Impacts of Lightning-Induced Overvoltage on a Hybrid Solar PV–Battery Energy Storage System

Nor Izzati Ahmad 1,*, Zaipatimah Ali 1,*, Mohd Zainal Abidin Ab. Kadir 2,*, Miszaina Osman 1,*, Nur Hazirah Zaini 3 and Muhammad Hakirin Roslan 4

1 Institute of Power Engineering (IPE), Universiti Tenaga Nasional, Putrajaya Campus, Jalan Ikram-UNITEN, Kajang 43000, Malaysia; miszaina@uniten.edu.my
2 Centre for Electromagnetic and Lightning Protection Research (CELP), Advanced Lightning, Power, and Energy Research Centre (ALPER), Faculty of Engineering, Universiti Putra Malaysia, Serdang 43400, Malaysia
3 Faculty of Engineering and Built Environment, Universiti Sains Islam Malaysia, Nilai 71800, Malaysia; nurhazirah@usim.edu.my
4 Faculty of Engineering, Universiti Pertahanan Nasional Malaysia, Kem Sungai Besi, Kuala Lumpur 57000, Malaysia; hakirin@upnm.edu.my
* Correspondence: nor.izzati@uniten.edu.my (N.I.A.); zaipatimah@uniten.edu.my (Z.A.); mzk@upm.edu.my (M.Z.A.A.K.); Tel.: +60-13-465-2778 (N.I.A.)

Abstract: With increased electrical energy demands projected in the future, the development of a hybrid solar photovoltaic (PV)–battery energy storage system is considered a good option. However, since such systems are normally installed outdoors and in open areas, they are vulnerable to lightning strikes and may suffer from malfunctions or significant damage to sensitive components, which may result in a major breakdown and loss of revenue due to equipment replacement costs and inefficient operation. Thus, the objective of this paper is to investigate the effect of lightning-induced overvoltage on a hybrid solar PV–battery energy storage system, considering indirect lightning strikes nearby the system. The presented hybrid solar PV–battery energy storage system and lightning-induced overvoltage are modeled in Electro-Magnetic Transient Program-Restructured Version (EMTP-RV) software. The lightning-induced overvoltage is simulated based on a lightning waveshape of 10/350 µs using the Heidler expression, whilst the Rusck model is used to simulate the lightning-induced overvoltage. Different lightning current amplitudes (3, 19, and 169 kA), lightning strike locations (20, 50, and 100 m), and cable lengths (5, 10, and 20 m) are used to investigate the induced effects on the system and on the impulse withstand voltage of 6kV, as stated in MS IEC 60664-1 for solar PV–battery systems and inverters at the DC side. The results indicate that as the lightning strike distance increases from 20 to 100 m, the percentage of strikes exceeding the impulse withstand voltage reduces from 67% to 54% at 19 kA. At 169 kA, the impulse withstand voltage is exceeded by more than 100%, regardless of the strike distance (from 20 to 100 m). Furthermore, differences in cable length do not have much impact on the lightning-induced overvoltage due to the small voltage drop across the short cable length. This study provides useful information for PV systems owners and will be useful in assigning appropriate lightning protection schemes for PV farms.

Keywords: hybrid solar PV; battery energy storage; indirect lightning effect; lightning-induced overvoltage; EMTP-RV

1. Introduction

Malaysia has various energy resources from conventional sources, such as oil, natural gas, and coal, in addition to renewable energy resources, such as solar photovoltaic (PV) energy, hydropower, wind, and biomass. Currently, about 90% of electricity is generated from conventional resources, especially in Peninsular Malaysia. Therefore, conventional
resources are gradually depleted, which is becoming a big concern for Malaysia and will require overcoming the nation’s overzealous reliance on conventional resources. To overcome this problem, there is a need to balance the usage of both conventional and renewable energy resources. Therefore, the Malaysian government has introduced certain policies; the earliest was the Renewable Energy Act 2011, which introduced the Feed-In Tariff (FiT) system [1]. In order to make an industry of renewable energy sources more effective and profitable, the Net Energy Metering (NEM) scheme was launched by the Energy Commission and Sustainable Energy Development Authority (SEDA) Malaysia in 2016. Both of these schemes have the same objective, which is to allow any private individual or organization to generate electricity by using solar PV systems, since Malaysia is the third-largest producer of solar PV energy in the world. The Malaysian government has also planned a ten-year master plan, known as Malaysia Electricity Supply Industry 2.0 [2], which will benefit consumers in the long term by lowering the cost of production, resulting in lower tariffs [3]. Figure 1 shows that Malaysia has abundant levels of solar radiation, receiving about 6 h of sunlight per day.

Figure 1. Irradiation (yearly average value) in Malaysia. [4].

Hybrid solar PV–battery energy storage systems are usually installed in outdoor areas, whereby the likelihood of lightning strikes is very high, especially in the areas that are vulnerable to lightning. For instance, Malaysia is recognized as the “Crown of Lightning”, experiencing an average of 200 thunderstorm days every year [5,6].

Based on statistical data concerning the cause of typical damage to solar PV systems in South Africa, about 31.2% of the damage is due to lightning strikes [7]. Likewise, similar issues will be expected to occur in Malaysia due to the fact that its geographical location is close to the equator. As reported in [8–11], both direct and indirect lightning strikes can severely affect solar PV systems that incorporate battery energy storage; in Malaysia, such systems are not properly protected against lightning strikes [11].

Therefore, the objective of this research is to study the impacts of lightning-induced overvoltage on hybrid solar PV–battery energy storage systems and to provide an overview of the significance of such a system being struck by lightning. When such a system is required to operate in grid-connected mode, this might cause problems, as there is no specific or relevant standard guideline for when lightning-induced overvoltage occurs especially for hybrid solar PV–battery energy storage systems. Furthermore, based on the findings of this study, the selection of protection systems, placements, and ratings of surge protection devices (SPDs) can be discussed further in future studies.

Throughout this study, essential information on the effects of lightning-induced overvoltage on hybrid solar PV–battery energy storage systems is provided by conducting simulations of different lightning current amplitudes and lightning strike locations using Electro-Magnetic Transient Program—Restructured Version (EMTP-RV) software. By carrying out this study, we hope to provide ideas for an appropriate protection scheme to and suggest how it should be installed.
2. Overview of Hybrid Solar PV–Battery Energy Storage Systems

Solar PV systems can be grouped into two main types, namely stand-alone systems and grid-connected systems [12–14], as classified in Figure 2. A stand-alone system can act as a hybrid system, involving battery storage to ensure continuous power supply when there is no irradiance. In contrast, a grid-connected system is a system that is connected to the grid. The distributed solar PV system mostly comes from a roof-mounted system that acts as an additional supply to the grid to satisfy the maximum demand. In this study, a grid-connected hybrid solar PV system-battery energy storage will be discussed. A description of the required equipment is tabulated in Table 1.

![Figure 2. Classification of solar photovoltaic (PV) systems [12–14].](image)

Table 1. Basic components of hybrid solar photovoltaic (PV)–battery energy storage systems [15].

<table>
<thead>
<tr>
<th>Items</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar PV modules</td>
<td>• Type: Crystalline silicon; complies with standard MS IEC 61215 [16].</td>
</tr>
<tr>
<td>Combiner box</td>
<td>• Installed between solar PV and inverter.</td>
</tr>
<tr>
<td></td>
<td>• Used to allow engineers to optimize power and reduce labor costs by using the combined connections.</td>
</tr>
<tr>
<td>DC and AC cabling</td>
<td>• Used to give a path for electrical power supply to and from the inverter.</td>
</tr>
<tr>
<td>Inverter</td>
<td>• Used to convert DC to AC power with the required frequency of 50 or 60 Hz [17].</td>
</tr>
<tr>
<td>Power conditioning equipment</td>
<td></td>
</tr>
<tr>
<td>Charge controller</td>
<td>• Essential component in a solar PV system that has a battery energy storage.</td>
</tr>
<tr>
<td></td>
<td>• Used to control the flow of current to and from the batteries to prevent the batteries from damage that may arise from being overly discharged or overcharged.</td>
</tr>
<tr>
<td>Battery Energy storage</td>
<td>• Used as a back-up system and can be rechargeable to store and deliver the electrical energy, which complies IEEE Std 2030.2.1-2019 [18].</td>
</tr>
<tr>
<td>Circuit breaker</td>
<td>• A switching device to disconnect in case of a fault.</td>
</tr>
<tr>
<td>Fuse</td>
<td>• Safety device for protection against overcurrent or surges.</td>
</tr>
<tr>
<td>PV Electric meter</td>
<td>• Used to record AC electricity and connected between the AC breaker and AC grid isolator main switch.</td>
</tr>
<tr>
<td>Connectors, conduit, and brackets</td>
<td>• Used to connect all the parts safely and securely.</td>
</tr>
</tbody>
</table>
In this case, battery energy storage is used as a back-up system [12,19] and is designed based on IEEE Standard 2030.2.1-2019 [18]. Table 2 discusses the two main types of batteries, which are primary and secondary batteries, as well as their benefits. In this research, the ideal battery for secondary types is considered for the storage and delivery of electrical energy.

<table>
<thead>
<tr>
<th>Type of BESS</th>
<th>Description</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary BES</td>
<td>Non-rechargeable, however can store and deliver electrical energy and is known as a “dry battery”. Not used in PV systems.</td>
<td>Light, cheap, and high density. Mostly used in portable electronic devices.</td>
<td>Cannot be reused. Creates hazardous waste.</td>
</tr>
<tr>
<td>Secondary BES</td>
<td>Rechargeable and can store and deliver electrical energy. Mainly used for electrical energy storage purposes.</td>
<td>Lasts longer than the primary battery. Has better performance and can be reused.</td>
<td>Expensive. Lack of versatility. Rarely interchangeable. Creates hazardous waste.</td>
</tr>
</tbody>
</table>

3. Overview of Lightning Phenomenon

Lightning is well-known as a catastrophic phenomenon that occurs during thunderstorms and produces electric discharge in the form of a spark or flash that originates in a charge cloud [22]. Lightning discharges can be divided into two main categories, i.e., ground flashes and cloud flashes. Ground flashes are lightning discharges that strike the ground and can be classified into four types based on the charge polarity from the cloud to the ground, i.e., upward positive, upward negative, downward positive, and downward negative. Meanwhile, cloud flashes can be categorized into three main types, i.e., intracloud, air, and intercloud discharges [23]. Thus, lightning has always been one of the major threats to such systems, which can cause overvoltage due to direct lightning strikes and indirect lightning strikes.

In this study, indirect lightning strikes are the prime interest, since they can cause significant problems to power systems, even though they have less impact than direct lightning strikes. Indirect lightning strikes usually strike the ground surface or a nearby object, while the lightning-induced overvoltage occurs due to electromagnetic coupling between the system and the lightning strike channel [24]. The lightning-induced overvoltage also can be evaluated by using simulation based on the following practice [22,25].

1. The lightning return stroke current model should be used to calculate the electromagnetic field generated by the lightning return stroke current, as discussed in Section 4.2;
2. Then, the lightning-induced overvoltage should be obtained by modeling the coupling model, as described in Section 4.3.

The Risk of Lightning-Induced Overvoltage in Hybrid Solar PV–Battery Energy Storage Systems and the Previous Research

At present, solar PV energy is recognized as a competitive and mature renewable energy (RE) technology due to its huge benefits nationwide. Although solar PV energy only provides 2.6% of the global power output, it had greater capacity than any other technology in 2019 [26–29], which proves that solar PV energy still has great potential in generating electricity, as shown in Figure 3. In order to sustain solar PV growth and to cater to energy demands, grid-connected hybrid solar PV–battery energy storage has become a very attractive option [26,30,31]. The function of battery energy storage is to store and deliver energy, which may assist national electricity suppliers in ensuring the consistency of electricity supply to the grid. Figure 4 presents battery energy storage markets in European countries; Germany is the leading country, with 66% of the total in battery energy storage.
markets in 2019, however the growth of battery energy storage slowed down in 2020 due to COVID-19 pandemic [32].

Despite the massive installation growth of solar PV and battery energy storage in all countries, there is one natural phenomenon that cannot be avoided, which is lightning. Since such systems are usually located in outdoor areas, the possibility of lightning striking such systems is very high, especially when such systems are located in areas with a high likelihood of lightning, such as Malaysia.

This paper focuses on indirect lightning strikes, whereby the lightning does not directly strike the electrical equipment, however lightning-induced overvoltage can be generated and can travel over any equipment from the strike point. Essentially, indirect lightning strikes can cause many power outages, which directly reduce the system’s efficiency, and to some extent might cause equipment to malfunction [11,22,33–38]. Figure 5 presents the statistical data for the destruction of solar PV systems in Germany. About 31.2% of the damages were due to lightning strikes. This rate would raise concerns, however it could be even worse for lightning-prone countries such as Malaysia. Meanwhile, Table 3 tabulates the typical destruction due to lightning strikes on solar PV systems.
Figure 5. Statistics data for damage to solar PV systems (2005–2014) [7].

Table 3. Typical damage caused by lightning strikes [39].

<table>
<thead>
<tr>
<th>Components</th>
<th>Examples of Damage</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar PV module/array</td>
<td><img src="image1" alt="Image" /></td>
<td>Defects on the electronic parts, cracking of tempered glass, and arcing at the string ribbon.</td>
</tr>
<tr>
<td>Inverter</td>
<td><img src="image2" alt="Image" /></td>
<td>Damage to all electronic components and data communication parts.</td>
</tr>
<tr>
<td>Combiner box</td>
<td><img src="image3" alt="Image" /></td>
<td>Burning and melting due to short circuit events. Breakdown of sensitive components inside the combiner box.</td>
</tr>
<tr>
<td>Cabling</td>
<td><img src="image4" alt="Image" /></td>
<td>Burning and holes in the insulation of cables.</td>
</tr>
</tbody>
</table>

Based on the abovementioned problems shown in Figure 5 and Table 3, there have been several studies related to the lightning strike effects on either solar PV systems or hybrid solar PV–battery energy storage systems. Both simulations and experiments have been discussed in recent years. Table 4 gives a summary of the previous studies on the impacts of lightning occurrence on solar PV systems with battery energy storage.
Table 4. Previous studies on the effects of lightning strikes on solar PV systems with battery energy storage.

<table>
<thead>
<tr>
<th>No.</th>
<th>References</th>
<th>Year</th>
<th>Review</th>
<th>Type</th>
<th>Strike Type</th>
<th>External</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Rooftop Farm With Battery Energy Storage Direct Indirect Air Termination system Down Conductor Earth Termination system</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>[40]</td>
<td>2019</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>2</td>
<td>[41]</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>3</td>
<td>[42]</td>
<td>2018</td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>4</td>
<td>[43]</td>
<td>2017</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>6</td>
<td>[11,41]</td>
<td>2016</td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>7</td>
<td>[44]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>[45]</td>
<td>2015</td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>9</td>
<td>[46]</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>10</td>
<td>[38]</td>
<td>2014</td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>11</td>
<td>[47]</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>12</td>
<td>[48]</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>13</td>
<td>[49]</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>14</td>
<td>[50]</td>
<td>2013</td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>15</td>
<td>[51]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>16</td>
<td>[52]</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>17</td>
<td>[53]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>18</td>
<td>[54]</td>
<td>2012</td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>19</td>
<td>[55]</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>
4. EMTP-RV Model

4.1. Hybrid Solar PV–Battery Energy Storage System

The 1 Megawatt (MW) solar PV system was modeled based on real applications in Puchong, Malaysia, with an additional ideal battery energy storage system using Electromagnetic Transient Program—Restructured Version (EMTP-RV) software. The system consisted of 42 solar PV arrays at 250 W per module, 42 string inverters, as well as ideal battery energy storage, transformer, and grid components. A block diagram is presented as shown in Figure 6.

![Block diagram of a hybrid solar PV–battery energy storage system.](image)

Table 5. Details of the components in a hybrid solar PV–battery energy storage system.

<table>
<thead>
<tr>
<th>Components</th>
<th>Solar PV</th>
<th>Battery Energy Storage</th>
<th>Inverter</th>
<th>Transformer</th>
<th>Grid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specifications</td>
<td>Power</td>
<td>Voltage</td>
<td>Battery nominal capacity</td>
<td>Nominal AC Power per inverter</td>
<td>Rating</td>
</tr>
<tr>
<td></td>
<td>1 MW</td>
<td>715.2 V</td>
<td>5.26 MWh</td>
<td>20 kW</td>
<td>1.5 MVA</td>
</tr>
</tbody>
</table>

Based on the measured output voltages in Table 6, the hybrid solar PV–battery energy storage system converted about 715.2 V\(_{\text{DC}}\) from the inverter to an output of 354.7 V\(_{\text{AC}}\). The 354.7 VAC output was connected to the grid by a transformer with a rating of 1.5 MVA 433 V/11 kV. Graphs of DC and AC output voltages are given in Figures 7 and 8, respectively.

Table 6. Measured output voltage for a hybrid solar (PV)–battery energy storage system in Electromagnetic Transient Program—Restructured Version (EMTP-RV).

<table>
<thead>
<tr>
<th>DC Output (V(_{\text{DC}})) (Solar PV Array and BESS)</th>
<th>AC Output (V(_{\text{AC}})) (Before Transformer)</th>
</tr>
</thead>
<tbody>
<tr>
<td>715.2</td>
<td>354.7</td>
</tr>
</tbody>
</table>
4.2. Return Stroke Current Model

There are several types of mathematical expressions that can be used to model lightning current waveshapes. The most commonly used are the double exponential and Heidler functions. The double exponential function is usually known as the simplest function, while the Heidler function produces more realistic results and is also recommended by standard IEC 62305-1 [56]. This is because the Heidler function starts with steepness 0 at t equals 0, while the double exponential function starts with t equals 0 with the highest steepness. Hence, the Heidler function is used in this paper to represent the lightning waveshape.

The effects of lightning-induced voltage were simulated using the lightning waveshape 10/350 µs, with varied lightning current amplitudes within the range of 2 to 200 kA, as referred to in the International Council on Large Electric Systems (CIGRE) distribution. The lightning waveshape of 10/350µs was chosen as part of the international standard waveform for testing and also to represent the lightning severity (major stress of electrical and mechanical) within the surge protection device [11, 57, 58].

In this study, three lightning current amplitudes were selected, namely 3, 19, and 169 kA. These values were selected based on statistical lightning activity data in 2017 at Solar PV Farm Puchong Gateway, Selangor [59]. According to the abovementioned statistical data, the probability of lightning occurrence is 95% at 3 kA, 50% at 19 kA, and 5% at 169 kA [59] as Figure 9. Hence, the lightning waveshapes were modeled in the
Electro-Magnetic Transient Program—Restructured Version (EMTP-RV) software using the Heidler equation, as expressed in Equation (1):

\[ i(t) = \frac{I_m}{\eta} \left( \frac{t}{\tau_1} \right)^n \left[ 1 + \left( \frac{t}{\tau_1} \right)^n \exp\left(-\frac{t}{\tau_2}\right) \right] \]  

where \( I_m \) is the lightning peak current, \( \eta \) is the correction factor of the peak current, \( \tau_1 \) is the rise time constant, \( \tau_2 \) is the fall time constant, and \( n \) is the steepness factor. Table 7 tabulates the parameters of the Heidler equation used to model the lightning waveshape.

Figure 9. Lightning waveshapes (10/350 \( \mu \)s) at lightning current amplitudes of 3, 19, and 169 kA.

Table 7. List of parameters current waveforms \([56,60]\).

<table>
<thead>
<tr>
<th>Lightning Waveshape</th>
<th>Rise Time, ( \tau_1 ) (( \mu )s)</th>
<th>Fall Time, ( \tau_2 ) (( \mu )s)</th>
<th>( n )</th>
</tr>
</thead>
<tbody>
<tr>
<td>10/350 ( \mu )s</td>
<td>1.65</td>
<td>490</td>
<td>3</td>
</tr>
</tbody>
</table>

4.3. Lightning-Induced Overvoltage Model

Generally, lightning-induced overvoltage is generated when the lightning strike does not directly strike any parts of the electrical network, but rather travels over the network or system. The return stroke phase can also cause induced voltage, which is responsible for many power outages. The most frequently used models to calculate lightning-induced voltage are the engineering models, which can be expressed based on a few coupling models, as listed below \([61–63]\):

1. Rusck model;
2. Chowduri model;
3. Taylor model;
4. Rachidi model;
5. Agrawal model.

In this study, the Rusck model was applied because of its simplicity and mathematically correctness, in addition to being consistent with experimental results \([64]\). The Rusck
model was validated with standard IEEE Standard 1410–2004 [64] and modeled using Equation (2):

\[
V(x, t) = \frac{\zeta_0 I_0 h}{4\pi} \beta \left( \frac{ct - x}{d^2 + \beta^2 (ct - x)^2} \left( 1 + \frac{x + \beta^2 (ct - x)}{\sqrt{(\beta ct)^2 + x^2 + d^2}} \right) + \frac{ct + x}{d^2 + \beta^2 (ct + x)^2} \left( 1 + \frac{x + \beta^2 (ct + x)}{\sqrt{(\beta ct)^2 + x^2 + d^2}} \right) \right)
\]  

where \( \beta = \frac{v}{c} \) is the ratio between the return stroke velocity and the light speed, \( \zeta_0 \) is 376.730313 \( \Omega \) (free space characteristic impedance), \( I_0 \) is the return stroke current, \( d \) is the horizontal distance between the lightning channel and the system, \( x \) is the point nearest to the lightning strike, \( h \) is the system height, and \( \gamma \) is equal to \( \frac{1}{\sqrt{1 - \beta^2}} \). The graph pattern for lightning-induced overvoltage at 19 kA is shown in Figure 10.

4.4. Case study of Lightning-Induced Overvoltage on Hybrid Solar PV–Battery Energy Storage Systems

The case study demonstrated an indirect lightning strike by using a lightning current waveshape of 10/350 \( \mu \)s. The indirect lightning was considered to have struck the ground or a nearby object or system based on different strike locations and different lightning current amplitudes, which were induced in between the battery energy storage system and inverter. The lightning-induced overvoltage model and geometry case study are presented in Figure 11a,b respectively. Lightning was also induced at a common point in between the hybrid solar PV–battery energy storage and inverter, as shown in Figure 12.

Figure 11. (a) Lightning-induced overvoltage model. (b) Geometry adopted for the lightning-induced overvoltage.
5. Simulation Results and Discussion

In this study, the simulations were divided into three sections, namely the lightning-induced overvoltage effect analysis on the hybrid solar PV–battery energy storage system with different lightning current amplitudes (e.g., 3 kA, 19 kA, and 169 kA), the analysis of different distances of lightning strike locations (e.g., 20, 50, and 100 m), and the analysis of different cable lengths (e.g., 5, 10, and 20 m). The presence of a lightning current along the channel and in the hybrid solar PV–battery energy storage system at the point nearest the lightning strike, $x = 0$, was defined as outlined in Sections 5.1–5.3. The lightning current waveform of 10/350\µs was simulated using the Heidler function and lightning-induced overvoltage was simulated using the Rusck model. The parameters of the simulation and the recorded data for lightning-induced overvoltage are shown in Tables 8 and 9, respectively.

Table 8. List of parameters used for simulations of the hybrid solar PV–battery energy storage system.

<table>
<thead>
<tr>
<th>Lightning Current (kA) [56,59,60]</th>
<th>Height (m) [68]</th>
<th>Velocity (m/s) [64,66,67]</th>
<th>The Horizontal Distance between the Lightning Channel and the System, d (m) [68–70]</th>
<th>The Point Nearest to the Lightning Strike, x (m) [68–70]</th>
<th>Cable Length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>19</td>
<td>2.8</td>
<td>$1.2 \times 10^{-8}$</td>
<td>20</td>
<td>50</td>
<td>10</td>
</tr>
<tr>
<td>169</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>20</td>
</tr>
</tbody>
</table>

Table 9. Lightning-induced overvoltage based on the lightning current waveform (10/350\µs).

<table>
<thead>
<tr>
<th>Lightning Current $I_0$, (kA)</th>
<th>The Point Nearest to the Lightning Strike, x (m)</th>
<th>The Horizontal Distance between the Lightning Channel and the System, d (m)</th>
<th>Cable Length 5 m</th>
<th>Cable Length 10 m</th>
<th>Cable Length 20 m</th>
<th>Lightning-Induced Overvoltage, kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>50</td>
<td>20</td>
<td>1.9</td>
<td>1.9</td>
<td>1.9</td>
<td>$V_{PV/battery}$ $V_{DC}$</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>20</td>
<td>1.7</td>
<td>1.7</td>
<td>1.7</td>
<td>$V_{PV/battery}$ $V_{DC}$</td>
</tr>
<tr>
<td>19</td>
<td>0</td>
<td>20</td>
<td>12.1</td>
<td>12.1</td>
<td>12.1</td>
<td>$V_{PV/battery}$ $V_{DC}$</td>
</tr>
<tr>
<td>169</td>
<td>100</td>
<td>20</td>
<td>10.5</td>
<td>10.5</td>
<td>10.5</td>
<td>$V_{PV/battery}$ $V_{DC}$</td>
</tr>
</tbody>
</table>

Figure 12. Block diagram of lightning-induced overvoltage in the system.
5.1. Effect of Different Lightning Strike Distances

An investigation of lightning-induced overvoltage due to indirect lightning strikes was conducted on the hybrid solar PV–battery energy storage system when there was no lightning protection and no surge arresters were connected to observe the effects of lightning-induced overvoltage on the system. In this section, the impacts of different lightning strike distances on the system are discussed accordingly.

Figure 13a–c presents the effects of lightning-induced voltages at different lightning strike distances (20, 50, and 100 m) from the system; the closer the lightning strike location is to the system, the higher the lightning-induced overvoltage. For instance, d = 20 m was the closest lightning strike distance to the system, and thus the lightning-induced overvoltage value was much higher than at lightning strike points d = 50 m and d = 100 m.

Figure 13. (a) Induced voltage at x = 0 (d = 20 m, 50 m, 100 m, I₀ = 3 kA, β = 0.4, timescale 30 µs). (b) Induced voltage at x = 0 (d = 20 m, 50 m, 100 m, I₀ = 19 kA, β = 0.4, timescale 30 µs). (c) Induced voltage at x = 0 (d = 20 m, 50 m, 100 m, I₀ = 169 kA, β = 0.4, timescale 30 µs).

From Figure 14, it can also be seen that the closest lightning strike location to the system caused short circuits and disruption of energy supply to the grid. According to MS IEC 60664-1 [71], the impulse withstand voltage for solar PV–battery systems and inverters at the DC side is 6 kV. Hence, the results show that with increasing lightning strike distances for the lightning current amplitude of 3 kA, the lightning-induced overvoltage was less than the impulse withstand voltage, while for the lightning current amplitude of 19 kA, the lightning-induced overvoltage decreased from 12.1 kV at 20 m to 11.7 kV at 50 m and 10.5 kV at 100 m. These values exceeded the impulse withstand voltages by about 67% at 20 m, 64% at 50 m, and 54% at 100 m, respectively. However, the percentage of values exceeding
the impulse withstand voltage was found to be more than 100% in for 169 kA, regardless of the stroke distance (from 20 to 100 m).

![Figure 14](image_url)

**Figure 14.** Lightning-induced overvoltage peak versus horizontal distance \((x = 0, I_0 = 19 \text{ kA}, v = 1.2 \times 10^{-8} \text{ m/s})\).

5.2. Effect of Different Lightning Current Amplitudes

Next, in this section, the effects of lightning-induced overvoltage with different lightning current amplitudes are discussed. From this case study, it can be seen how much the lightning current amplitudes affect the performance of the hybrid solar PV–battery energy storage system.

Figure 15a–c demonstrates the effects of lightning-induced overvoltage when the system was struck by different lightning current amplitudes at different lightning strike distances, \(d\). When the lightning currents increased, the lightning-induced voltages also increased, as shown in Figure 16.

![Figure 15](image_url)

**Figure 15.** (a) Induced voltage at \(x = 0\) \((d = 20 \text{ m}, I_0 = 3 \text{ kA}, 19 \text{ kA}, 169 \text{ kA}, \beta = 0.4, \text{ timescale } 30 \mu\text{s})\). (b) Induced voltage at \(x = 0\) \((d = 50 \text{ m}, I_0 = 3 \text{ kA}, 19 \text{ kA}, 169 \text{ kA}, \beta = 0.4, \text{ timescale } 30 \mu\text{s})\). (c) Induced voltage at \(x = 0\) \((d = 100 \text{ m}, I_0 = 3 \text{ kA}, 19 \text{ kA}, 169 \text{ kA}, \beta = 0.4, \text{ timescale } 30 \mu\text{s})\).
15 of 19

Based on the abovementioned results, insulation coordination is needed for equipment at low voltages. The lightning impulse withstand voltage for the electronic equipment in low-voltage systems is listed in Section 4.3.3.2.2 of MS IEC 60664-1 [71], whereby the equipment in hybrid solar PV–battery energy storage systems, especially the solar PV, battery energy storage, and inverter components, are assumed to be in overvoltage category II, i.e., 6kV. Therefore, it can be seen that the system modeled herein requires a surge protection device to protect the equipment from damage by an indirect lightning strike.

5.3. Effects of Different Cable Lengths

Lastly, in this part, the effects of lightning-induced overvoltage with lightning current amplitude \( I_0 = 19 \text{ kA} \) at \( d = 50 \text{ m} \) on different cable lengths (5, 10, and 20 m) are discussed accordingly. The flexible tinned copper cable was designed according to standard IEC 60228 class 5, as shown in Table 3 [72].

It can be observed from Table 9 and Figure 17 that the lightning-induced overvoltage was the same for all three cable lengths (5, 10, and 20 m). This was because the cable lengths were considered short and the voltage drops for all three cable lengths were too small. Figure 18 also presents the lightning-induced overvoltage profile, whereby the lightning overvoltage was induced at an observation point of 10 m and the induced overvoltage was measured every 2 m thereafter across a total cable length of 20 m. This resulted in the same induced overvoltage values. However, if the cable lengths were longer than 20 m, the impacts of lightning-induced overvoltage could have been noticed, since the cable resistance would be large enough for the high-voltage drop along the line [24,73].

![Figure 16](image1.png)

**Figure 16.** Lightning-induced overvoltage peak versus lightning current peak value \( (x = 0, d = 50 \text{ m}, v = 1.2 \times 10^{-8} \text{ m/s}) \).

![Figure 17](image2.png)

**Figure 17.** Lightning-induced overvoltage versus cable length (5, 10, and 20 m; \( I_0 = 19 \text{ kA}, x = 0, d = 50 \text{ m}, v = 1.2 \times 10^{-8} \text{ m/s}) \).
Figure 18. The lightning-induced overvoltage profile when the lightning is induced at an observation point of 10 m, with the lightning-induced overvoltage values measured at every observation point (spaced 2 m apart, for a total cable length of 20 m; \(I_0 = 19\) kA, \(x = 0\), \(d = 50\) m, \(v = 1.2 \times 10^{-8}\) m/s).

6. Conclusions

Throughout this paper, the impacts of different lightning current amplitudes, lightning strike locations, and cable lengths on hybrid solar PV–battery energy storage systems have been analyzed. Although one can logically infer that lightning-induced overvoltage is increased with increased lightning current amplitude, it was indeed the aim of this paper to quantify the results based on several parameters, such as the cable length and distance from the lightning source. The results obtained allowed us to quantify this sought-after information, particularly related to strike distance and cable length, which are often discussed in international working groups such as International Council on Large Electric Systems Working Group Committees 4.44 (CIGRE WG C4.44) on Electromagnetic Compatibility (EMC) for Large Photovoltaic Systems.

In this work, the differences in cable length did not have much impact on the lightning-induced overvoltage, since the voltage drop was too small due to the cable lengths being short. It is quite interesting that the effects of cable length were much more significant in the case of a direct strike [11]. Nevertheless, since the effects of lightning-induced voltages on the hybrid solar PV–battery energy storage system were highly dependent on the abovementioned factors, an insulation coordination study is crucially needed to ensure the security of grid-connected systems, as well as to assign and coordinate appropriate protection schemes. This work is in line with the current direction of the CIGRE Working Group C4.44 on EMC for Large-Scale Solar Systems, which is in the midst of developing its technical brochure. Overall, this study has spurred some ideas on the requirements for lightning protection system (LPS) installations, i.e., how the appropriate protection scheme should be coordinated and the numbers and ratings of surge protection devices for hybrid solar PV–battery energy storage systems. This is due to the fact that the possible risk posed by lightning strikes, as well as the requirements for lightning protection, are crucial steps in designing a lightning protection system. Essentially, a lightning protection system is a must-consider item for system protection. Therefore, the results and analyses presented in this paper will be useful information and sources for other researchers, as well as a basic guideline for conducting future research on insulation coordination in hybrid solar PV–battery energy storage systems.


Funding: This research and APC were funded by Ministry of Higher Education, Fundamental Research Grant Scheme (FRGS) scheme, grant number FRGS/1/2018/TK07/UNITEN/02/5, and
also the Building Opportunity Leading Dreams (BOLD) publication fund provided by Universiti Tenaga Nasional.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

**Acknowledgments:** The authors would like to express their sincere gratitude to the Ministry of Higher Education, Institute Power Engineering, and Building Opportunity Leading Dreams (BOLD) Scholarship of Universiti Tenaga Nasional (UNITEN).

**Conflicts of Interest:** The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

**References**


44. Christodoulou, C.A.; Ekonomou, L.; Gonos, I.F.; Papanikolaou, N.P. Lightning protection of PV systems. Energy Syst. 2016, 7, 469–482. [CrossRef]


51. Ittarat, S.; Hiranvarodom, S.; Plangklang, B. A computer program for evaluating the risk of lightning impact and for designing the installation of lightning rod protection for photovoltaic system. *Energy Procedia* 2013, 34, 318–325. [CrossRef]


66. Cooray, V.; Montano, R.; Rakov, V. A model to represent negative and positive lightning first strokes with connecting leaders. *J. Electrost.* 2004, 60, 97–109. [CrossRef]


