Earthing system for stand alone PV solar house

M. Nassereddine, J. Rizk, M. Nagrial, A. Hellany

School of Computing, Engineering & Mathematics, Western Sydney University, Penrith, Australia.

Abstract
Renewable energy is becoming an essential element when it comes to climate change. The advance technology in energy storage increases the installation of standalone system for residential houses. As the solar system is the sole power source for the property, a rigid reliability system should be designed. The paper addresses the earthing requirement for the standalone system to mitigate lightning strike, transfer voltage from nearby high voltage infrastructure and adequate protection operation. Case study is also included.

Copyright © 2016 International Energy and Environment Foundation - All rights reserved.

Keywords: Earth grid; Earth potential rise; Lightning; Soil resistivity; Transfer voltage.

1. Introduction
Climate change is a contemporary issue, and the international communities have accepted the dangers of greenhouse gas emissions. Methodologies and policies on how to address this important issue, is now a popularly debated topic. Renewable energy is one of the hot topics when it comes to greenhouse gas emissions treatments. Solar system is one of the renewable energy power sources that help in reducing the carbon dioxide from the atmosphere. In the recent days, more standalone systems are being installed worldwide. The system consists of the followings [1-5]:

- Solar panels
- Controller charger
- Energy storage
- Inverter

The design and installations should take into consideration the earthing aspect of the electrical system. Different standards have different approach when it comes to earthing for the PV solar system. For example, the information in [6] only permit the earthing of the metallic body of the system, the voltage terminals are not earthed while other systems allow for earthing the negative terminals of the PV solar system.

The neighboring between residential properties and high voltage infrastructure introduces the risk of transfer voltage [7-10]. The current research shows that high voltage fault has the potential to transfer to nearby conductive structures [11-17]. The magnitude of the transferred voltage could reach an unsafe condition and jeopardize safety of the residence. Therefore, earthing system shall be considered to mitigate the issue of the transfer voltage.

In addition, standalone house is the only power source; therefore it should be protected against lightning strike. Earthing system is an essential element when it comes to lightning performance [18, 20]. The adequate earthing system absorbs the lightning energy into the ground without causing any damage to the standalone system.
The paper addresses the different type of earthing to ensure system compliance against direct lightning strike, internal fault, protection operation and transfer voltage from nearby high voltage asset.

2. Theoretical study
This section is divided into the following subsections:
- Lightning system
- Transfer EPR
- Internal fault protection
It should be noted, this paper focuses on the lightning system and transfer EPR.

2.1 Lightning design
Lightning strike can cause fatality, damage to building and electrical infrastructure. The solar system for a standalone house form the only power source, therefore, it is critical to design and adequate earthing system to avoid any disturbance to the system.

When the lightning strikes the ground, it chooses a path with low resistance and direct to the ground [18]. According to the IEEE standard [19] “the stroke occurs in two steps, the first is ionization of the air surrounding the centre and the development of stepped leaders, which propagate charge from the cloud into the air”. The second step is the return stroke, according to the same standard, “the return stroke is the extremely bright streamer that propagates upward from the earth to the cloud following the same path as the main channel of the downward stepped leader”.

The lightning current magnitude changes with the striking distance. The most comment equations that links the distance to the current magnitudes are [19, 20]:

\[
\text{Darveniza } S = 2I + 30 \left( 1 - e^{-\frac{I}{6.8}} \right) 
\]

\[
\text{Love } S = 10I^{0.65} 
\]

\[
\text{Whitehead } S = 9.4I^{\frac{2}{3}} 
\]

\[
\text{IEEE } S = 8I^{0.65} 
\]

\[
\text{Suzuki } S = 3.3I^{0.78} 
\]

where: \( I \) is the return stroke current in kA, \( S \) is the strike distance in meters.

Table 1 shows the 4 protection levels as per the Australian standard [20]. Depending on the location and probability assessments, the designer choose one of these protection levels for the lightning design.

<table>
<thead>
<tr>
<th>Protection Level</th>
<th>Sphere radius (m)</th>
<th>Interception Current (kA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20</td>
<td>2.9</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>5.4</td>
</tr>
<tr>
<td>3</td>
<td>45</td>
<td>10.1</td>
</tr>
<tr>
<td>4</td>
<td>60</td>
<td>15.7</td>
</tr>
</tbody>
</table>

This paper follows the rolling sphere lightning protection to ensure system compliance for direct lightning strike. The rolling sphere method uses the mast to capture lightning strike. The mast characteristics depend on the strike distance. Figure 1 shows the concept behind the rolling sphere. The figure shows that proposed mast protect the object; the lightning sphere doesn’t interfere with the object. The PV solar system is usually installed on the roof. Figure 2 shows the proposed lightning protection mast layout. The heights of the masts and numbers depend on the roof angle and area.
The details of the masts can be found by analyzing Figure 3. Equation 6 is generated by analyzing the geometric dimensions of Figure 3.

\[
H = \frac{2S - \sqrt{4S^2 - C^2}}{2\cos(\alpha)}
\]  

(6)

where: \(H\) is the mast heights above roof (it is assumed both masts has the same heights, \(S\) is the strike distance, \(C\) is the separation between the two masts, \(\alpha\) is the title angle of the roof.

For the proposed house lightning protection, the distance between the masts are equal. Figure 4 shows the proposed distance and also show the proposed distance \(C\). Based on Figure 4, \(C\) is presented by equation 7

\[
C = 1.44L
\]

(7)

For an effective lightning system, these masts should be connected to a low earth grid resistance [19-21]. The earth grid resistance depends on the soil resistivity structure of the area. Below are the four commonly used methods for obtaining the soil resistivity of the area [22-24].
2.1.1 Wenner method
Wenner method consists of four electrodes, two are for current injection and two for potential measurement, Figure 5 shows the Wenner method.

![Figure 5. Wenner four probe arrangement](image)

The soil resistivity formula associated with Wenner method is shown in equation 8 where $R$ is the resistance measured by the machine, $a$ is the spacing of the probe

$$\rho = \frac{2\pi aR}{\pi}$$

\hspace{1cm} (8)

2.2.2 Schlumberger array
Figure 6 shows the arrangement for the Schlumberger Array. The soil resistivity can be calculated using equation 9:

$$\rho = \frac{\pi l^2 R}{2l}$$

\hspace{1cm} (9)

where: $L$ is the distance the centre from the outer probe, $l$ distance to the centre from the inner probe.

![Figure 6. Schlumberger array layout](image)

2.2.3 Driven rod method
This method is also called the three probe method or three pin method (Figure 7). This method is most suitable for an area where the physical layout makes the usage of the previous two methods difficult; the soil resistivity under this method can be calculated using equation 10:
\[ \rho = \frac{2\pi R}{\ln\left(\frac{8l}{d}\right)} \]  

(10)

where: \( l \) is the length of driven rod in contact with earth, \( d \) driven rod diameter.

Figure 7. Driven Rod test layout

After obtaining the soil resistivity data from the field tests, equation 11 uses the obtained soil resistivity to compute the grid resistance of single electrode.

\[ R_s = \frac{\rho}{2\pi L}\left(\ln\left(\frac{8L}{d}\right)-1\right) \]  

(11)

where: \( L \) is the buried length of the electrode in meters, \( D \) the diameter of the electrode in meters.

If one electrode could not achieve the required resistance level, placing few electrodes in parallel will help in reducing the grid resistance, equation 12 shows the resistance for the grid formed with few electrodes in parallel.

\[ R = \frac{\rho}{\pi L}\left(\ln\left(\frac{2L}{b}\right)-1\right) \]  

(12)

where: \( L \) is the buried length of the electrode, \( b \) equivalent radius off the electrode at the surface.

\[ b = (dhS)^{0.25} \]

\[ S = (4h_s + s^2)^{0.5} \]  

(13)

where: \( d \) is the diameter of the electrode, \( h \) buried depth, \( s \) distance between 2 parallel electrode, \( S \) distance from one electrode to the image of the other in meters.

The earth grid could also consist of mesh grid buried at a depth of 0.5 meters or more, the mesh could consist of multiple horizontal conductors buried at the required depth. Equation 14 shows the resistance of this mesh:

\[ R = \frac{\rho}{\pi L}\left(\ln\left(\frac{4L}{(dh)^{0.5}}\right)-1\right) \]  

(14)

where: \( h \) is the buried depth, \( L \) length of the electrode, \( d \) diameter of the electrode.
For lightning purpose, the earth grid resistance shall maintain a low resistance, usually below 10ohms [19-21].

2.2 Transfer EPR

Standalone house could be located near high voltage infrastructure. In Sydney, it is possible for the high voltage Padmount to be located within the same lot. Under high voltage fault condition, the generated EPR could transfer to the installed lightning earth grid at the standalone house. Figure 8 shows the touch voltages on the house due to transfer voltage. The figure shows magnitude of 915V transferred to the installed grid. The simulation is completed using the following inputs:

- Fault current of 2kA
- Padmount easement of 3.3x5.3m
- 5 electrodes (5m)
- House dimensions, 9x20m
- 4 electrodes for lightning (1.44m)
- Soil resistivity of 50ohm.m

The touch voltage on the lightning earth grid varies between 450V and 1300V. These values could jeopardize the human safety.

Regarding the theory behind the transfer voltage, please refer to the work in [11, 22].

Two options are available to address the issue of high transfer voltages:

- Request the owner of the Padmount to reduce its EPR
- Change the proposed layout of the lightning earth grid

Figure 8. Touch voltage due to Padmount EPR
It is clearly shown that high potential could exist on the earthing system of the standalone solar system. These transfer voltages have the potential to cause human fatalities and damage to equipment.

2.3 Protection and earthing
The standalone solar system should have an adequate earthing system to ensure system compliance. The earthing of the solar system form one of the main elements to ensure protection compliance. Depending on the design, earthing could be an essential element for fault detection and to ensure circuit breaker operates as per the design [25, 26].

3. Theoretical discussions
The design of the standalone system should meet the required reliability as it form the sole power source. The theoretical study highlighted the lightning design requirements to reduce the risk of direct lightning strike. The proposed arrangement ensures system projection again lightning strike. Furthermore, the paper introduces the enhanced equation that aid with the determination of the lightning mast details. The equation can be used by householders to check the compliance of the system if required.

In addition, the paper shows the issue presented with the existence of the high voltage infrastructure near the stand alone system. The work briefly proposed three methods to address the existing risks. It should be noted that the high transfer voltage could exceed the equipment rating which leads to system malfunction. As the solar system is the sole power source, the design should eliminate all source of disturbance including transfer EPR. In addition, the paper provides the owners with the basic information that can be used to check against the stand alone design for their properties.

Based on the works, the following diagram can be generated (Figure 9).

![Figure 9. Reliability diagram for standalone system](image)

4. Case study
A newly constructed house is designed for standalone solar system. The followings are the house details:
- Roof that faces north has an area of (5x10) 50m²
- Roof tilt is 20 degree
- 5kW solar system is proposed

4.1 Lightning design
The assessment of the lightning shows level 3 protections is required. The assessment is based on the Australian standard [19]. Therefore the strike distance is 45m.
L is 5m as per the design input. Therefore equation 7 gives:

\[ C = 1.44 \times 5 = 7.2m \]  

Equation 6 is used to compute the mast heights:

\[ H = \frac{2S - \sqrt{4S^2 - C^2}}{2\cos(\alpha)} = \frac{2 \times 45 - \sqrt{(4 \times 45^2 - 7.2^2)}}{2\cos(20)} = 0.153m \]  

(16)

Figure 10 shows the proposed masts layout. The generated equation is used to compute the details of the masts.

To complete the earthing system design of the proposed lightning masts, Wenner method is used to capture the soil resistivity of the ground. The results are shown in Table 2.

<table>
<thead>
<tr>
<th>Electrode Spacing a (m)</th>
<th>Apparent resistivity (ohm.m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>10</td>
<td>11</td>
</tr>
<tr>
<td>12</td>
<td>13</td>
</tr>
<tr>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>32</td>
<td>18</td>
</tr>
</tbody>
</table>

Based on the obtained soil resistivity data, 5m single electrode grid resistance is computed to be 2.144 ohms. Figure 11 shows the proposed earth grid with single 5m electrode.

The standalone system will be grounded to the earth grid shown in Figure 11. For example, the following will be connected to the earth grid: the inverter earth, frame of the solar panels, frame of the storage energy, switchboard earthing requirements, etc….

4.2 Transfer EPR

The padmount substation that feeds the proposed subdivision is located on a separate lot as shown in Figure 12. Distance is approximately 57m. The padmount system has separate earthing arrangement (HV and LV earth grid are separate).

CDEGS engineering software is used to compute the transfer voltage to the proposed lightning earth grid. The results shows that the transferred is below the acceptable limits and has no impact on the proposed system.
4.3 Final assessment

The house owner can use the diagram in Figure 9 to assess the compliance of the system against the required reliability. The assessment path is shown in red within Figure 13. The results show that the proposed standalone house comply to the proposed reliability diagram.
5. Conclusion
The paper addresses the minimum requirements to ensure the designed standalone house is protected against lightning strike. Also, it generates equation 6 which aids in determining the mast details. The case study shows that equation 6 makes the assessment of the lightning masts simple. Also the paper discussed the soil resistivity measurements and its relation to the earth grid resistance. Furthermore, the paper highlighted the issue with the transfer voltage from nearby high voltage infrastructure. In addition, the paper introduces the reliability diagram as shown in Figure 9. The case study confirms the advance engineers when using the proposed diagram.

Acknowledgements
This work was supported by NEEC PTY LTD (www.neecgroup.com)

References
[10] AS 2067:2008 “Substation and high voltage installations exceeding 1kV A.C.”.
[23] IEEE 142-2007 “Grounding of industrial and commercial power systems”.

Mohamad Nassereddine obtained his BEng (electrical) and M. Eng. (Hons) from University of Western Sydney, Sydney, Australia. He has many publications in the earthing and lightning design and he has many publications in the field of Switched Reluctance Generator for Wind Energy Applications. He is also a Ph.D. researcher at University of Western Sydney. Mr. Nassereddine has more than 10 years engineering experience in the design and construction of substations and transmission lines. His research interests are in the fields of earthing and lightning design for substations and transmission lines, renewable energy for standalone home and smart grid.
E-mail address: m.nassereddine@westernsydney.edu.au

Jamal Rizk is a member of the Research Group: “Intelligent and Sustainable Electrical Systems (ISES)” research group. He has a doctorate from Kharkov Polytechnic, Ukraine and a Ph.D. from University of Western Sydney, Australia. Dr Rizk is a Senior Lecturer in the school of Engineering and Industrial Design, University of Western Sydney. He has attended and presented results of his research at different Australian and International Conferences. Dr Rizk has developed special expertise in the magnetic analysis of different types of permanent magnet machines. He has been involved in design, fabrication and testing of electrical drives. Dr Rizk was the postgraduate and research coordinator in the school of Engineering and Industrial Design, WUS. Dr Rizk has acted as reviewer for papers for National and International conferences. His research interests are in the fields of renewable energy systems, electric drives and high voltage earthing system.
E-mail address: j.rizk@westernsydney.edu.au
Mahmood Nagrial obtained his Ph.D. from University of Leeds, UK. Dr Nagrial is Group Leader for Research Group “Intelligent and Sustainable Electrical Systems”. Dr Nagrial has been a leading researcher in the area of renewable energy systems, permanent magnet, variable reluctance machines and drive systems. He has provided leadership in the accreditation of various engineering degree programs from I.E. Aust. He has been Head, Electrical & Computer Engineering. He has also been responsible for initiating postgraduate courses and higher degree research programs in Electrical & Computer Engineering. He has supervised Ph.D. and M.Eng. (Hons) Research Theses and postdoctoral fellows in his general area of research. He had many research grants to support his research activities. He has extensive experience in Power Electronics and Drive Systems, Renewable Energy Systems. His research interests are in the fields of renewable energy systems, power quality and electric machines.

E-mail address: m.nagrial@westernsydney.edu.au

Ali Hellany holds a BE in Telecommunication, ME (Hons) in Electrical Engineering and a Ph.D in Electrical Engineering, from University of Western Sydney (Australia). Ali is a member of IEEE, Executive member of IEEE NSW Section and Chairing the student activities. Ali is a member of the Electromagnetic society. Ali Hellany is a senior lecturer in Electrical Engineering, University of Western Sydney since 2002. Dr Hellany is a member of the Research Group: “Intelligent and Sustainable Electrical Systems (ISES)” research group. Dr Hellany has published numerous papers in the Electromagnetic Compatibility, power quality, AC Interference, teaching styles and digital forensics area in journals and presented his research in many International conferences. His research interests are in the fields of AC interference, renewable energy and power quality.

E-mail address: a.hellany@westernsydney.edu.au