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Earthing system for stand alone PV solar house

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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.

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]:

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

Love $S = 10I^{0.65}$ (2)

Whitehead $S = 9.4I^{\frac{2}{3}}$ (3)

IEEE $S = 8I^{0.65}$ (4)

Suzuki $S = 3.3I^{0.78}$ (5)

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 1. Lightning current capacity with respect to the strike distance

Protection Level	Sphere radius (m)	Interception Current (kA)
1	20	2.9
2	30	5.4
3	45	10.1
4	60	15.7

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.

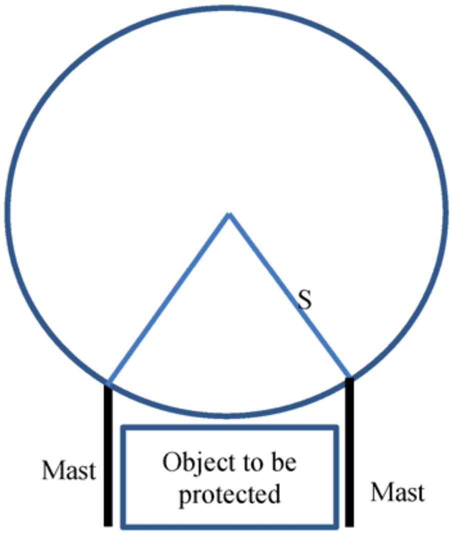


Figure 1. Rolling sphere for lightning protection

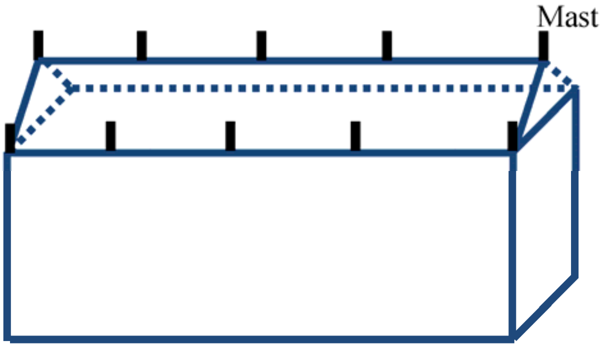


Figure 2. House lightning masts location

The details of the masts can be found by analyzing Figure 3. Equation 6 is generated by analyzing the geometric dimensions of Figure 3.

$$H = \frac{2S - \sqrt{4S^2 - C^2}}{2Cos(\alpha)} \tag{6}$$

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, α 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

$$C = 1.44L \tag{7}$$

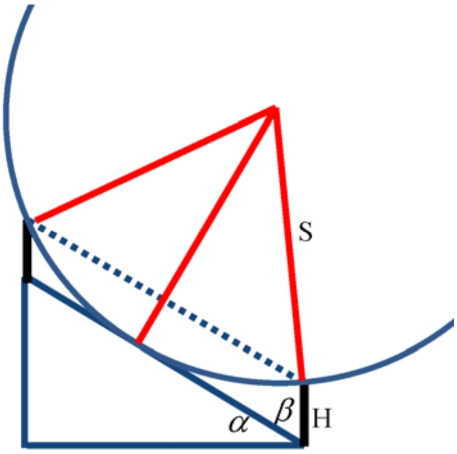


Figure 3. Lightning mast protecting the roof

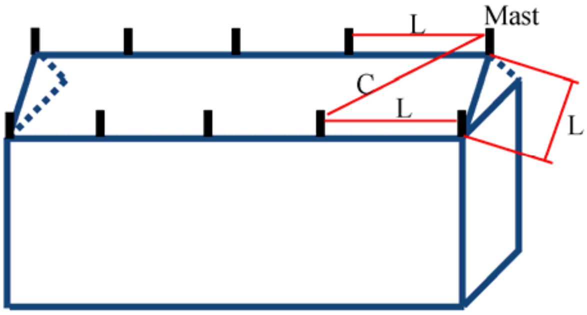


Figure 4. Proposed mask layout

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.

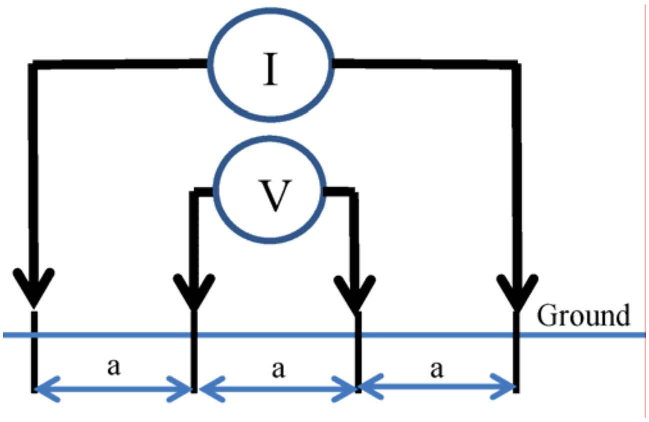


Figure 5. Wenner four probe arrangement

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

$$\rho = 2\pi aR \tag{8}$$

2.2.2 Schlumberger array

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

$$\rho = \frac{\pi L^2 R}{2l} \tag{9}$$

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

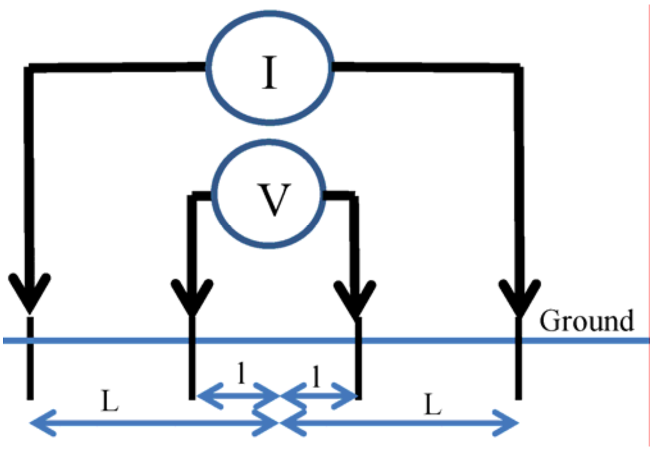


Figure 6. Schlumberger array layout

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:

$$\rho = \frac{2\pi l R}{\ln\left(\frac{8l}{d}\right)} \tag{10}$$

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

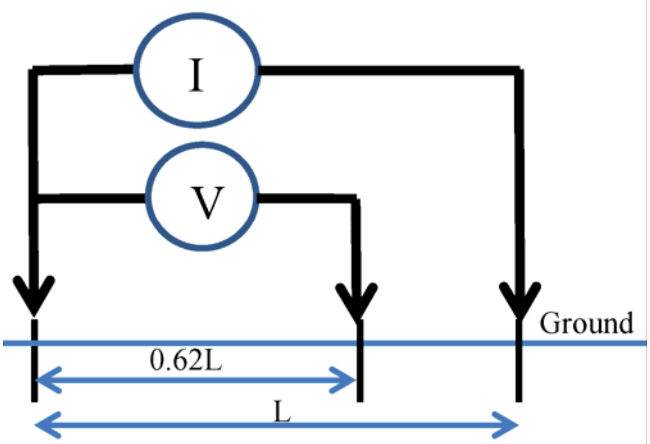


Figure 7. Driven Rod test layout

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.

$$R_g = \frac{\rho}{2\pi L}\left(\ln\left(\frac{8L}{d}\right) - 1\right) \tag{11}$$

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.

$$R = \frac{\rho}{\pi L}\left(\ln\left(\frac{2L}{b}\right) - 1\right) \tag{12}$$

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

$$\begin{aligned} b &= (dhsS)^{0.25} \\ S &= (4h_2 + s^2)^{0.5} \end{aligned} \tag{13}$$

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:

$$R = \frac{\rho}{\pi L}\left(\ln\left(\frac{4L}{(dh)^{0.5}}\right) - 1\right) \tag{14}$$

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 gird. 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

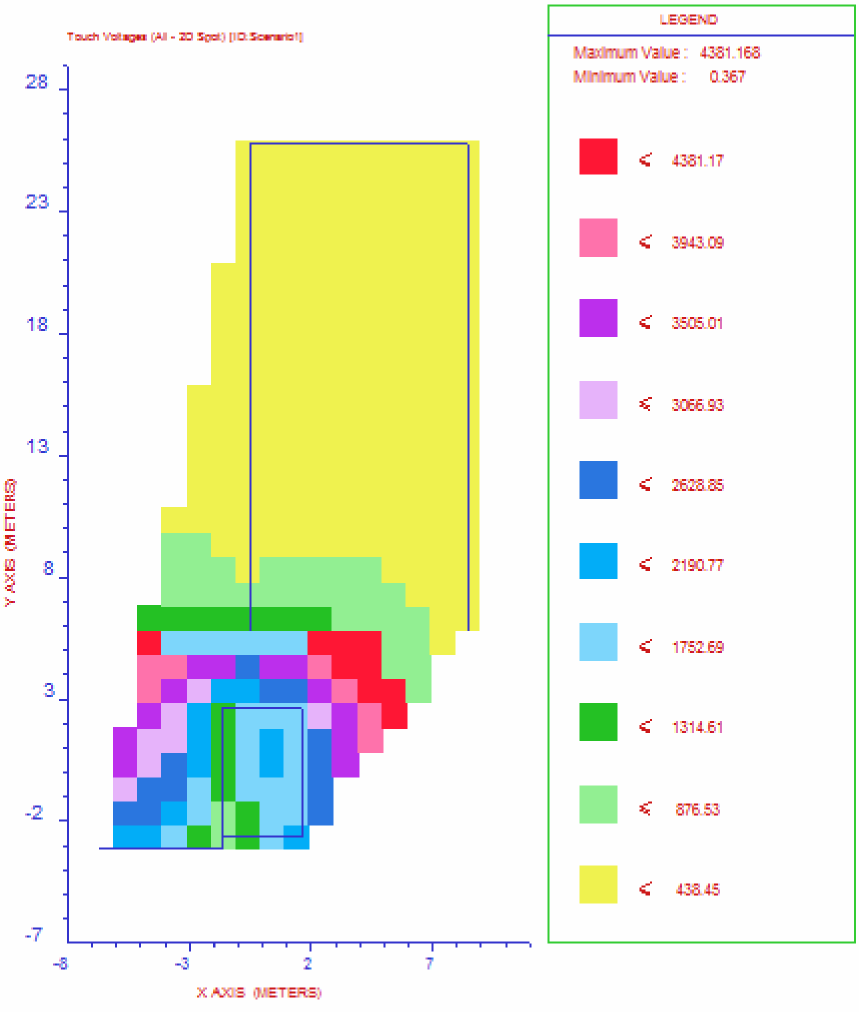


Figure 8. Touch voltage due to Padmount EPR

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).

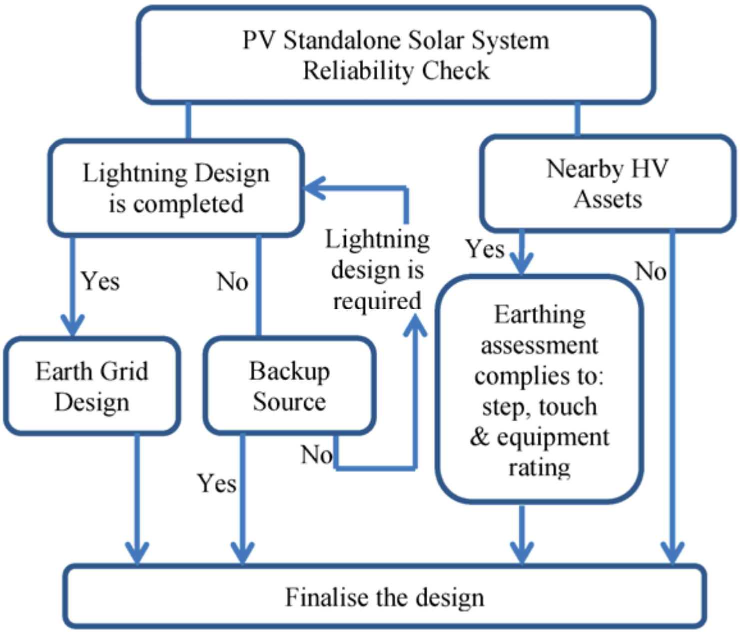


Figure 9. Reliability diagram for standalone system

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) 50m^2
- 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:

$$C = 1.44 \times 5 = 7.2m \tag{15}$$

Equation 6 is used to compute the mast heights:

$$H = \frac{2S - \sqrt{4S^2 - C^2}}{2\cos(\alpha)} = \frac{2 \times 45 - \sqrt{(4 \times 45^2 - 7.2^2)}}{2Cos(20)} = 0.153m \tag{16}$$

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.

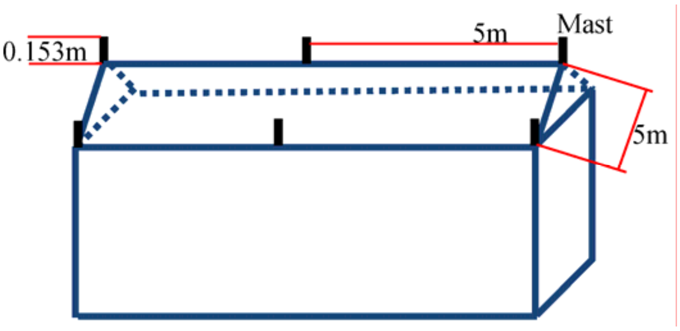


Figure 10. Lightning mast location and heights

Table 2. Soil resistivity field data

Electrode Spacing a (m)	Apparent resistivity (ohm.m)
1	5
2	4
3	6
4	7
5	6
8	8
10	11
12	13
16	16
32	18

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 gird. The results shows that the transferred is below the acceptable limits and has no impact on the proposed system.

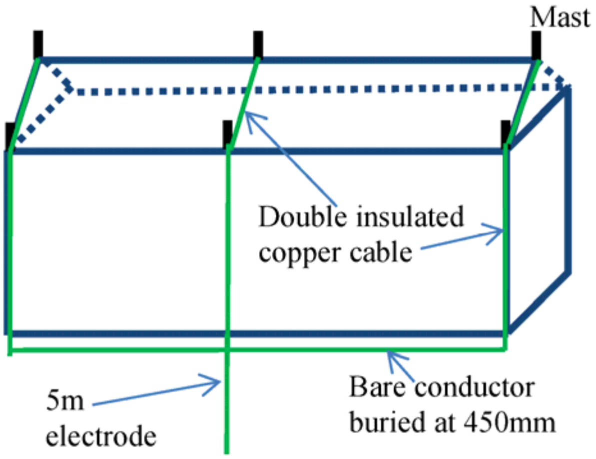
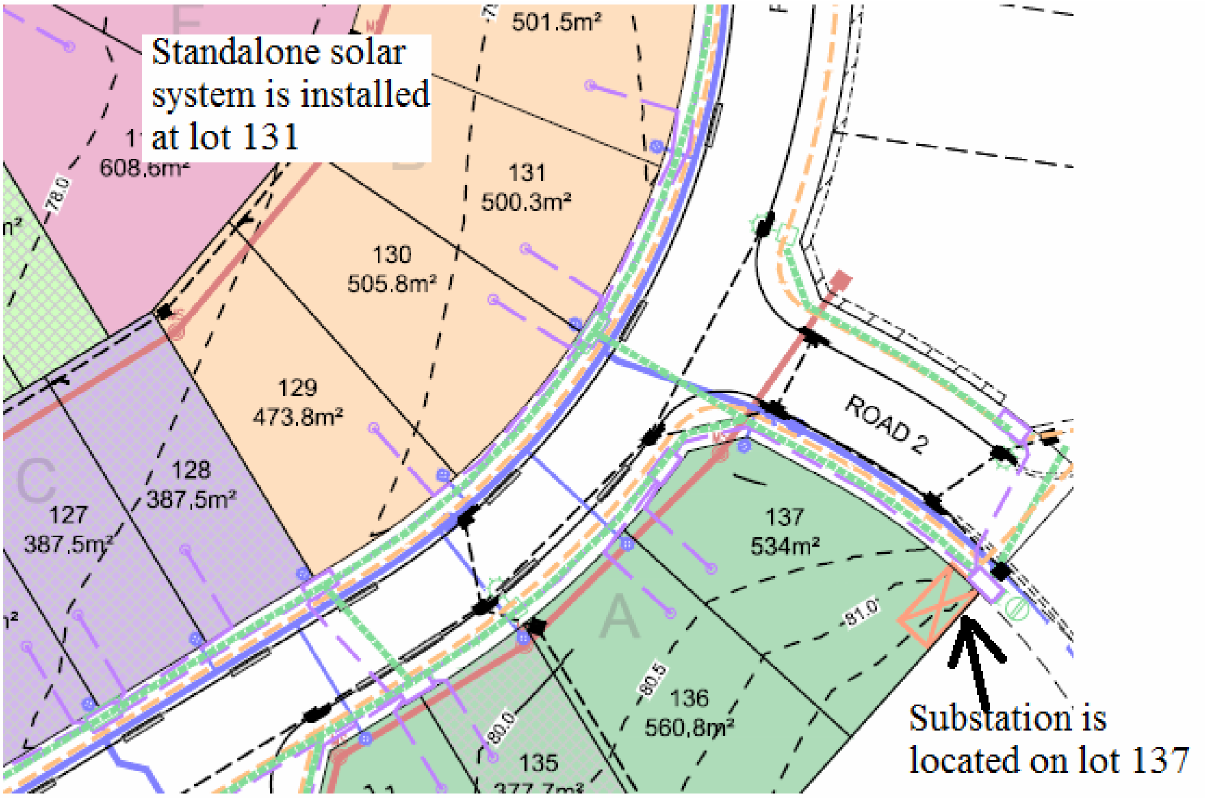


Figure 11. Proposed earthing arrangement


Standalone solar system is installed at lot 131

Substation is located on lot 137

Figure 12. Proposed Padmount substation location in respect to the stand alone house

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.

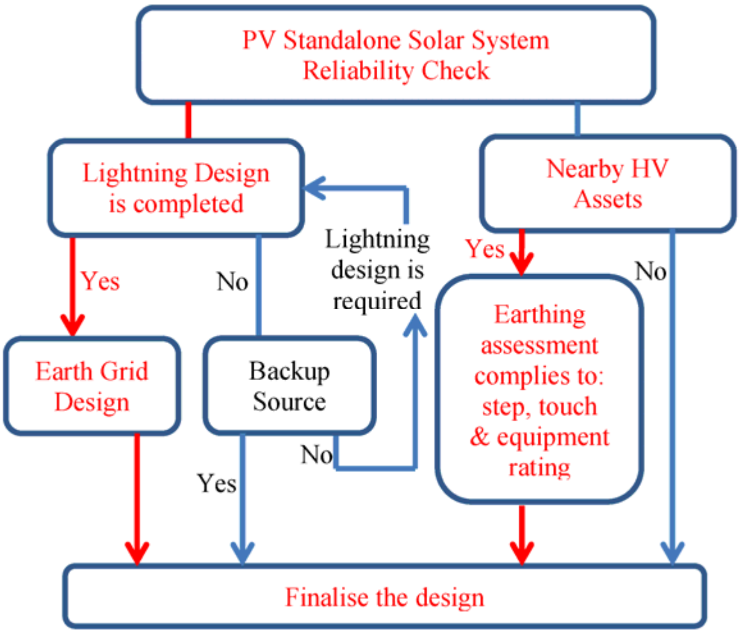


Figure 13. Reliability assessment

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

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References

[1] Lakshmo M., Sai Babu C. and Prasad S. “Design of off-grid homes with renewable energy sources” IET Chennai 3rd International Conference on Sustainable Energy and Intelligent Systems. 27-29 Dec. Tiruchengode, 2012.
[2] Menka D., Shailendra S. and Rakesh S. “Solar PV stand-alone water pumping system employing PMSM drive” IEEE Conference on Electrical, Electronics and Computer Science. 1-2 March. Bhopal 2014.
[3] Das M. and Agarwal V. “Novel high performance standalone solar PV system with high gain, high efficiency DC-DC converter power stages” IEEE Transactions on Industry Applications. Issue 99. Vol. PP.
[4] Swarna K., Oo V., Shafiullah M. and Stojcevski A. “Modelling and power quality analysis of a grid connected solar PV system” Australasian Universities Power Engineering Conference. 28 Sept. Perth 2014.
[5] Jain. S and Agarwal V. “A single stage grid connected inverter topology for solar PV systems with maximum power point tracking” IEEE Transactions on Power Electronics. Vol. 22. Issue 5. PP. 1928-1940. 2007.
[6] AS/NZS 5033:2014 “Installation and safety requirements for photovoltaic (PV) arrays”.
[7] Nassereddine M., Hellany A. and Rizk J. “How to design an effective earthing system to ensure the safety of the people” International Conference on Advances in Computational Tools for Engineering Applications, PP. 416-42, 2009.
[8] IEEE guide to safety in AC substation grounding, IEEE, New York, 2000.

[9] Nassereddine M., Hellany A., Nagrial M. and Rizk J. “Safety Compliance of Substation Earthing Design” World Academy of Science, engineering and Technology , Vol 60, PP. 525-529. 2011.

[10] AS 2067:2008 “Substation and high voltage installations exceeding 1kV A.C.”.

[11] Nassereddine M., Rizk J., Hellany A. and Nagrial M. ”Updated equation to compute the soil voltage contour under fault condition” International Journal of Energy and Environment, Vol. 6, Issue2, PP. 115-124, 2015.

[12] AS/NZS 4853:2012. Electric hazards on metallic pipelines.

[13] AS/NZS 3835.1: 2006. Earth potential rise-protection of telecommunication network users personnel and plant, code of practice.

[14] AS/NZS 3835.2: 2006. Earth potential rise-protection of telecommunication network users personnel and plant, application guide.

[15] AS/NZS 7000:2010. Overhead line design-detailed procedures.

[16] Andrenyi, J. “Analysis of transmission tower potentials during ground faults” IEEE Transactions on Power Apparatus and Systems, Vol. Pas-86, Issue 10. PP. 1274-1283. 1967.

[17] Nahman, J. and Dordevic, V. “Distribution of zero sequence current for earth fault occurring along a transmission line and proximity effects”. IEE Proc. Gen., Trans. and Dist., Vol. 140, Issue 5. PP. 427-432. 1993.

[18] Nassereddine M and Hellany A, 2009, Designing a Lightning Protection System Using the Rolling Sphere Method, Proceeding in the 2009 International Conference on Computer and Electrical Engineering, pp 502-506.

[19] IEEE 998:2012 Guide for direct lightning stroke shielding of substations.

[20] AS/NZS 1768:2007 “Lightning protection”.

[21] Nassereddine M., Rizk J., Hellany A., Nagrial M. and Nassereddine G.. “Overhead Distribution Lightning Performance on Joint Use Concrete Poles with Transmission Lines” 17th IEEE Mediterranean Electrotechnical Conference MELECON 2014, April, Beirut Lebanon.

[22] IEEE 81-2012 “IEEE Guide for measuring earth resistivity, ground impedance, and earth surface potential of a grounding system”.

[23] IEEE 142-2007 “Grounding of industrial and commercial power systems”.

[24] Nassereddine M., Rizk J. and Nasserdine G. “Soil Resistivity Structure and Its Implication on the Pole Grid Resistance for Transmission Lines” 2013 World Academy of Science, engineering and Technology, Dubai, United Emirates.

[25] Bingjian Y., Gyan G., Ziaoguang and Zhiyuan H. “A hybrid circuit breaker for DC-application” IEEE First International Conference on DC Microgrids (ICDCM). Atlanta. PP. 187-192. 07-10 June 2015.

[26] Sungnim L. and Kim H. “A study on low-voltage DC circuit breaker” IEEE International Symposium on Industrial Electronics. Taipei, Taiwan. PP. 1-6. 28-31 May 2013.

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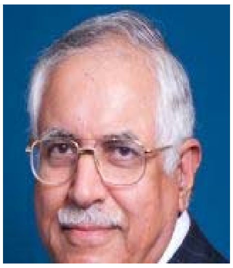

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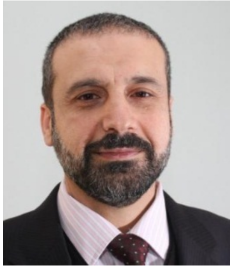

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