Analysis of Lightning Surge Effects on Small-scale Rooftop Photovoltaic Systems

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***Abstract*—Small-scale rooftop PV systems have become an attractive investment for small businesses and home owners. PV systems are inherently exposed to lightning phenomena and hence protection of the electrical system is required. In this paper, a simulation approach using MATLAB and Simulink is adopted to analyse the impacts of lightning induced effects on small-scale, rooftop, grid-connected PV systems. It is found that based on different coupling points, lightning surges could cause damage to the PV array, inverter as well as the connected load. The installation of surge protective devices could mitigate the potential damaging effects. In analysing the surge effects on the PV system, an understanding of the associated risk of damage to the PV system can be developed and hence the requirements for lightning protection of small-scale rooftop grid-connected PV systems can be comprehended.**

***Index Terms*—Lightning protection, Modelling, Photovoltaic systems, Simulation, Surge protection**

I. INTRODUCTION

The global photovoltaic (PV) market has seen significant growth with an installed on-grid capacity of over 76 GW in 2016. This constitutes a more than 50% increase in capacity from 50 GW in 2015 [1]. The proliferation of solar PV broadly acknowledges the impact of global warming and more specifically signifies the development of device technologies aimed at improving the performance of installed systems. Electrical protection of PV equipment is one technological aspect to consider. The requirement of unobstructed exposure to direct sunlight means that PV modules, and thereby the accompanying equipment, are intrinsically exposed to climatological phenomena. One such phenomenon is lightning.

Globally, there are about 100 cloud-to-ground lightning flashes per second [2]. These flashes could cause damage to PV installations with respect to both direct and indirect effects. In terms of small-scale rooftop PV, there is no definitive risk assessment methodology for possible lightning damage. In order to design an effective lightning protection system for structures fitted with rooftop PV systems, an understanding of the effects of lightning on PV equipment is necessary. Modelling and simulation of lightning damage to PV systems would be one way to quantify these effects. However, there is no matured methodology for modelling lightning protection in PV systems. In this paper, the surge effects associated with lightning in PV systems are analysed. A simulation approach using MATLAB and Simulink is adopted to analyse the impacts of lightning surges on small-scale, rooftop, grid-connected PV systems.

II. BACKGROUND

A. The Growth of Photovoltaics

The drop in cost of PV components has been a significant driver in global exponential growth. In utility scale PV installations, the global weighted average cost of energy generation in 2015 was USD 0.13/kWh. However, in 2016, a bid of only USD 0.0299/kWh for a utility scale installation in Abu Dhabi, provides evidence of the drop in cost [3]. The large manufacturing base of PV panels in China has contributed to the price drop and hence global expansion of the PV market. Chinese, Indian and American markets have seen a rapid rise in installed capacity. On the other hand, the European market has seen a drop in installation capacity due to the introduction of a new renewable energy regulatory framework [1]. In the African market, growth has reached more than 300% from 500 MW capacity in 2013 to 2100 MW at the end of 2015. As of 2015, solar PV accounted for only 0.1% of the continents total energy generation. This is despite the high levels of insolation throughout [4].

The data collected above is applicable to large-scale, grid-connected systems. However, in household and commercial applications, small-scale PV installations have become an attractive investment. This is partly driven by the drop in component costs and PV being readily available. Small-scale PV systems, which are typically roof mounted, are a means of reducing reliance on grid supply. The installation of these systems requires somewhat of a retrofitting of the electrical reticulation of a structure. As such, transients in the PV system can cause significant damage to electrical and electronic systems and the PV installation itself. One source of potentially harmful transients is lightning.

B. Lightning Climatology

Lightning flashes are a global occurrence. In terms of protection, cloud-to-ground lightning is considered based on the consequential effects of direct and indirect flashes. Direct lightning could have damaging structural effects and indirect lightning, damaging electrical induced effects [2]. The factor of location is also a determinant in the likelihood of lightning damage. Lightning ground flash density is a measure of the number of cloud-to-ground lightning flashes per square kilometre per year. A global ground flash density map from NASA Earth Observatory with data obtained between 1995 and 2013 can be found in [5]. This map indicates that lightning occurs globally but is more prevalent in tropical regions. The northern hemisphere, mostly in parts of Europe, is less susceptible to cloud-to-ground lightning. The areas of highest ground flash density are in central Africa, north western South America and south eastern Asia [5]. Despite the differences in ground flash density between these regions, lightning damage remains a threat throughout.

A review of the literature indicates that while there has been much research on surge analysis, the relatively modern status of PV technology means that in many countries, standards for lightning protection are underdeveloped and hence, lightning protection is often overlooked. While there has been research on surge analysis in medium to large scale free-field PV [6]–[14], more work needs to be conducted particularly with regards to small-scale rooftop PV. The appeal of grid-tied, small-scale, rooftop PV brings into question the risk associated with damage to electrical equipment as well as persons in the structure. Through investigating the potential risk and adverse effects of lightning surges on small-scale rooftop PV, a suitable design of an internal lightning protection system (LPS) can be established. This paper will analyse the potential adverse effects of lightning surges on the electrical system of a structure fitted with a small-scale, grid-connected, rooftop PV system.

III. SYSTEM MODELLING

To analyse the effects of lightning surges on small-scale, grid-connected PV installations, two pertinent systems are modelled:

- The induced lightning stroke, and;
- The grid-connected PV system.

The above-mentioned system models take realistic conditions into account using the applicable standards. The systems are modelled using MATLAB and Simulink.

A. Lightning Surge

The induced lightning stroke represents the surge through the PV system which will produce an expected overvoltage under transient conditions. To study the effects of lightning surges, the appropriate surge parameters must be utilised. The electromagnetic compatibility (EMC) standard IEC 61000-4-5 [15] on surge immunity testing is applicable. This standard serves as a guide for surge immunity testing of electrical equipment under lightning or switching transients. This includes recommended test levels and procedures. According to [15], a combination generator is required to conduct surge testing under open-circuit voltage and short-circuit current conditions for 1.2/50 μs and 8/20 μs wave shapes respectively. In this case, a voltage surge will be applied to the PV system to analyse the induced overvoltage on the equipment under test (EUT). IEC 61000-4-5 also provides a guide on different classes of installations for selection of appropriate peak voltages for the surge generator. The classes of installation are summarised in Table I [15].

TABLE I
IEC CLASSIFICATION OF ELECTRICAL INSTALLATIONS

Class	**Description of electrical system**	**Surge (kV)**
Class 0	Well protected	0.025
Class 1	Partly protected	0.5
Class 2	Well-separated cables	1
Class 3	Signal and power cables in parallel	2
Class 4	Outdoor cables/interconnections	4
Class 5	Telecom cables to equipment	user defined
Class X	Product/equipment specific	user defined

Due to the outdoor exposed nature of a PV system, a Class 4 installation is considered. Hence, the damage to the EUT can be analysed under the recommended overvoltage surge conditions of 4 kV. This will assume the damage caused by the first stroke of a lightning flash. To model the surge based on the parameters in IEC 61000-4-5, the IEEE model for the characteristic surge voltage is employed. IEEE Std C62.45 - 2002 [16] for surge testing of equipment connected to low voltage systems specifies the applicable 1.2/50 μs wave equation as:

$$V(t) = AV_p(1 - exp\frac{-t}{\tau_1})exp(\frac{-t}{\tau_2}) \tag{1}$$

where $V(t)$ is the voltage as a function of time, A is a constant equal to 1.037, V_p is the peak voltage in V and τ_1 and τ_2 are time constants equal to 0.4047 μs and 68.22 μs respectively [16]. The voltage function is modelled as a timeseries signal in MATLAB driven by a controlled voltage source in Simulink. Fig. 1 is a graphical representation of the wave shape modelled from (1).

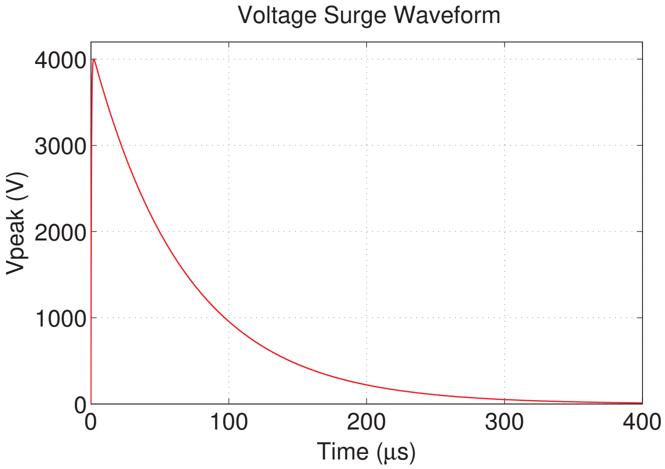


Figure 1. IEEE model of a 1.2/50 μs voltage surge waveform

The voltage surge will be induced in the modelled small-scale rooftop grid-connected PV system. The importance of the lightning transient conditions will be analysed based on the surge effects on the system.

B. Grid-connected Rooftop PV System

To model the small-scale, grid-connected, rooftop PV system, typical values will be considered for the equipment and operating conditions. Since the salient analyses are of the transients in the system, only the essential control elements for system operation will be considered. The basic layout of the grid-connected system is illustrated in Fig. 2.

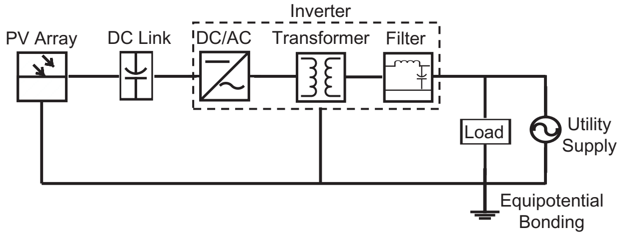


Figure 2. Block diagram of small-scale grid-connected PV system

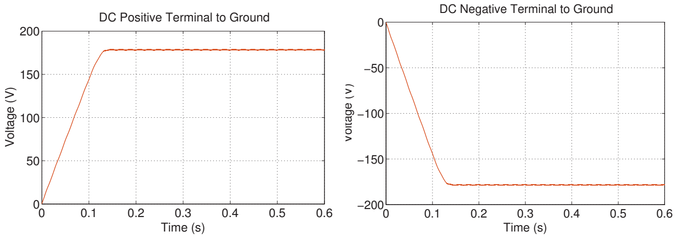
The system is modelled with an output power capacity of 2.5 kWp which is typical for a small rooftop-mounted configuration. The DC to AC conversion will be implemented by a PWM controlled inverter with an h-bridge switching configuration. The inverter is collectively viewed as a subsystem consisting of an h-bridge, transformer and an LC filter. It should be highlighted that the specific design of the inverter may vary in practice, however this does not affect the presented modelling approach. A 2 kW RLC load is used which is supplied by both the inverter and the utility. AC line impedances for the cable lengths between the inverter and load and load and utility are included. Also, a small resistance for the DC cable length from each terminal of the PV array to the inverter is applied. The components used in the PV system are connected to an equipotential bonding point for realistic grounding requirements as illustrated in the IEC 60364-7-712 standard for electrical installations of PV systems [17]. The full specifications of the PV system model are indicated in Table II. This includes the V_{oc}, V_{mp}, I_{sc} and I_{mp} parameters, referring to the open-circuit voltage, maximum power voltage, short-circuit current and maximum power current respectively. This is based on the characteristic curve of power production for a PV module.

Using the PV system parameters in Table II, the expected waveforms of the system are generated. Fig. 3 is an illustration of the waveforms on both the DC and AC sides of the system obtained from the simulation on Simulink. The outputs shown in Fig. 3 at the different locations in the system are as expected, in line with operating requirements of the PV system. The waveforms indicate an initial system startup until steady state is reached.

The models of the induced lightning surge and PV system are integrated in order to analyse the effects of the surge at different coupling points. Capacitive coupling for a line-to-ground system is included which makes use of a cou-

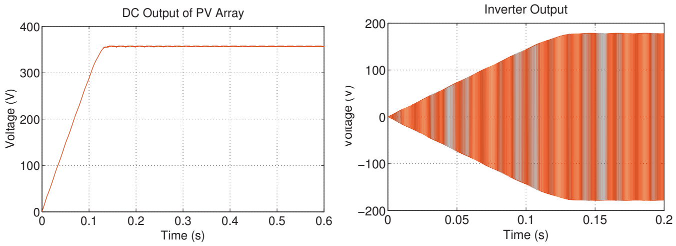
TABLE II
GRID-TIED PV SYSTEM SPECIFICATIONS

PV system specifications	
PV array	10 module string
	P_{max} = 2500 W
	V_{oc} = 37.2 V (per module)
	V_{mp} = 30.1 V (per module)
	I_{sc} = 8.87 A (per module)
	I_{mp} = 8.30 A (per module)
Inverter	H-bridge configuration
	PWM control with 50 Hz reference
	260/230 V_{rms}, 50 Hz transformer
	LC filter
Load	RLC load
	P = 2000 W
Grid side	Utility supply = 230 V_{rms} at 50 Hz



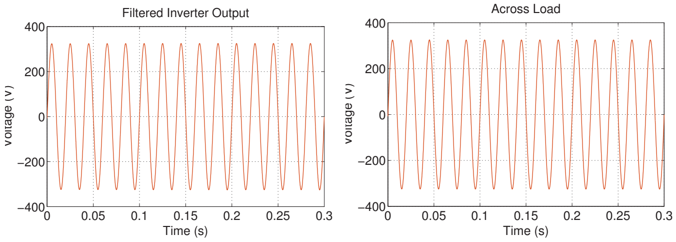
(a) DC positive to ground

(b) DC negative to ground



(c) Total PV DC output

(d) Inverter output



(e) Filtered inverter output

(f) Voltage across load

Figure 3. (a) - (f) Characteristic waveforms of grid-tied PV system model

pling resistor and coupling capacitor according to [15]. The capacitive coupling condition prevents DC feedback to the surge generator. Specific conditions are required to regulate the simulation process and produce the expected results under typical system operating conditions. Fig. 4 illustrates the integrated lightning surge and grid-tied PV system models used in the simulation methodology.

IV. RESULTS AND DISCUSSION

A. Simulation Setup and Parameters

To implement the simulation, system conditions for the lightning surge and PV system models are configured. This includes the PV system operating conditions as well as the lightning surge coupling points. Fig. 5 illustrates the input operating conditions including the aforementioned surge coupling points.

The input parameters of the PV array are standard test conditions (STC) of irradiance 1000 W/m^2 and temperature 25 $^{\circ}C$ according to IEC 61215 for testing of crystalline PV modules [18]. The remaining PV system specifications are given in Table II. The lightning surge is coupled to the DC, AC and service points. The surges at these points are treated as isolated coupling conditions such that the full effect of the coupled surge can be analysed for the EUT. Hence, each point is coupled to the surge generator individually when running the simulation. The surge propagation through the equipment is measured with respect to ground which is the reference for surge protective devices (SPDs). The relevant EUT for the simulation, for which protection is paramount, are the PV array, inverter and the load. The surge is applied to the system after a delay of 0.205 seconds. This corresponds to the point where PV DC steady-state is reached and the AC sine wave peak of the positive half cycle. Therefore, peak transient conditions for the system as a whole can be analysed.

B. Results

The simulation results of the coupled surges to the DC, AC and service points are presented. In Fig. 6 the overvoltages due to the DC coupled surge are measured from the PV array positive and negative terminals to ground, the inverter terminal to ground and across the load. Similarly, the overvoltage conditions for the AC and service coupled surges are illustrated in Fig. 7 and Fig. 8 respectively.

The results of the simulations are summarised in Table III. The values of the peak overvoltages for the measurement points with respect to the coupling points are indicated.

TABLE III
SIMULATION RESULTS FOR OVERVOLTAGE SURGE AT COUPLING POINTS

	Peak overvoltage conditions (V)			
Coupling	DC +	DC -	Inverter	Load
DC	4692	3979	326	325
AC	179	-179	3018	533
Service	179	-179	1829	4160

The DC coupling results indicate that the full surge is propagated through each of the terminals to ground while the AC side of the system suffers no effects. Due to the aforementioned requirement of equipotential bonding of equipment as stipulated in [17], the PV module mounting system is physically connected to ground. Consequently, when the surge is coupled to the DC side, the low impedance path from terminal to ground is measured. Hence, the complete isolated surge is propagated through the DC side of the system. When the surge is coupled to the AC side of the system i.e. the filtered output of the inverter, there is an effect on both the inverter and the load while the DC side remains unchanged. The overvoltage on the inverter terminal is higher than that across the load which is expected due to the coupling point of the surge. Likewise, for a surge through the service, the DC side remains unaffected with a higher overvoltage across the load than the inverter.

The peak voltage of the generated surge is appropriated by the recommended coupling resistor and capacitor values of 10 Ω and 9 μF according to [15]. However, under realistic conditions, coupling impedance values can be altered by a number of unique factors. To address this point, the case of service coupling is utilised. Using different resistor and capacitor values, the peak voltages across the equipment are obtained in Table IV.

TABLE IV
EFFECT OF SURGE SERVICE COUPLING CONDITIONS ON OVERVOLTAGES IN THE PV SYSTEM

	Peak overvoltage conditions			
Coupling values	DC +	DC -	Inverter	Load
R = 10 Ω, C = 9 μF	179	-179	1829	4160
R = 20 Ω, C = 18 μF	179	-179	1240	4008
R = 30 Ω, C = 27 μF	179	-179	978	3906
R = 40 Ω, C = 36 μF	179	-179	839	3857

Table IV indicates that a higher coupling impedance by the surge generator produces a lower overvoltage in the system. This is due to the higher voltage drop in the surge generator itself. Conversely, if there is high impedance in the system itself, such as in the cabling or load, a higher overvoltage would be induced and measured. Coupling impedance could vary inconsistently and hence the measured overvoltages in a physical system are difficult to quantify.

C. LPS Considerations

The LPS design requirements take into consideration the indirect effects or lightning electromagnetic impulse (LEMP) through the system as specified by lightning protection standard IEC 62305 - 1 [19]. The different coupling points take into consideration a distributed type of coupling for studying the effects of indirect lightning. The results of the simulations indicate that a coupled surge can cause damage to the PV array, inverter as well as the load. The results were obtained using isolated coupling points. In a realistic scenario, the lightning surge could couple simultaneously at more than one point

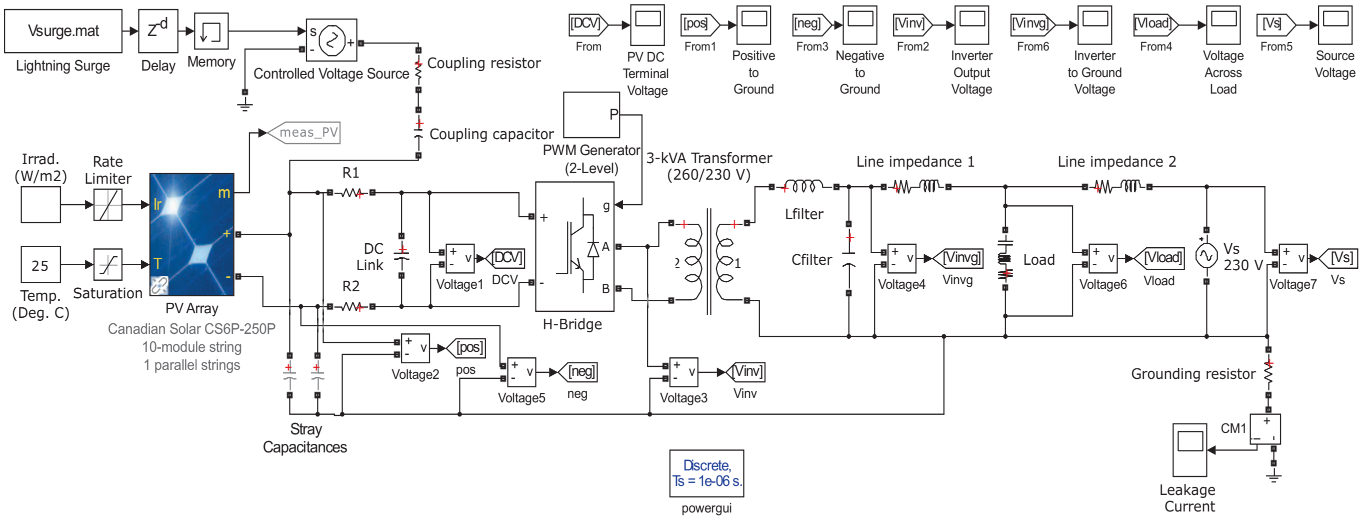


Figure 4. Simulink model of lightning surge coupled to PV system

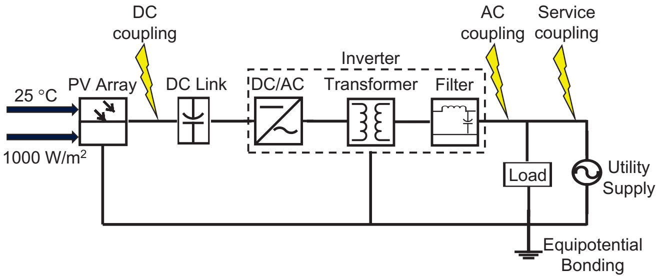
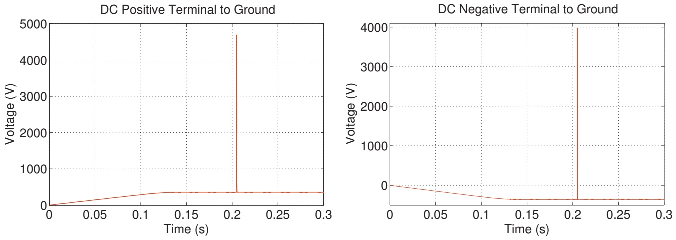
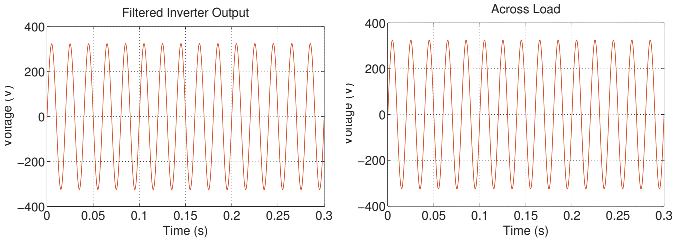


Figure 5. Surge coupling points in grid-tied PV system



(a) DC positive to ground

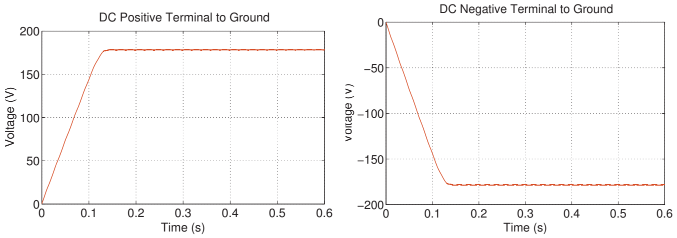
(b) DC negative to ground



(c) Inverter output

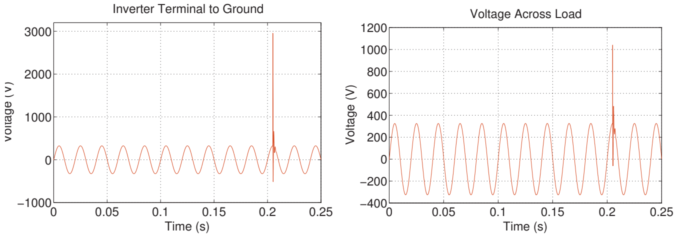
(d) Load voltage

Figure 6. (a) - (d) DC coupling of lightning surge to PV system



(a) DC positive to ground

(b) DC negative to ground



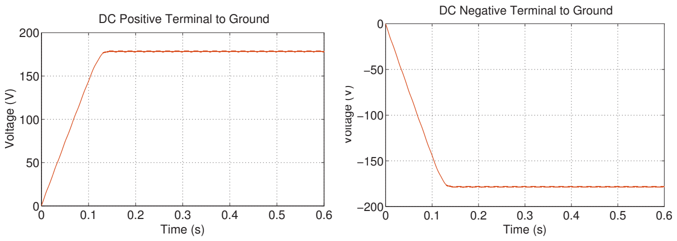
(c) Inverter output

(d) Load voltage

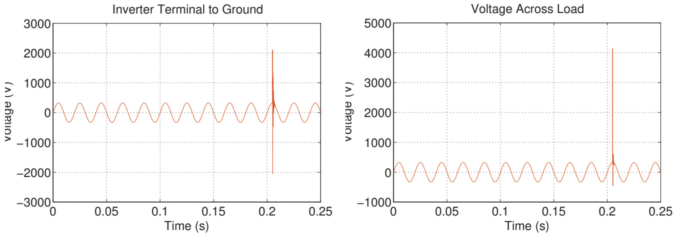
Figure 7. (a) - (d) AC coupling of lightning surge to PV system

through galvanic and inductive coupling. The unpredictability of lightning means that the surge peak voltage could vary and hence protection under the worst possible conditions should be employed. Damage could be mitigated by installing SPDs. The locations of the SPDs are important. In this case, the results show that SPDs are required for the positive and negative terminals of the PV array, the inverter output and from the service entering the load. Hence, all inputs and outputs of the PV system and load are protected. Although inverters are often designed with internal protection, an external SPD would act as the primary protection under extreme conditions. This comes into play when analysing the risk of damage to the PV system i.e. the insertion of an external protective device will reduce the risk of damage to PV system components.

When considering the common rooftop nature of small-



(a) DC positive to ground (b) DC negative to ground



(c) Inverter output (d) Load voltage

Figure 8. (a) - (d) Service coupling of lightning surge to PV system

scale, grid-connected PV systems, direct lightning strikes could be more common which could result in higher surge currents through the system. Spatial shielding in the structure could attenuate the surge currents which would result in lower overvoltages for indoor equipment. There is also the question of line impedances in the system. For structures with high rooftops, cable lengths will affect the impedance values which will in turn affect the overvoltages in equipment through coupling as shown in the simulation results. Coupling conditions could vary significantly for different types of installations and structures based on line impedances, materials and thereby current flow through the reticulation. This is in relation to grounding impedance where equipotential bonding is of high importance. For SPDs to be effective in simultaneously mitigating overvoltages in the system at different points, potential differences between grounding points must be minimised as far as possible. A combination of protective measures in an LPS design must be employed in order to mitigate potential adverse effects of lightning surges through PV system interconnections.

V. Conclusion

The results of the simulations indicate that lightning surges can cause significant overvoltages on the PV array, inverter and load for a grid-connected PV system. The results are also applicable to larger rooftop PV systems where similar scenarios could be considered. Surges through PV systems could have an impact on the overall risk of damage and hence must be considered when designing an LPS for protection against LEMP. The modelling and simulation methodology can be applied to analyse a number of scenarios related to small-scale PV systems with respect to unique practical applications. This methodology therefore serves as an analytic assessment step that precedes the design of the lightning protection system for small-scale rooftop PV. The overall comprehension of the interaction between lightning surges and small-scale rooftop PV systems will aid in understanding risk and developing standards for the expansive market of consumer PV installations in the renewable energy industry.

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