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Photovoltaic System Protection Against Lightning

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Abstract. Lightning strikes pose a significant threat to photovoltaic (PV) `systems, which are increasingly utilized for renewable energy generation. This paper presents a comprehensive overview of the potential risks associated with lightning strikes on PV systems and explores various protection measures to enhance their resilience. The study delves into the characteristics of lightning and its interaction with PV installations, identifies vulnerabilities within the system, and discusses the principles and techniques for effective lightning protection. The paper emphasizes the importance of comprehensive risk assessment, surge protection devices, grounding systems, and maintenance practices to mitigate the damaging effects of lightning strikes. By implementing appropriate protection strategies, PV system owners and designers can safeguard their installations and ensure the longevity and reliability of their renewable energy infrastructure.

1 Introduction

Solar and photovoltaic systems are among the most widely used renewable energy sources. Due to their susceptibility to weather and their dependence on electrical components, PV systems are vulnerable to various environmental risks, including lightning strikes. Various measures can be taken to protect PV systems from lightning strikes [1]:

- Lightning Protection System (LPS): The installation of a properly designed and implemented lightning protection system is crucial for the protection of PV systems. An LPS typically includes lightning rods or air terminals placed at elevated points such as the roof or mast of the building to intercept lightning strikes. Down conductors, called arresters, are used to safely conduct the lightning current into the ground.
- Earthing and equipotential bonding: Adequate earthing and wiring are essential to protect PV systems from lightning-induced surges. Earthing involves connecting various metallic components of the system, such as solar modules, mounting structures and equipment housings, to the earth. This helps to dissipate the electrical energy in the event of a lightning strike. Earthing ensures proper electrical continuity between all metallic components and minimises potential differences that could occur during a lightning strike.

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- Surge Protective Devices (SPDs): Surge protection devices limit voltage spikes caused by lightning strikes or other transient events. These devices are usually installed at critical points within the PV system, e.g. at the DC input terminals of inverters, distribution boxes and other sensitive equipment. SPDs discharge excess voltage to earth, preventing it from damaging connected components [2-5].
- Shielding and routing: Crossing and properly routing cables can help minimise the risk of lightning-induced surges. Metal conduit or armoured cables can provide shielding against electromagnetic interference and direct lightning strikes. Cables must be routed away from roofs and other lightning-prone regions, as well as from long parallel lines that could cause voltage spikes.
- Overvoltage protection: To protect against voltage spikes caused by lightning strikes, PV systems should be equipped with overvoltage protection. When the voltage reaches a certain threshold, these devices monitor the voltage levels and either disconnect the system from the grid or isolate important components. Inverters, transformers, and other sensitive equipment can be protected from damage by using a surge protector.
- System design factors: Local building codes, lightning activity and geographic location should be considered when designing a PV system.

Planners and installers should assess the risk of lightning strikes and install appropriate protection measures accordingly. These include selecting lightning-resistant equipment, ensuring adequate spacing and following best installation practises.

It is important to note that while these measures can significantly reduce the risk of damage from lightning strikes, they do not guarantee absolute protection. Lightning is a powerful natural phenomenon; under extreme conditions, direct strikes or induced surges can still pose a risk to PV installations. Regular maintenance, inspection and monitoring of the system's protective measures are crucial to ensure lasting protection. When implementing lightning protection for PV installations, it is strongly recommended to seek advice from qualified professionals and to comply with local electrical and safety regulations.

2. PHOTOVOLTAIC CELLS

The photoelectric cell is a small component of the solar energy conversion system. It is usually square and has a side length of 12.5, 15 or 20 cm. Mostly, they are plates made based on monocrystalline, polycrystalline or film silicon.

Photoelectric cells made of crystalline silicon are currently the main sources for converting solar energy into electricity, but other possibilities for conversion are also being investigated. Photoelectric cells ensure the conversion of solar radiation into electrical energy based on the internal photoelectric effect.

In principle, photoelectric cells are semiconductor diodes with a large surface area. The conductivity is achieved by doping the diode components. Due to the doping, one of the components has an excess of electrons and the other has a minus of electrons. The energy determined by the light radiation enables the transition of the electrons from the valence band to the conduction band and the occurrence of the electric current in the external circuit (if this is closed) (Fig. 1).

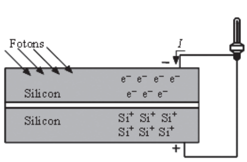

Fig 1. The basic structure of a photoelectric cell

The mechanical work required to transfer an electron from the valence band to the conduction band is 1.1 eV for Si.

The electrons are generated by the photoelectric effect. However, if no electric field is applied, the electrons do not move in a certain direction and do not generate an electric current. In the internal photoelectric effect, the electric field is generated by a sandwich of two differently doped silicon layers, the N-type (which contains electron-donating phosphorus) and the P-type (which contains electron-accepting boron).

The electrons move in the electric field created between the two layers.

The cell uses the energy of the photons to create an electron-hole pair. In theory, 25% of the solar energy used is converted into electricity (in practise about 15%). In silicon, 1.1 eV is required to form an electron-hole pair. If the photon has the energy < 1.1eV, the pair is not formed. If the photon has the energy > 1.1eV, the additional energy is consumed without another pair being formed. Energy can only be transferred quantised (the law of the photoelectric effect). The value of 1.1 eV is the width of the band gap and a material property of silicon.

To increase the number of electrons that can pass from the valence band to the conduction band, a material with a smaller band gap should be chosen. Nevertheless, the charged power $P = U \times I$, in Watts, depends on the number of electrons (I- current in Ampers), on the one hand and on the voltage (V- voltage in Volts) at the terminals on the other (determined by the width of the forbidden zone). What is gained by increasing the number of electrons is lost in the voltage at the terminals. The calculation shows that a band gap of 1.4 eV gives the maximum power.

Silicon is a shiny material, i.e., it reflects strongly. When the semiconductor is exposed to light, it absorbs the light's energy and transfers it to negatively charged particles in the material. This extra energy allows the electrons to flow through the material as an electrical current. This current is extracted through conductive metal contacts – the grid-like lines on a solar cell – and can then be used to power your home and the rest of the electric grid. The efficiency of a PV cell is simply the amount of electrical power coming out of the cell compared to the energy from the light shining on it, which indicates how effective the cell is at converting energy from one form to the other. The amount of electricity produced from PV cells depends on the characteristics (such as intensity and wavelengths) of the light available and multiple performance attributes of the cell.

An important property of PV semiconductors is the bandgap, which indicates what wavelengths of light the material can absorb and convert to electrical energy. If the semiconductor's bandgap matches the wavelengths of light shining on the PV cell, then that cell can efficiently make use of all the available energy. The photons that are reflected are a loss for the photoelectric cell. The photoelectric cell has an anti-reflective layer that reduces the reflection losses by 5%. In addition, the photocell must contain a protective layer and electrical contact elements (fig. 2).

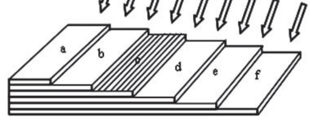

Fig 2. Components of a photoelectric cell: a - protective layer (glass); b - anti-reflective layer; c - contact layer (positive pole); d - silicon N; e - silicon P; f - support layer (negative pole).

The electrical properties of the photoelectric cells, the short-circuit current I_{sc}, the voltage U_{0c} in no-load operation and the power generated at the maximum point depend on the temperature of the cell junction (Fig. 3) [4].

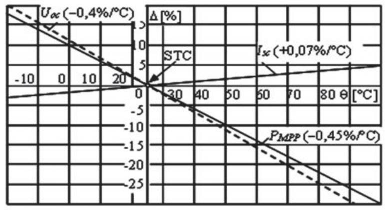

Fig. 3. Variation with temperature of the electrical characteristics of photoelectric cells.

The data in Figure 3, which refers to the STC (Standard Test Condition) value, makes it clear that in the practical implementation of photoelectric systems, the cooling conditions of the system must be considered, as the performance depends on the temperature. If the temperature increases by one degree, the generated power decreases by 0.5 % and at 600 °C the power is 20 % lower than at 200°C.

3. LIGHTNING PROTECTION, EARTHING/GROUNDING AND SURGE PROTECTION

3.1. Damage due to lightning

Solar systems do not make buildings more vulnerable to lightning strikes. Therefore, a second lightning protection system is not necessary. However, in its VDS 2010 rule, the Association of Damage Insurers prescribes the installation of lightning and surge protection systems according to the standards of lightning protection class III and V D E. (According to V D E 0185, the protection level of a building is divided into four lightning protection classes from I to IV. From lightning protection class, I to IV, less lightning and surge protection is required. The building laws of the individual federal states contain the legal requirements for lightning protection in Germany. the best level of protection

In the case of direct lightning strikes, lightning protection systems are designed to provide personal protection. If the PV system is in an exposed area, it is necessary to use a suitable lightning conductor.

Figure 4 shows the selection of lightning and surge protection measures for PV systems on buildings without valuable data technology equipment [6].

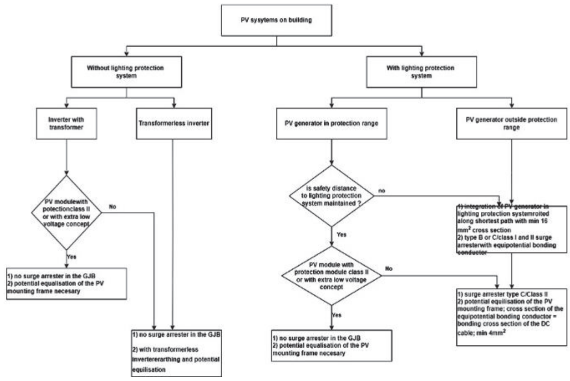

Fig 4. Selection of measures for lightning and overvoltage protection for PV systemson buildings without valuable data technology equipment

3.2. Direct strike protection

The probability of a direct lightning strike can be determined based on the dimensions of the building, the environmental data, and the typical number of lightning strikes for the area. The risk of lightning strikes and the most practical and cost-effective safety precautions are determined by special software. The probability of a lightning strike to an average residential building in an urban area is one in a million.

3.3 Indirect lighting effects and lighting protection

Each lightning strike indirectly affects its surroundings within a radius of about 1 km. The probability of a building being struck by indirect lightning is therefore much greater than the probability of the building being struck by direct lightning. It can be assumed that a PV system will be affected by lightning strikes in the surrounding area numerous times during its lifetime.

The indirect effects of lightning are inductive, capacitive, and galvanic coupling. These couplings generate overvoltage from which the building's electrical systems must be protected. Internal lightning protection includes all measures and equipment in the building that serve not only to protect e.g. electronic devices from indirect lighting effects, but also from the effects of switching operations in the public power grid. The greater the lightning risk to the building and the more valuable the data technology, the more extensive measures must be taken for internal lightning protection.

Lightning can induce overvoltage in the PV modules, the module cables, and the DC main cable. The voltages induced in PV modules with metal frames are about half as high as the voltages induced in frameless PV modules. To reduce the overvoltage in the module cables, the positive and negative cables (+ and -) of each string should be laid as close to each other as possible [7].

Care should be taken to ensure that the cable routing is short-circuit proof. The smaller the areas for the open loops in the PV generator circuit, the lower the induction voltage generated by the lightning current in the module cables (see figure 5) [6].

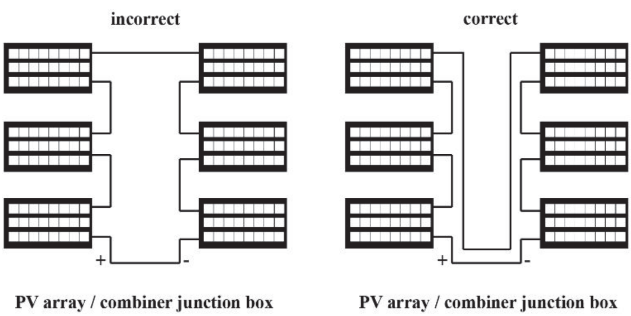

Fig 5. Loop formation in module wiring

The positive and negative cables should be as close together as possible to reduce induced voltage peaks in the DC main cable. For systems that could be struck by lightning, single cables with shielding are recommended. The cross-section of the shield should be at least 16mm2 copper (Cu). The shortest path connects the upper end of the shield to the PV module frames and the metallic substructure. A metallic protective tube can also be used. Surge arresters with a rated leakage current of about l0kA must be connected to the active conductors if shielded cables are not used. For shielded connections, surge arresters with a rated leakage current of about l kA are sufficient.

Each pole must be connected to a surge arrester connected to earth or ground. Class II surge arresters must have a switch-on and build-up voltage that is 1.4 times the maximum PV voltage. Only install models with thermal disconnect devices and fault indicators in systems at risk of lightning. After every thunderstorm or once every six months, the system operator should visually inspect the surge arresters. Surge arresters should be placed with a remote fault indication control if the installation location is not conveniently accessible. The visual fault indicator is placed where the system operator can easily see it. When using inverters with insulation monitoring, separate remote monitoring is not necessary, as the tripping of the surge arresters can also be reported.

It is also possible to dispense with external protection against atmospheric overvoltage if you use PV components (mostly varistors) for which the manufacturer has provided overvoltage protection. When varistors are triggered, they are detected by the insulation monitoring of the inverters [8-10, 11-14].

3.4. Overvoltage protection of photoelectric installations

As it is described in [18,19], PV modules are more vulnerable to direct lightning strikes than conventional low-voltage power distribution systems, due to installation on roofs, facades of buildings, and, in general, on unsheltered areas. For this, a risk assessment must be considered and if it is deemed necessary, a thorough study of the LPS of PV park must be conducted [20].

The earthing system has a crucial importance for the safe and effective discharge of the lightning current into the ground. An earthing resistance of less than 10 Ω is recommended. To avoid galvanic corrosion, the material of the earthing electrodes and the connection terminals should be carefully selected, considering the materials of the PV frame and the supporting structure. Electrode arrangements for ground-mounted PV systems are used for lightning protection. In addition, the basic task of the inner LPS is to prevent dangerous sparking caused by the lightning current flowing through the outer LPS or other conductive parts of the installation. The electrical connection can be established by equipotential bonding and surge protection devices if the direct connection with equipotential bonding conductors is not suitable.

Because solar installations occupy relatively large areas, the probability of being struck by lightning or affected by surges caused by lightning strikes in nearby areas is relatively high.

For a rectangular structure with length a, width b and height h, it can be assumed that the lightning strike area A_c can be determined from the relationship [6]:

$$A_c = (a + 6 \cdot h) \cdot (b + 6 \cdot h) \tag{1}$$

The number of lightning strikes N falling on the surface Ac follows from the relation [6]:

$$N = N_s \cdot A_c \tag{2}$$

Where *Ns* is the density of lightning strikes in an area defined by the keraunic index *kc* (the number of stormy days a year).

The keraunic index indicates the number of thunderstorm days per year in a specific area or location. The keraunic level is subject to strong regional fluctuations and ranges from less than 1 in the Arctic and Antarctic to up to 180 near the equator. If the local keraunic levels are plotted on a map, lines of equal frequency, so-called isokerauns, can be drawn around areas of constant levels.

For a keraunic index *kc* = 20 specific to the southern part of the country, a density of lightning strikes *Ns* = 2.8 lightning strikes/km^2 and year results. A photoelectric installation occupying an area of 10,000 m^2 (one hectare) could be struck by about 0.03 lightning strikes in a year (once every 30 years) [1].

In order to limit the overvoltage induced due to lightning strikes that fall near the installation (the values can be higher than 5000 V), when connecting the panels, attention must be paid to the electrical connections so that the loops of the electrical circuit are made in such a way as to cover as small an area as possible.

Figure 6 shows an example of making electrical connections to an installation mounted on a building [6, 15-17].

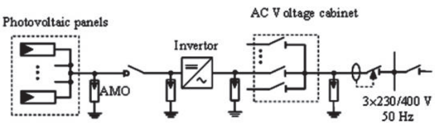

Fig 6. Overvoltage protection of the photovoltaic installation

Protection against the overvoltage induced in the circuits is achieved by installing arresters with metal oxides (AMO) between the live bars and the earth. The distance between the arresters is determined by calculation according to the pulse holding voltages of the circuit components.

4. Future Prospective

Protecting photovoltaic (PV) systems against lightning is essential to ensure the safety and longevity of the system. Lightning strikes can cause extensive damage to PV installations, leading to downtime, costly repairs, and even safety hazards.

Lightning can directly strike PV panels or other system components, causing immediate damage. PV panels are particularly vulnerable because they are often installed in open areas, making them more susceptible to strikes.

Even if lightning does not directly strike the PV system, it can induce transient overvoltage in the system's electrical components. This overvoltage can damage inverters, controllers, and other sensitive electronics.

Proper grounding and earthing are crucial for dissipating the energy from a lightning strike safely. Ensuring the PV system is adequately grounded can be challenging, especially in remote or uneven terrain.

SPDs are commonly used to protect against transient overvoltage caused by lightning. However, selecting the right SPDs for PV systems can be challenging due to the unique characteristics of PV installations.

Monitoring and Maintenance: Continuous monitoring of the PV system's health and lightning protection components is essential. Identifying and addressing damage or degradation can be complex, especially in large-scale installations.

Advanced Surge Protection: Research and development in surge protection technology are ongoing. More sophisticated and tailored surge protection devices for PV systems are likely to emerge, offering better protection against lightning-induced overvoltage.

Improved lightning prediction and warning systems can help PV system operators prepare for potential strikes. These systems can trigger protective measures and disconnect the system when lightning is imminent.

Advanced Grounding Techniques: Developing better grounding and earthing techniques, especially for PV installations in challenging terrains, will be crucial for ensuring lightning energy is safely dissipated.

Future PV systems may incorporate lightning protection as an integral part of their design. This could include lightning-conductive materials and structures to divert lightning away from sensitive components.

Advances in remote monitoring and diagnostics technology can enable real-time assessment of PV system health, including the condition of lightning protection components.

As the PV industry matures, insurance products and risk mitigation strategies specific to lightning-related damage may become more prevalent, helping system owners manage the financial risks associated with lightning strikes.

Governments and industry organizations may develop more comprehensive and specific standards for lightning protection in PV systems, providing clearer guidance for system design and installation.

Protecting PV systems against lightning remains a significant challenge, but ongoing research and advancements in technology offer promising prospects for improved protection and risk mitigation in the future. Proper design, installation, and maintenance practices, combined with evolving protective measures, will be essential to ensure the resilience of PV installations in the face of lightning strikes.

Conclusion

In summary, protecting photovoltaic (PV) systems from lightning strikes is critical to ensure their safe and reliable operation. Lightning strikes pose a significant risk to PV systems because they are exposed to the elements and are installed on roofs or in open areas. Without proper protective measures, a lightning strike can cause direct damage to system components, resulting in equipment failures, downtime and potential safety risks.

Several protective measures should be taken to protect PV systems from lightning strikes:

- surge protectors at key points in the system, such as the DC input side, the AC output side and communication lines, helps to dissipate excessive transient currents caused by lightning strikes. SPDs are designed to absorb and dissipate the energy of surges to protect sensitive equipment from damage
- A well-designed earthing and connection system is essential to provide a low impedance path for lightning-induced currents. Proper earthing helps reduce the potential difference between system components, minimising the risk of equipment damage. Earthing ensures that all system elements are interconnected and form an equipotential plane, reducing the risk of side flashovers
- Installing lightning rods or air-termination structures near PV systems helps to attract and harmlessly direct lightning strikes into the ground. These structures provide a preferential path for lightning, reducing the likelihood of a direct strike to PV panels or other system components
- The use of shielding techniques such as earthed metal pipes or metal-sheathed cables for cable connections can minimise the risk of induced surges or electromagnetic interference from lightning strikes. Isolating sensitive equipment, such as inverters or control systems, from the rest of the system can provide an additional layer of protection
- In the design phase, it is important to consider factors such as system layout, separation distances and component positioning. Appropriate spacing between conductors, adequate distance from nearby buildings and positioning of sensitive components away from potential impact paths can help mitigate the risk of lightning-related damage

Regular inspection, maintenance and testing of protective measures is essential to ensure their effectiveness. It is recommended that a qualified professional or electrical engineer with experience in PV system design be consulted to determine specific protection requirements based on local lightning protection conditions, regulations, and industry standards.

By implementing a comprehensive lightning protection strategy, PV system owners can mitigate the risks associated with lightning strikes, protect their equipment, and maintain the performance and longevity of their solar energy systems.

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