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On the Effect of Surge Protection Devices (SPDs) Placement for Grid-connected Solar PV Farm

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***Abstract*—The solar PV farm is expected to gain greater popularity in Malaysia as an alternative energy source. Malaysia lies in the tropics and enjoys abundant sunlight, but is also prone to frequent lightning strikes. The solar PV farm is at great risk of being struck by lightning because of its location and installation in an open and flat area. Due to the high cost of maintaining the solar PV farm, a suitable lightning protection system should be installed to avoid or minimise the potential damage. Hence, the objective of this study is to offer a basic reference for the installation of a surge protection device (SPD) for a proper location according to the standard.**

Keywords-solar PV farm; lightning current waveshape; transient voltage; transient current; SPD; cable length.

I. Introduction

Malaysia is moving towards renewable energy sources for generating electricity due to diminishing limited fossil fuels and also because of growing concern about environmental problems like acid rain, greenhouse effect and ozone layer depletion [1]. In Malaysia, the solar PV system is seen to surpass all other renewable energy options because of high daily radiation and high number of sunny days in most parts of the country [2, 3].

Unfortunately, Malaysia is also highly exposed to lightning events [4] and solar PV system has high possibility of being struck by lightning because of installation in a wide open areas. The lightning strike will cause sustained damage and meltdown or fracture of the electronic components of the solar PV farm [5, 6]. Ultimately this leads to high cost of repair and replacement of the damage components.

In this study a solar PV farm grid-connected system is modelled with the PSCAD/EMTDC software and a lightning current waveform is applied to observe the performance with and without the installation of SPD. Further investigation is e made in determining a suitable location to install the SPD in the solar PV farm according to the standard.

II. Solar PV Farm Grid-connected System

A case study of 1 MW solar PV farm grid-connected system was modelled in the PSCAD/EMTDC software and

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consisting mainly of solar PV array, inverter, transformer and grid as shown in Fig. 1.

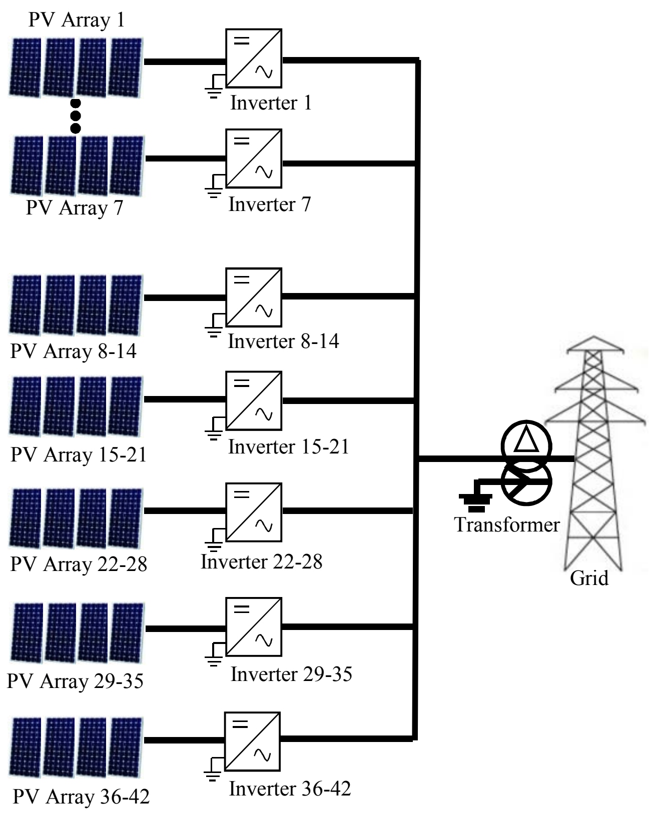

Figure 1: Solar PV Farm Grid-connected System

This solar PV farm was built from 250 W multi-crystalline solar PV modules to form a 42 solar PV array with 42 string inverter to convert DC output from solar PV to AC output. Then the inverter output is connected to the step-up transformer before being supplied to the grid. Details of all components applied in the mode are listed in Table I.

TABLE I. DETAILS OF COMPONENTS IN A SOLAR PV FARM.

Component	Quantity	Specifications
Solar PV Modules	4032 modules	60 multicrystalline solar cells Power solar PV modules = 250 W Voltage of solar PV modules = 29.8 V Current of solar PV modules = 8.39 A
Inverter	42	Nominal AC Power per inverter = 20 kW
Transformer	1	1500 kVA step-up transformer (433 V/11 kV)
Grid	-	11 kV

The output of the solar PV farm grid-connected system is simulated in the PSCAD/EMTDC as summarised in Table II.

TABLE II. OUTPUT OF SOLAR PV FARM GRID-CONNECTED SYSTEM SIMULATED IN PSCAD/EMTDC

DC output (PV Array)		AC Output			
		(AC Inverter)		(before transformer)	
V_{max} (V)	I_{max} (A)	V_{max} (V)	I_{max} (kA)	V_{max} (V)	I_{max} (kA)
714.97	33.42	353.39	0.040	353.45	1.96

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III. LIGHTNING CURRENT WAVESHAPES

Lightning current waveshapes, can be modelled ising mathematical expressions. There are two mathematical expressions of lightning current waveshapes that are widely used in examining the effects of lightning which are double exponential and Heideler functions. The double exponential [7] can be expressed in Equation (1) where I_m is the peak current while α and β are constants.

$$i(t) = I_m[e^{-\alpha t} - e^{-\beta t}] \quad (1)$$

In determining the lightning current waveshape, these two important parameters are employed to obtain the tail time t_t and front time t_f respectively. The Heideler function in Equation (2) and Equation (3) was proposed by Heideler [8] as follows:

$$i\,(t) = \frac{I_m}{\eta}\frac{(t/\tau_1)^n}{1+(t/\tau_1)^n} exp\left(-\frac{t}{\tau_2}\right) \quad (2)$$

where $$\eta = \exp\left[\frac{-\tau_1}{\tau_2\left(n\tau_2/\tau_1\right)^{(1/n+1)}}\right] \quad (3)$$

The simplest equation of the lightning current waveshapes is represented by the double exponential function. Unfortunately, the Heideler function provides more realistic results because the Heideler function starts when $t = 0$, while the double exponential starts when $t = 1$ µs. Hence, the Heideler function was selected in this study for the lightning current waveshape model. Two standard waveshapes of lightning currents, 8/20 µs and 10/350 µs were simulated as shown in Fig. 2 and Fig. 3 respectively, which are applied in the case studies.

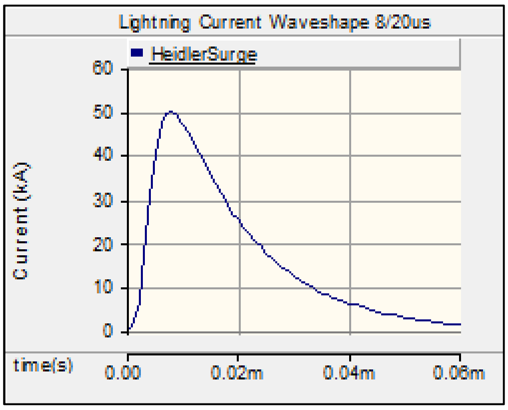

Figure 2: Lightning Current Waveshape 8/20 µs

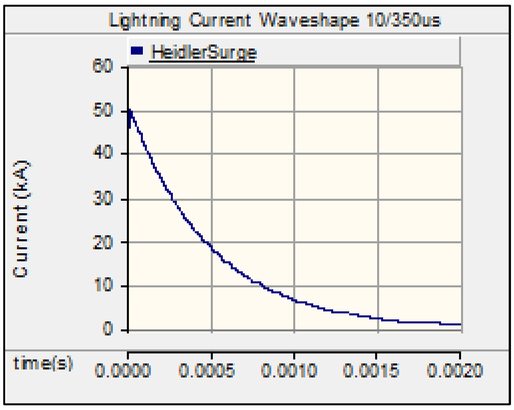

Figure 3: Lightning Current Waveshape 10/350 µs

IV. Surge Protection Devices (SPDs)

A SPD contains at least one non-linear component like varistors, suppressor diodes spark gaps, GDT, triacs and thyristors. Metal oxide varistors (MOVs) and spark gaps or GDT are the common components used in the SPD for the low voltage power distribution system [9]. In this research, the SPD will be modelled based on the MOV component following from the SPD that is practically used in a solar PV farm in Puchong.

According to the CLC 50539-12 standard [10], the numbers and location of SPDs depend on the cable length between the solar panels and inverter on the DC side and the cable length between inverter and SPD on the AC side. On the DC side the SPD (SPD B) needs to be installed near the inverter if the length is less than 10 meters. If it the length of the cable exceess 10 meters, a second SPD (SPD A) is required and should be located in the box close to the solar panel, the first one is located in the inverter area. Meanwhile, on the AC side, if the length of the SPD (SPD D) and the inverter is greater than 10m, it is necessary to protect the inverter with a complementary second SPD (SPD C). All these can be seen in Fig. 4.

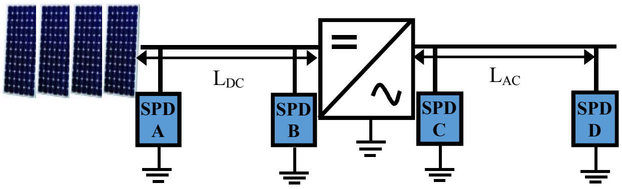

Figure 4: Configuration of SPD installation

Table III summarizes the installation of the SPD on the DC and AC side based on Fig. 4.

TABLE III. TABLE TYPE STYLES

	DC Side		AC Side	
Location	Solar PV Array	Inverter DC Side	Inverter AC Side	SPD D
If cable length L_{DC} or L_{AC} < 10 m	No need	SPD B	SPD C	No need
If cable length L_{DC} or L_{AC} > 10 m	SPD A	SPD B	SPD D	SPD C
Type of SPD	SPD Type I / SPD Type II	SPD Type I / SPD Type II	SPD Type I / SPD Type II	SPD Type I / SPD Type II

V. Result and Discussion

Two case studies were conducted; Case 1-lightning strike without SPD and Case 2-lightning strike with SPD installed as per standard CLC 50539-12. The lightning strike was applied between the solar PV array and the string inverter where five measurements at critical points were recorded as illustrated in Fig. 5.

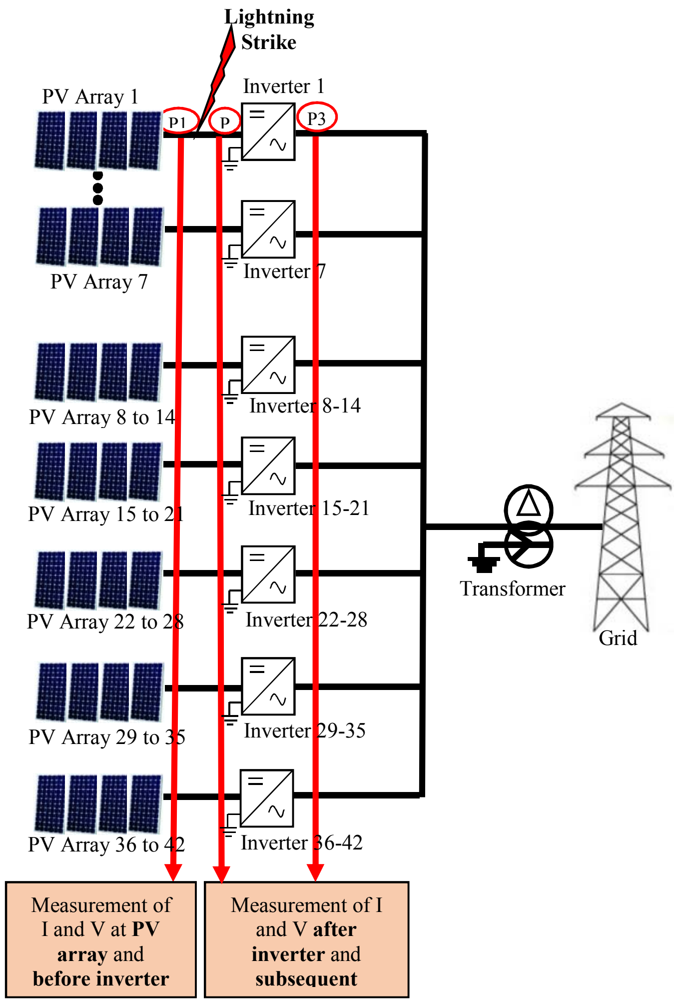

Figure 5: Lightning Strike at Solar PV Farm and Measurement Points

A. Case 1:Lightning Strike at Solar PV Farm Without SPD

In this Case 1, the solar PV farm is without SPD and the lightning strike is applied between the solar PV array and the string inverter as shown in Fig. 5. Lightning current waveshape 10/350 µs was used as the solar PV farm exposed to the LPL I. Table IV tabulates all the five measurement points.

TABLE IV. LIGHTNING STRIKE WITHOUT SPD

Lightning Amplitude (kA)	P1 (PV Array)		P2 (before Inverter)		P3 (after Inverter)	
	Vpv (MV)	Ipv (kA)	Vinv DC (MV)	Iinv DC (kA)	Vinv AC (kV)	Iinv AC (kA)
2	0.0135	0.024	0.0045	2.04	0.18	0.11
5	0.033	0.50	0.0113	5.04	0.44	0.24
10	0.066	1.42	0.023	9.97	0.89	0.47
20	0.133	3.35	0.045	19.42	1.78	0.94
30	0.197	5.29	0.068	28.40	2.67	1.40
40	0.264	7.58	0.091	37.32	3.55	1.87
50	0.329	9.22	0.113	46.22	4.44	2.33
100	0.656	19.08	0.227	90.69	8.89	4.67
150	0.984	28.94	0.340	135.13	13.32	7.01
200	1.312	38.81	0.454	179.55	17.77	9.35

The results show that the solar PV farm there can be huge damage of most of the components when lightning strikes, where the solar PV Array 1, all string inverters and transformer will be affected. Even if the lightning strike is between the solar PV Array 1 and string inverter 1, the lightning current will travel along the cables and badly damage the string inverter and transformer.

B. Case 2:Lightning Strike at Solar PV Farm With SPD

The installation of the SPD on the DC and AC side was based on Table III as discussed in Section IV. Then the lightning strike was applied to the installation of SPD to observe the effect. Case 2 was split into three parts: cable length 5 m, cable length 10 m and cable length 15 m (connection between the solar PV array and inverter). Table V shows the result for voltage measurement while Table VI shows the result for current measurement.

TABLE V. MEASUREMENT OF VOLTAGE

Lightning Amplitude (kA)	Cable Length 5 m			Cable Length 10 m			Cable Length 15 m		
	P1	P2	P3	P1	P2	P3	P1	P2	P3
	Vpv (MV)	Vinv DC (kV)	Vinv AC (kV)	Vpv (MV)	Vinv DC (kV)	Vinv AC (kV)	Vpv (MV)	Vinv DC (kV)	Vinv AC (kV)
2	0.0055	0.39	0.0417	0.009	0.39	0.0417	0.011	0.39	0.0417
5	0.013	0.77	0.0533	0.023	0.77	0.0533	0.026	0.77	0.0533
10	0.026	0.94	0.106	0.044	0.94	0.106	0.050	0.94	0.106
20	0.047	1.13	0.25	0.088	1.13	0.25	0.099	1.13	0.25
30	0.050	1.31	0.305	0.130	1.31	0.305	0.148	1.31	0.305
40	0.098	1.46	0.397	0.174	1.49	0.397	0.196	1.49	0.397
50	0.124	1.60	0.458	0.218	1.64	0.458	0.246	1.64	0.458
100	0.244	2.19	0.624	0.434	2.17	0.624	0.491	2.17	0.624
150	0.367	2.69	0.747	0.649	2.69	0.747	0.734	2.69	0.747
200	0.487	3.19	0.784	0.862	3.19	0.784	0.978	3.19	0.784

TABLE I. MEASUREMENT OF CURRENT

Lightning Amplitude (kA)	Cable Length 5 m			Cable Length 10 m			Cable Length 15 m		
	P1	**P2**	**P3**	**P1**	**P2**	**P3**	**P1**	**P2**	**P3**
	Ipv (kA)	Iinv DC (kA)	Iinv AC (kA)	Ipv (kA)	Iinv DC (kA)	Iinv AC (kA)	Ipv (kA)	Iinv DC (kA)	Iinv AC (kA)
2	0.0024	0.98	0.026	0.024	0.98	0.18	0.059	0.98	0.18
5	0.219	2.44	0.06	0.50	2.44	0.25	0.571	2.44	0.80
10	0.974	4.89	0.128	1.42	4.89	0.46	1.53	4.89	1.46
20	2.64	9.78	0.25	3.34	9.78	0.93	3.51	9.78	2.78
30	4.35	13.76	0.351	5.29	13.76	1.37	5.52	13.76	4.03
40	6.07	17.47	0.421	7.25	17.47	1.81	7.54	17.47	4.68
50	7.81	20.96	0.467	9.22	20.96	2.13	9.57	20.96	5.11
100	16.52	36.99	0.628	19.07	36.99	4.56	19.70	36.99	6.62
150	25.25	50.96	0.739	28.93	50.96	7.05	29.85	50.96	7.56
200	34.00	64.31	0.838	38.79	64.31	8.66	40.00	64.31	8.56

According to these two tables, the cable length does not have high influence to reduce the impact of the transient voltage and current. Moreover, the SPD that is installed near the inverter is not adequate to protect the solar PV modules.

I. CONCLUSION

The lightning strike contributes to a high transient voltage and current that can cause great damage to the solar PV modules and other electronic components. Therefore, this study was conducted to assign a proper location of the SPD in order to protect the solar PV modules and inverter. The SPD was installed according to the CLC 50539-12 standard. This study observed that installation of only one SPD is not enough, especially to protect the solar PV modules. The SPD should be installed besides the solar PV modules and inverter in order to minimise the impact of the lightning strike. Moreover, the SPD rating Type 2 is not enough to protect the solar PV farm. Further study can be done in terms of proper location and rating of the suitable SPD to apply at the solar PV farm.

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