductive loop placed at the upper position

The voltage induced by lightning strike into the support construction was measured on the open end of the conductive loop which was placed either in the lower area or in the upper one of the panel plane (see Fig. 11). The measurement was performed by a standard impulse current 8/20 µs (50 kA) which was applied either at the point A or B (similar to Fig. 3). Two manners of grounding were considered (at the middle node of the lowest conductor or at all three nodes). Many test measurements were done and the same configurations were analyzed numerically by the above described procedure. The comparison of some results, given in the Table I, shows a sufficient agreement between the measured and the calculated values.

TABLE I. Comparison of measured and calculated results

I_{max} = 50 kA	**at point A**				**at point A**		
grounding	**middle node is grounded**				**three nodes are grounded**		
loop position	lower		upper		lower		upper
d [cm]	0	15	0	15	0	15	15
U meas [V]	100	130	80	110	140	185	130
U calc [V]	107	120	73	100	130	183	130

It was found, that the peak value of induced voltage strongly depends not only on the rise time of the lightning current, but also on the local position of loop's ending[1] related to the axis of the support-construction A1-bars (the loop ending position at distance *d* = 0 and *d* = 15 cm from the bar axis was considered).

If the loops ends over the bar-axis (d = 0, symmetrical position) the induced voltage is smaller in comparison with the case of asymmetrical position (d = 15 cm). In the asymmetrical case the magnetic field in this area is not fully compensated and its contribution to the whole magnetic flux is higher (see Tab. 1). The comparison of the measured and calculated results of all these effects demonstrates the validity of the developed model and the performed procedure. Using this model including the proposed procedure the maximum values of voltage induced by other shapes of lightning strikes respectively in other panel configurations could be estimated.

VI. Summary

Modeling a typical photovoltaic system with a grounded pillar construction covered by solar panels the influence of lightning strikes was investigated. It was found out, that the construction arrangement and the lightning parameter (shape, peak value and the rate of current rise) have a significant influence on induced over-voltages. Very important is especially the position of "striking point". To estimate the peak value of induced voltage it is necessary to evaluate the current distribution within the pillar construction, the distribution of the magnetic field within the panel plane and the effective magnetic flux coupled with a conductive loop within the panel strings. The rise time of the lightning current has a major influence on the value of the induced voltages. If assumed a subsequent impulse 0.25/100 µs even with a lower maximal current value of 50 kA, the over-voltages occurring are significantly higher than in the case of the first positive impulse 10/350 µs even with a higher maximal current value of 200 kA. Despite the influence of the lightning current parameters, the induced voltages are higher if the "striking point" is asymmetrical to the panel plane configuration e.g. edges. If the "striking point" more central to the configuration, then the induced voltages will be practically compensated and can be neglected. This behavior has significant practical consequences with regard to the placement of lightning protection for photovoltaic systems.

References

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[3] IEC 62305 Ed. 2 : 2010 Protection against lightning.

[4] Network-calculation-programm TINA, ZCU Pilsen (2010).

[5] J.Birkl, P. Zahlmann, "Lightning currents in low-voltage installations", in Proc. 29th ICLP, Uppsalla, Sweden, 2008.

[1] the loop's ending is practically the connecting place of the panel to the inverter