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(Article)

Assessment of the Impact of Double-Peaked Lightning Strikes on PV Farms

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ABSTRACT

The extension of PV farms across large terrain exposed to hazardous climatic conditions has threatened their reliable performance as a renewable energy source. One of those major threats to PV farms is lightning strikes. In this paper, a PV system was subjected to double-peaked lightning strikes that were based on real-life recordings of lightning cases. The system was modeled using PSCAD software. The main contribution of this paper is the inclusion of double-peaked lightning strikes rather than regular single-peaked strikes usually used in lightning impact studies. In addition to that, the study relies on real-life recordings for lightning strike events at Mount San Salvatore and Morro do Cachimbo stations. The simulation results for both recorded double-peaked strikes showed the ability of the surge protection devices to provide adequate protection levels for the PV farm against these strikes in terms of their ability to withstand the overvoltage and absorb the energy injected with the strikes.

Keywords: double peaked lightning strikes; PV farm; surge protection.

1. Introduction

Renewable energy sources play a vital role in modem power systems. The selection of a proper energy source depends on the location and weather conditions. The methodology used for that selection depends on systematically analyzing the weather conditions within a specified location. Solar Photovoltaic (PV) farms have emerged as one of the most widely employed renewable energy sources. That has led researchers to investigate their performance widely and contribute to their advancements [1 – 8]. However, their extension over the large exposed area has exposed them to the hazards of climatic conditions, including lightning strikes [9 – 13]. The impact of lightning strikes on PV farms varied depending on the type of strikes [14 – 17]. Direct strikes have been shown to impose a higher risk level on the PV farm in comparison to indirect strikes [18, 19]. One of the most important aspects in studying the impact of lightning strikes is the consideration of realistic representation of the lightning strikes. On such a way, measurements of recorded lightning strikes were modeled in [17]. The recorded lightning strikes differed from the regular impulse curve usually employed in literature [14 – 16, 18 – 20]. However, the realistic records for lightning strikes in [17] had shown the formation of double peaks in the strike. Recently, researchers have been attracted to the study of the impact of these double peaked strikes upon protection systems of different types of renewable resources [21 – 23].

The presence of double-peaked lightning strikes imposes an increased threat in terms of the increased voltage levels for those peaks and the increased amount of the injected energy of such strikes. On the other hand, PV farms are located in open areas that are subject to the threat of these double-peaked strikes. The increased amount of energy injected within the strike would impose a real threat to the protection system of the PV farm. Therefore, it is highly advantageous to study the impact of double-peaked strikes upon PV to ensure their protection. Further, double-peak strikes would inject more energy into the system than single-peak strikes.

Meanwhile, single peak strikes with higher would result in higher overvoltages. So, it could be summarized that for double peaks, the main concern would be the amount of energy injected while for single peaks, it would be the magnitude of the overvoltages. For this reason, the main problem this paper deals with is investigating the impact of double-peaked lightning strikes upon PV systems. The main contributions of this paper are:

1. Investigation of the impact of realistically recorded double peaked lightning strikes on PV farms.
2. Consideration of the increased injected energy upon the protection systems of PV farms.

The rest of this paper is organized in the following order. Section 2 describes the modeling process for double-peaked lightning strikes using PSCAD software. Section 3 presents the modeling process for the PV farm. Results of the simulation process for the impact of double-peaked lightning strikes upon the studied PV system are presented in section 4. Finally, the conclusion is presented in section 5.

2. Modeling of Double Peaked Lightning Strikes

The modeled representation of a randomization phenomenon such as lightning strikes has always been challenging for the research field. It has been customarily modeled as an injected current source at the strike point in the network such that the current waveform is considered an impulse. The Heidler function has been considered one of the most used functions to model lightning strikes [15, 18 - 20]. The numerical form of the impulse function, according to Heidler, is given in (1) & (2).

$$i(t) = \frac{I_o}{\eta} \cdot \frac{(t/\tau_1)^n}{1 + (t/\tau_1)^n} \exp(-\, t/\tau_2) \tag{1}$$

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

where I_o is the peak value of the lightning strike; τ_1 is the rise time of the impulse, τ_2 is the tail time of the impulse, η is the correction factor for the magnitude of the peak impulse, and n is the exponent factor. To model the Heidler function on PSCAD software, numerical and mathematical blocks are considered, as shown in Figure 1.

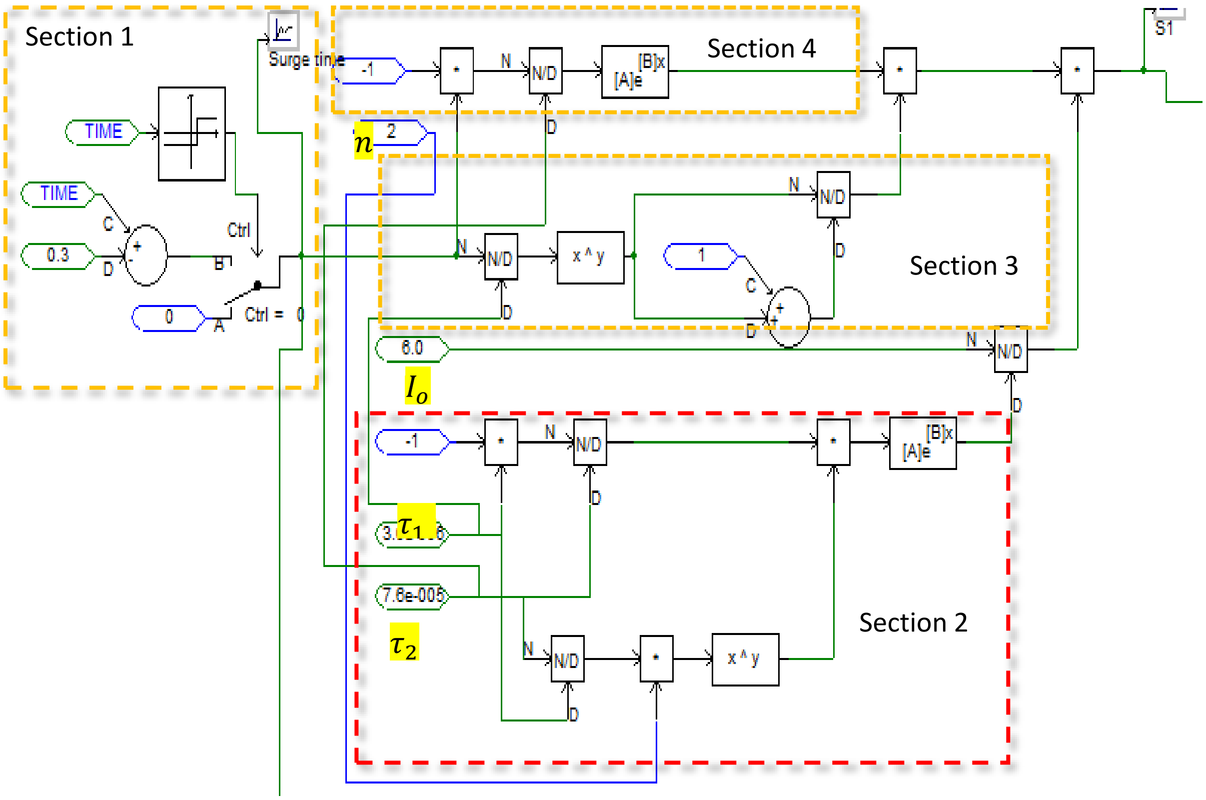

Figure 1. PSCAD model for Heidler function.

The modeling of the Heidler function shown in Figure 1 is subdivided into four sections to allow an easier understanding of its flow of operations. The flow of each section is explained as follows:

- **Section 1**: allows the extraction of the time domain from the PSCAD software during the simulation. The block "time" inheritably injects the timing instant of the simulation. However, it should be noted that the function is built such that the impulse starts at zero time instant. Therefore, any delay at the instant of the lightning strike is inserted by subtracting the value of that instant from the time block.
- **Section 2**: computes the correction factor η according to (2). At the first row of section 2, τ_1 is multiplied by -1 constant and then divided by τ_2 using N/D block. At the second row τ_2 is multiplied by n and then divided by τ_1. The results of both

rows are multiplied together, and their exponential value is computed using the "A(x)eB(x))" block. The obtained result is η.

- **Section 3**: The $\frac{(t/\tau_1)^n}{1+(t/\tau_1)^n}$ part of (1) is computed. At the first part of this section, the time dimension 't" is taken from section 1 and then divided by τ_1 and the results is powered to the value n using x^y block. Following that, two lines are taken; the lower line adds constant 1 to the computed $(t/\tau_1)^n$ Computed in the previous part. While the upper line divides the first part $(t/\tau_1)^n$ to that from the lower line $1+(t/\tau_1)^n$ and the result is the part required from this section.
- **Section 4**: computes the exponential part from (1)

Finally, the results of sections 3 and 4 are multiplied together by I_o divided by the correction factor from section 2. The final result is the impulse Heidler function. The values of $I_o, \tau_1, \tau_2$and n have been the main parameters defining the impulse function. In this study, real value based on recordings from actual lightning strokes is used. The recorded lightning strikes have shown a major difference from regular single-impulse lightning in terms of having two peaks and a non-uniform impulse shape. Two main double-peaked strikes are employed in this study; one was recorded in reality at Mount San Salvatore (MSS), and the second one was recorded at Morro do Cachimbo (MCS) station. To model each of those double-peaked strikes, a superposition of seven impulses whose parameters are given in Table 1 according to [17].

Table 1: Parameters of MCS and MSS lightning strikes

Curve #	Recorded at MSS				Recorded at MCS			
	I_P (kA)	n	τ_1 (μs)	τ_2 (μs)	I_P (kA)	n	τ_1 (μs)	τ_2 (μs)
1	3	2	3	76	6	2	3	76
2	4.5	3	3.5	25	5	3	3.5	10
3	3	5	5.2	20	5	5	4.8	30
4	3.8	7	6	60	8	9	6	26
5	13.6	44	7.6	60	16.5	30	7	23.2
6	11	2	100	600	17	2	70	200
7	5.7	15	11.7	48.5	12	14	12	26

The parameters for MCS double-peaked lightning strikes were created from the values in Table 1 and applied to the model shown in Figure 1 for each signal of the seven signals. The representation of each impulse signal of the MCS is shown in Figure 2. The superposition of these signals is presented in Figure 3, which is the double-peaked MCS lightning strike. The same procedure could be used for an MSS double-peaked lightning strike.

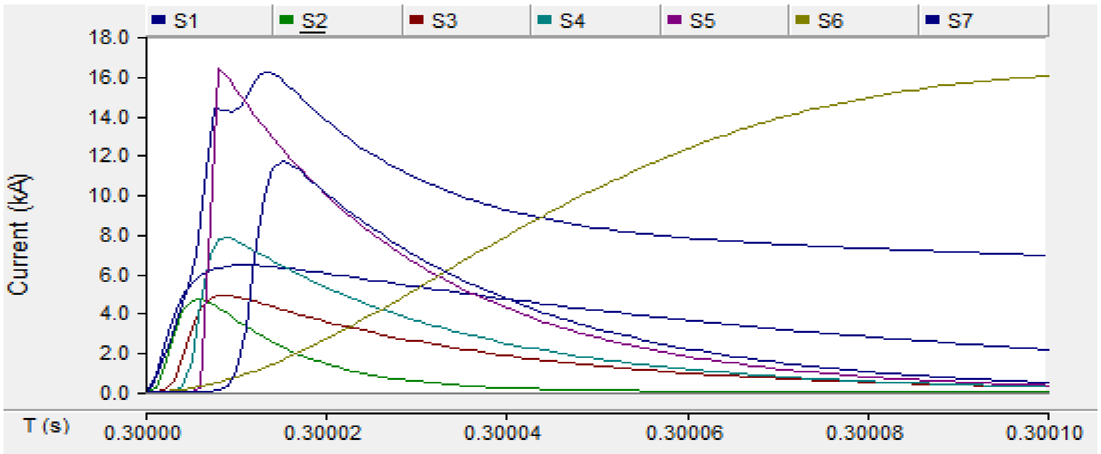

Figure 2. Seven impulse signals of MCS represented separately.

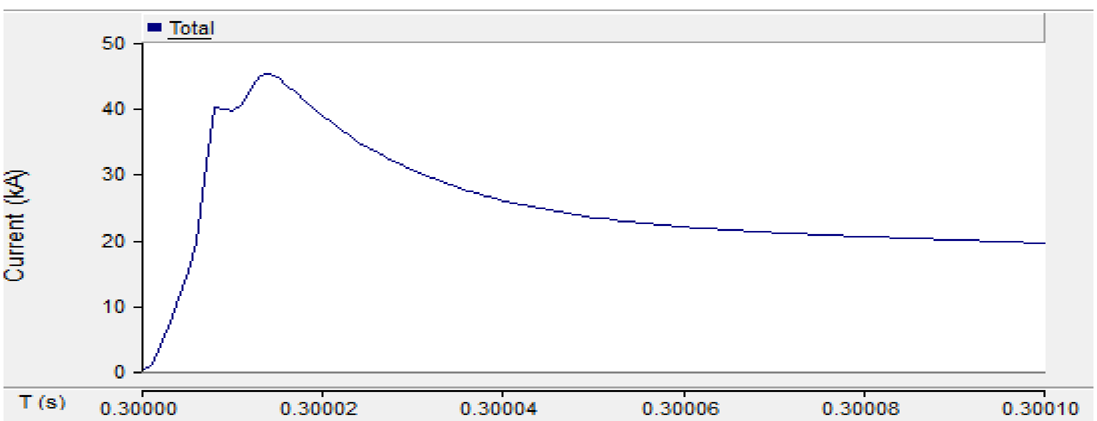

Figure 3. MCS function.

3. Modeling of the testing system

The testing system consists of a 0.4 MW PV farm and a 365 kW three-phase load bank connected to a 0.48 kV bus, as shown in Figure 4, and their data, as introduced in [24]. The 0.48 kV bus is connected to a 33 kV electrical grid through a three-phase 0.480 kV/33 kV transformer. The PV farm consists of two hundred and fifteen parallel strings, each with twenty-two series modules. The PV array was modeled using the PV-Source component available within the PSCAD library, as shown in Figure 5. The PV array is connected to the inverter through a 7800 μF capacitor. A distribution board connects The inverter to a 0.480 kV AC bus. PV modules are operated at a fixed temperature of 25 °C and 1000 W/m² irradiation level. Surge protection devices (SPDs)were inserted to protect the PV farm at the shown locations with their specifications, as mentioned in [18]. The SPD at the DC side of the PV farm was selected at 0.85 kV with a protection level of 4.2 kV according to the datasheet in [25], and the energy absorption capability of SPD of 2.98 kJ according to the IEC 60099-4 Ed 3.0-2014 [26].

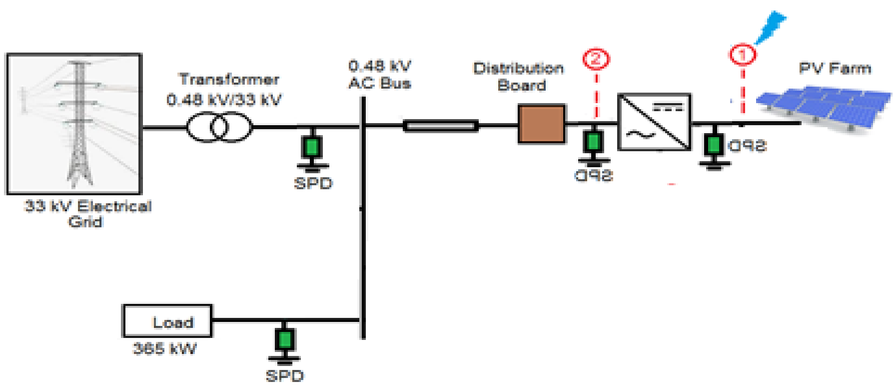

Figure 4. Single-line diagram of the testing system.

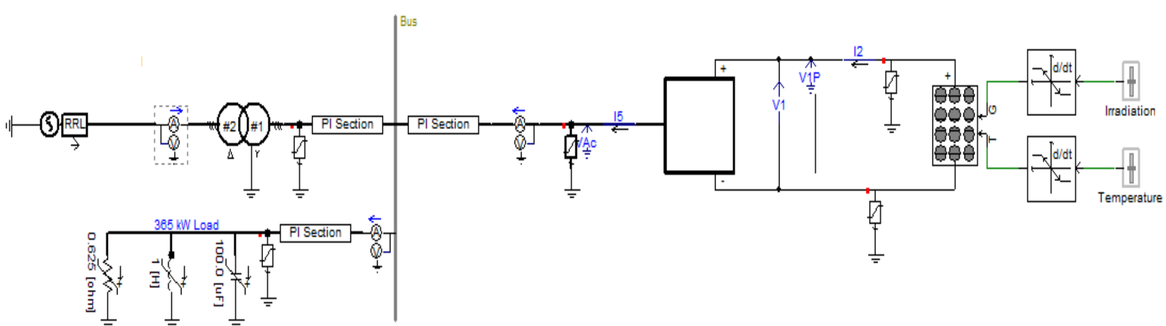

Figure 5. PSCAD model of the PV system.

4. Results and Discussion

To investigate the impact of double-peaked lightning impulses upon PV systems, MCS and MSS strikes were applied at DC side of PV farm as shown in Figure 4. The results of each case are detailed in the following sections.

4.1 MSS Lightning Strike

The MSS impulse was applied to the DC side of the PV farm, as shown in Figure 4, at an instant of 0.3 s of simulation time. The simulation assumed that the strikes occurred on 23 of January 2023 at 3 a.m. The simulation duration was 0.5 seconds. The voltages and currents at the DC and AC sides of the PV farm are shown in Figures 6 and 7, respectively. It can be seen from the figure that the voltages did not exceed 1.5 kV, which is far below the protection level of SPD. The energy induced at SPDs located at the DC side at positive and negative poles are shown in Figure 8. The injected energy is still below the energy absorption capability of the SPD. Even though the data of the double peak strikes are based on real measurements and cannot be changed, some conclusions could be made analytically. Extending the time between the two peaks would lead to loner duration of the entire strike and higher energy amount to be injected. Changing the relative values between the two peaks would also increase the amount of the injected energy and threaten the protective devices.

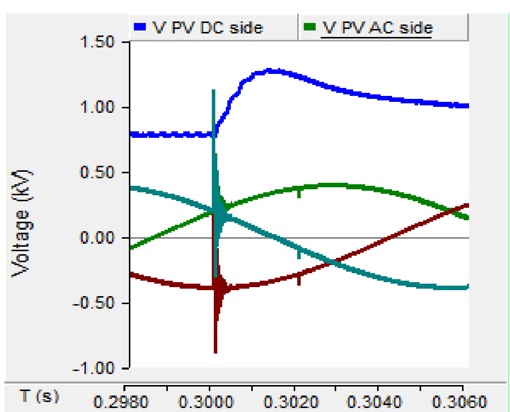

Figure 6. DC and AC side voltages of the PV farm during MSS strike.

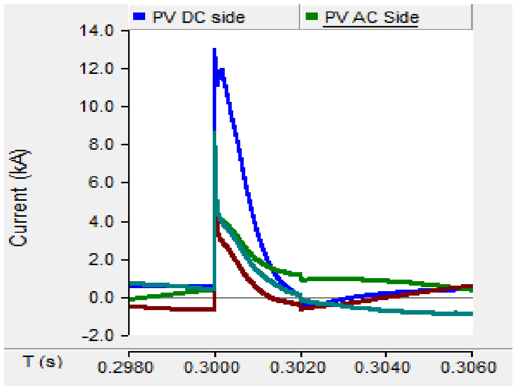

Figure 7. DC and AC side currents of the PV farm during MSS strike.

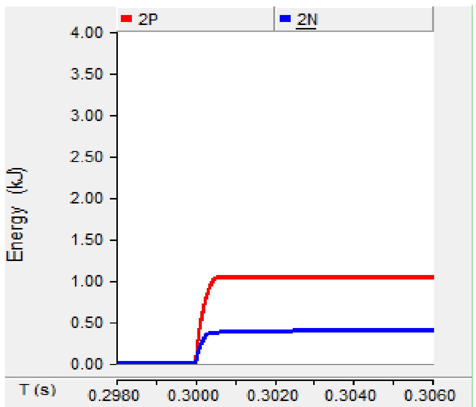

Figure 8. Injected energy to SPDs during MSS strike.

4.2 MCS Lightning Strike

In the same manner as the earlier test, the MCS impulse was applied to the DC side of the PV farm at an instant of 0.3 s of simulation time. The voltages and currents at the DC side and AC side of the PV farm, in addition to the injected energy to SPDs, are shown in Figures 9, 10, and 11, respectively. It could be seen from the figures that the voltages did not exceed the protection level of SPD. Also, the energy injected at SPDs was still below the energy absorption capability of the SPD.

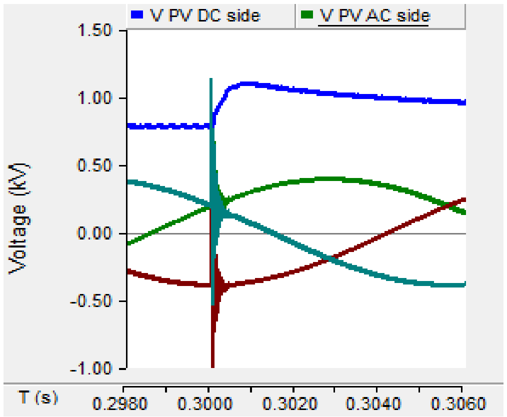

Figure 9. DC and AC side voltages of the PV farm during MCS strike.

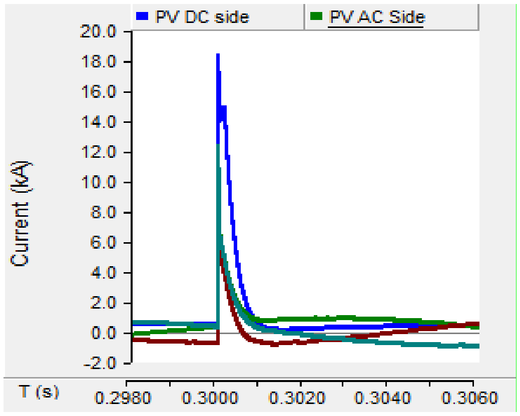

Figure 10. DC and AC side currents of the PV farm during MCS strike.

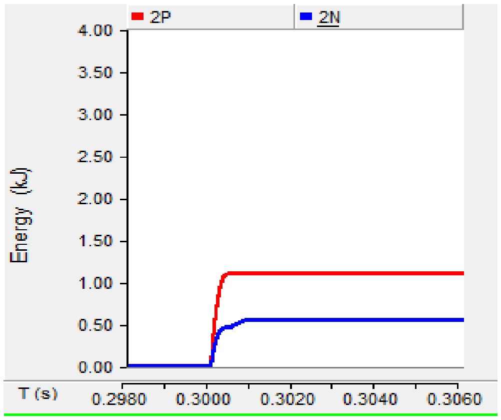

Figure 11. Injected energy to SPDs during MSS strike.

4. Conclusion

The increased reliance on renewable energy sources in power systems has increased the focus on their protection systems. In this paper, a PV system was modeled using PSCAD software. The system was subjected to double-peaked lightning strikes based on realistic measures at MSS and MCS stations. The results included the subsequent current, voltage, and energy injected following the lightning strike. The results showed the success of the SPDs in ensuring the protection of the PV farm during double-peaking lightning strikes.

- **Conflict of Interest**

The author declares that there is no conflict of interest.

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