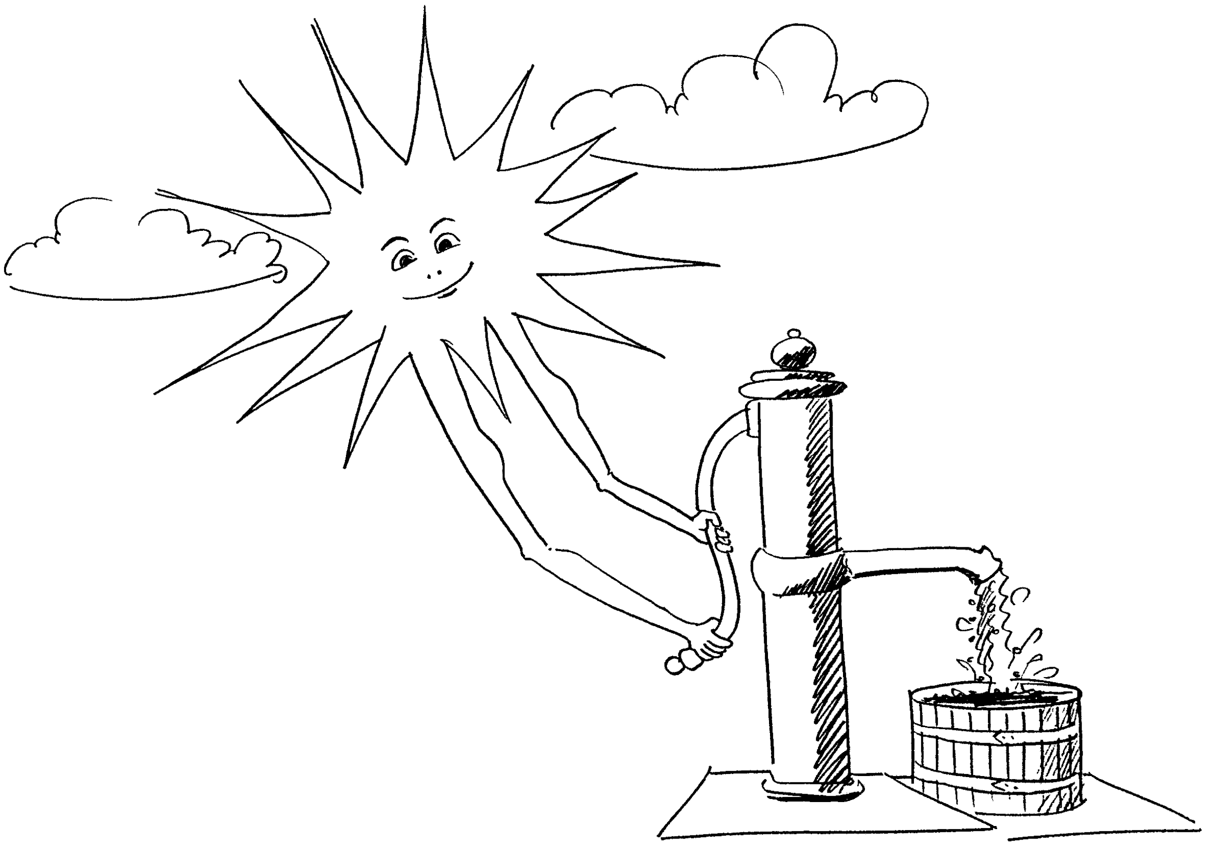
Lightning and Overvoltage Protection of PVPS



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1. THEORETICAL FUNDAMENTALS OF LIGHTNING AND OVER-VOLTAGE PROTECTION

The natural occurrence of thunderstorms and the accompanying lightning discharge have always frightened and fascinated mankind. At the beginning of the 18th century parallels were surmised between lightning discharge and spark discharge in electro-static experiments. After 1750 this correlation was confirmed when small electrical sparks were successfully struck from thunder clouds with long iron strings of flying kites. Such experiments finally led to the realisation that buildings with well-earthen rods or taut wires could be protected against lightning striking.

With the commencement of electrification from 1880 and the correspondingly necessary expansion of the overhead system the experience was very quickly made that electrical equipment was often being destroyed by very high voltages and / or currents caused by lightning. The damage was not only caused by direct strikes, but also by overvoltage as a consequence of switchover operations or remote lightning discharge.

Consequently, suitable protective equipment and installation techniques were very quickly developed in order to protect appliances and to improve the safety of supply.

1.1 The Formation of Thunderstorm Cells

The basis of each thunderstorm activity is the formation of so-called thunderstorm cells, by which one understands cloud configurations mainly with a diameter of several kilometres, which extend up to heights of more than 10 km. The lower boundaries of the cloud lie at a height of 1 to 2 km. For the formation of these thunderstorm cells warm masses of air with sufficiently high humidity must be transported to the corresponding heights.

During the ascendant phase the warm air cools down and condenses, clouds are formed. In parts of the clouds this cooling down phase takes place so severely that the water droplets freeze. The energy released during this cooling process heats up the remaining air again and accelerates its ascent additionally, whereby the air reaches ascendant speeds of up to approximately 100 km/h. This intense air movement atomises and rubs the ice particles and water droplets against one another, whereby these individual particles and droplets are electrostatically charged. For physical reasons the positively charged particles offer the upwind a larger point of impact and, through the predominantly vertical air movement within the thunderstorm cells, are carried into the upper layers of the cloud. The negative charges remain in the lower area of the cloud. This process consequently separates the charges, and the thunderstorm cells become electrostatically charged.

Beside this charge separation within the thunderstorm cells, the lower negative cloud charge displaces all negative charge carriers on the ground through influence. Consequently the earth's surface is positive charged.

1.2 Lightning Discharge Process

If the local electrical field strength between the space charges rises to several 100 kV/m, then lightning discharge can commence. More than 80 % of lightning discharges take place within the thunderstorm cells, the so-called cloud-cloud-flashes. Lightning discharges to the earth mainly originate in the middle, i.e. negative section of the thunderstorm cloud. These negative downward flashes are, with a proportional share of ca. 90 %, the most frequent type of discharge to the earth.

A so-called leader moves across from the negative charge centre of the cloud in the direction of the earth (figure 1). The forward expansion of the leader moves in jerks of several 10 m with a velocity of approximately 300 km/h. When the leader has come to earth within a distance of between 10 m to 100 m the field strength between the head of the leader (negative potential) and protruding peaks on the earth (positive potential) increases so intensely, that a upward-leader expands from the earth towards the leader.

The point of strike of the lightning flash is consequently determined. Once the leader and upward leader have met, the main discharge flows from the earth to the cloud at a speed of about 100,000 km/s and lasts for up to several 100 ps. The sparks channel heats up to temperatures of up to 30,000 °C, whereby the pressure of the heated air rises up to 100 bar. Thunder is formed through the explosion of the sparks channel. With nearly all negative lightning flashes several additional discharges follow the first discharge in intervals of milliseconds. As they use the same channel, impulse currents may repeatedly hit the object concerned.

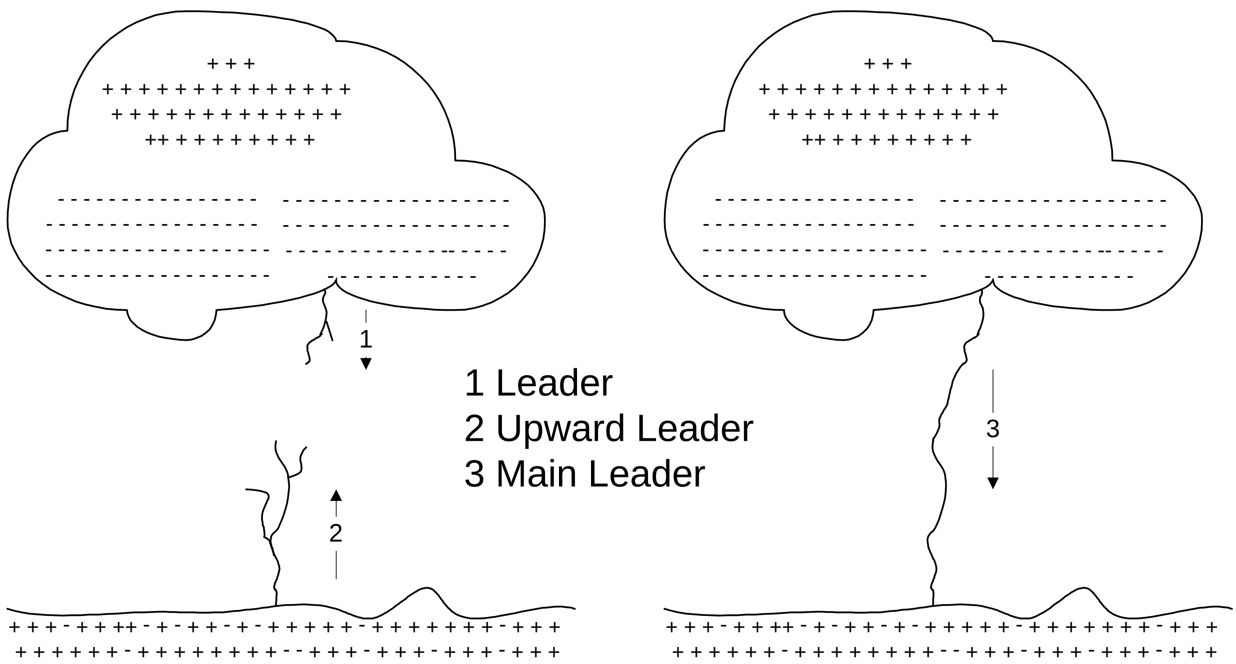

Fig. 1: Negative downward flash

1.3 Electrical Characteristics of Lightning Flashes

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A lot of measurements and counts of lightning discharge have been carried out in the last years so that it be statistically evaluated very well. Table 1 shows the most important electrical quantities and their frequency distribution.

Frequency of lightning [%]	**50**	**10**	**5**	**2**
I_{max} [kA]	30	80	100	200
Max. rise [kA/µs]	20	90	100	100
Charge [As]	10	80	100	400

Tab. 1: Electrical quantities and frequencies of lightning

1.4 Probability of Direct Lightning

The owners and operators of property which is endangered by lightning strikes often pose the question as to whether and how often their property can be hit by lightning. This question cannot be answered exactly in the sense of prophesying the time and place of lightning discharge. The knowledge gained by observation of the frequent occurrence and regional distribution of lightning discharge permit, however, a statistic evaluation of the probability of lightning strikes.

Occasionally, the opinion exists that buildings with PV-generators, solar collectors or antenna systems are hit by lightning more often than other buildings. This assumption is only correct to a certain extent. The extensive nature and form and appearance of the earth's surface have an influence on the formation of a thunderstorm cloud, and consequently also an effect on the regional probability of lightning discharge. The basis of lightning discharge is however determined exclusively by the local field strength in the interior of the thunderstorm cloud. The influence of the type of object on the ground is very small, especially due to the distance of several thousand meters. From this, to a certain extent, purely coincidental starting point the leader expands in the direction of the earth. Only when this leader has come within a distance of less than 10-100 m to the earth, does the field strength at protruding peaks on the earth increase so strongly that from this point onwards the upward leader breaks away and expands towards the leader. Once the upward leader has reached the leader, then it is earthen and the point of strike of the lightning flash is determined. The electric field strength in the vicinity of a leader reaches the highest values on protruding metal constructions and consequently antenna systems or, due to their size, also PV-generators and solar collectors are preferential places for lightning strikes. Although this does mean that lightning is more likely to strike in these installation components than in other points of the same building. such systems do not have an effect on the local frequency of lightning discharge.

2. GALVANIC, INDUCTIVE AND CAPACITIVE COUPLING

Every thunderstorm activity influences its surroundings not only through the electric field of the thunderstorm cells but also through the electromagnetic field of the actual lightning discharge itself (figure 2). These electric and magnetic fields give rise to voltages and currents in electrical systems and electrically conductive constructions. If these voltages and currents exceed the values for which the systems are dimensioned then one speaks of overvoltage and respectively of overcurrent. In practice damage as a result of overvoltage dominates. Depending on the tripping influencing variable of the overvoltage, one speaks of inductive, capacitive or galvanic coupled overvoltage. In PV-systems the PV-generator is considered to be the dominating source of overvoltage. The development of overvoltage and overcurrent within PV-systems (which is valid also for solar thermal systems) is therefore explained in more detail in the following.

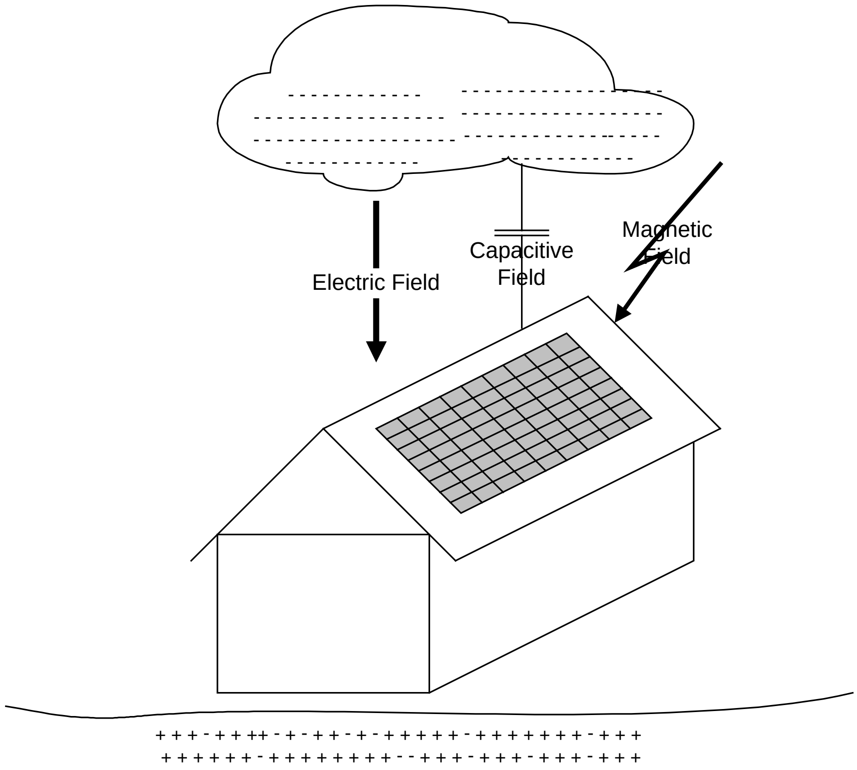

Fig 2: Risks as a result of thunderstorm activity

2.1 Galvanic coupling

Direct lightning strikes in PV-systems or solar thermal systems drive currents over the mechanical components of these systems in the direction of the earth. If, as a consequence of this lightning discharge, the insulation of the electrical equipment fails, then parts of the lightning stroke current will also flow off over this electrical equipment in the direction of the earth. One then speaks of galvanic coupling.

2.2 Inductive coupling

Each lightning discharge goes along with the creation and subsequent collapse of a magnetic field, whereby the field extends concentrically around the flash channel of the discharge path and around all conductors which carry the lightning stroke current. This change in the field induces voltages in building constructions and all electrical installations, which can damage these installations. The level of the voltage is thereby essentially determined by the rate of rise of the lightning current, the distance to the discharge path and the magnitude of the conductor loops of the technical equipment.
PV-generators fundamentally consist of a series connection of several PV-modules, the so-called strings. As a rule several of these strings are switched in parallel in order to increase the system rating. In the case of a close-up lightning discharge a transverse voltage is induced between L+ and L- of such a string. In the most unfavourable case the series connection of the PV-modules would result in the induced transverse

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voltages of the individual modules adding up to a transverse voltage of the whole PV-generator. This transverse voltage would then arise directly at the d.c. input of the PV-inverter. Figure 3 shows the inductive coupling of transverse-overvoltage in a PV-generator string.

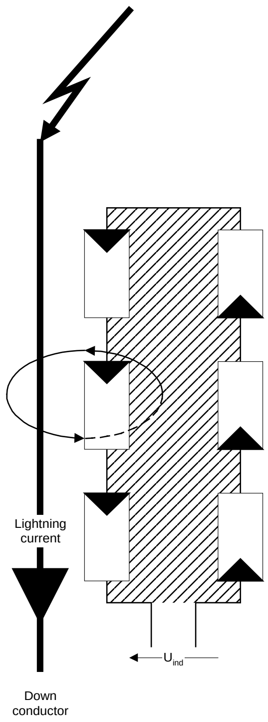

Fig. 3: Inductive coupling of transverse-overvoltage in a PV-generator string

Not only direct strikes but also nearby strikes induce voltages in all conductor loops which can destroy the electrical equipment of the PV-system.

2.3 Capacitive coupling

If a PV-generator is located within the electrical field of a thunderstorm cloud, the freely moving charge carriers in the metals and semiconductors of the PV-generator are displaced; a charge separation occurs. The charge transfer results for so long until the electrical field no longer appears in the interior of the PV-generator.

If one assumes that the PV-generator is a metal plate aligned parallel to the earth's surface, then a potential forms on the surface directed at the earth and the reverse potential on the opposite generator side (figure 4). Which potential is set to which generator side is determined by the polarity of the thunderstorm cloud.

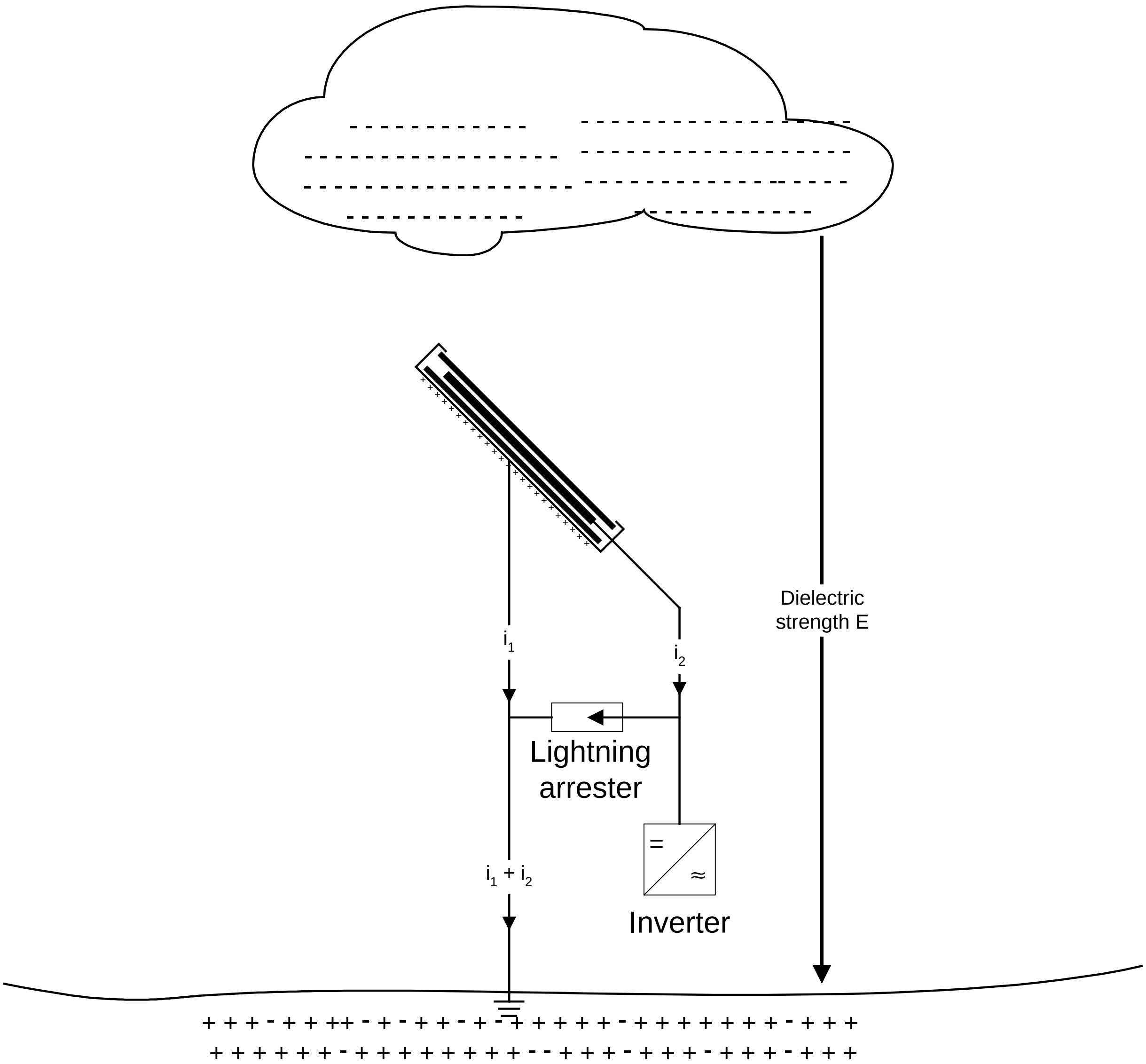

Fig. 4: Capacitive coupling of an overvoltage in the PV-d.c. circuit

A PV-generator is an inhomogeneous product, which, with the exception of the module frame and the generator frame, is made of non-conductive materials, respective y of semiconductors. In an idealistic examination the electric field of the thunderstorm cells causes a charge separation not only in the metal constructions of the generator frame but also in the actual cells themselves. With PV-modules with metal frames this effect appears spatially distorted as the electric field lines converge on the metal frames. Consequently an increase in the field strength and a field weakening in the area of the actual PV-cells occurs in these areas. The electric field which collapses at the moment of lightning discharge causes a charge transfer once again. On all conductors which are connected to the earth the charge then flows off in the form of a transient wave to the earth. Depending on the system construction these are the active conductors or the earth conductors (i_1 in figure 4) of the PV-generator frame. In all conductive components of the generator, which do not have any connection to the earth, a harmless balancing of the charges takes place internally. Capacitive coupled overvoltage can also damage PV-systems.

Galvanic, inductive and capacitive coupled voltages can reach levels of several thousand volts. The extent to which damage results depends on the dielectric strength of the components deployed. For example PV-modules, which are identified as Safety Class II Equipment, are tested at a voltage of 6000 V. Consequently they are as a rule sufficiently surgeproof against coupled voltages.

3. INTRODUCTION INTO METHODS OF EXTERNAL LIGHTNING PROTECTION

3.1 General LPS

An external Lightning Protection System (LPS) has the task of preventing severe damage through fire or mechanical destruction in case lightning strikes into a protected building.

The essential components of an external lightning protection system are:

- Air-termination system
- Down-conductor
- Earth-termination system

With an air-termination system the concrete and consequently controllable points of the lightning stroke are prescribed to the lightning, the lightning current is then diverted via so-called down-conductors to an earth-termination system. Air-termination systems are occasionally simple lightning rods, mostly however a combination of smaller lightning rods and meshes made of taut wires or rigid wires which are mounted directly on the main body of a building. These arrangements create a protection zone where, with a certain statistical probability, no direct lightning will take place. The efficiency of a lightning protection system is defined through the number of lightning flashes which can reliably be intercepted and diverted and is standardised in the European Draft Standard ENV 61024-1:1995 as so-called Safety Classes.

The requirements regarding the height of the lightning rods, the size of the meshes or the number of down conductors then result from the selection of the protection level.

The earth-termination system should safely divert and distribute the lightning current into the earth. In most cases earth-termination systems are designed as ring earth electrodes or foundation earth electrodes. Due to the good electrical properties and long service life of a conductor embedded in concrete, almost only foundation earth electrodes are deployed in newer structures. If no foundation earth electrode exists, the down conductors are in most cases connected to deep-driven earth electrodes, which as far as possible are connected to each other via ring conductors at earth level.
The installer of a PV or solar thermal system must make sure, whenever possible of the effectiveness of the earth termination system through inspection or measurement. A ground resistance of at the most 10 Ω is to be considered sufficient. As with a direct stroke of lightning the voltage rise towards remote earth’s, e.g. the earth potential of the

neutral conductors, should be as low as possible, a lower ground resistance is to be aimed at.

3.2 PVPS Protection

If water is to be pumped in places without an adequate energy infrastructure then PV-pump systems are a suitable alternative to pump drives with combustion engines. Typically such systems consist of a PV-generator with several kWp rating which supplies an electrical pump via power electronics. The pumped water is either directly transported to an application site or temporarily stored in a container.

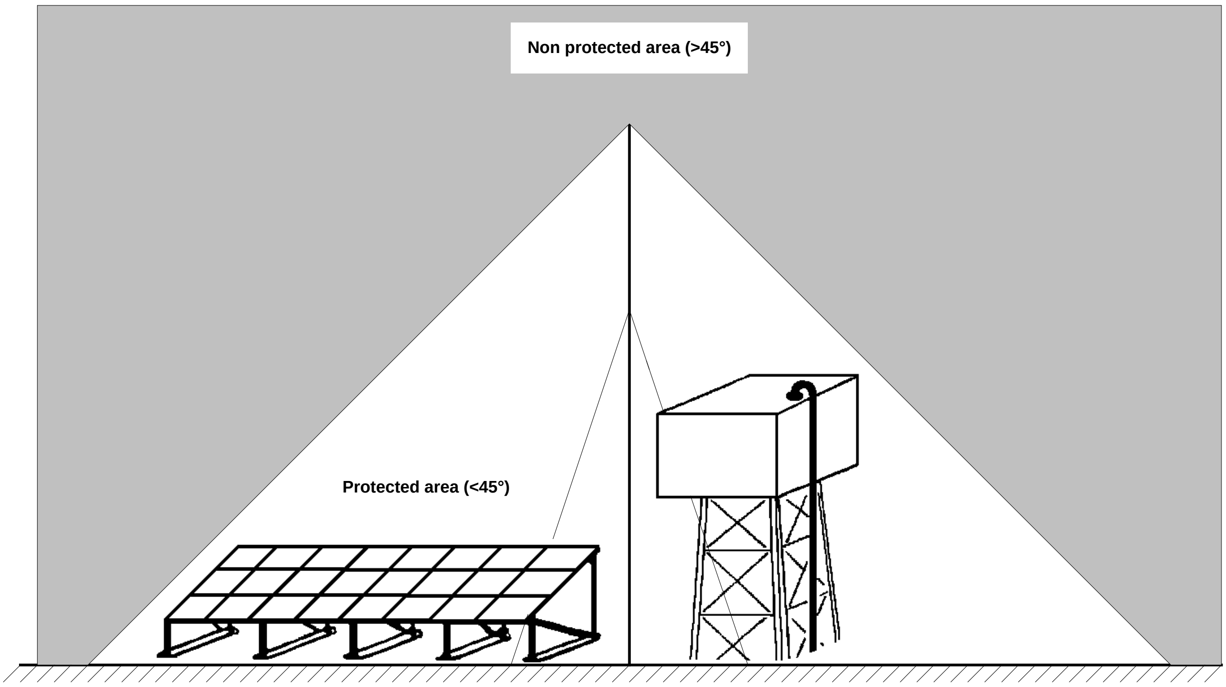

Fig. 5: Lightning protection of a PVPS

As with all larger PV-systems there is also a considerable risk of damage through overvoltage in photovoltaic pump systems. In many cases protection against direct lightning strikes is necessary due to the additional requirements regarding the availability of this equipment. In the example given the PV-generator stands freely on the ground. The protection zone is formed by a sufficiently high lightning rod (figure 5). With PV-generators of larger spatial extent several lightning rods are necessary in most cases which, as far as possible, are still connected between each other to the cables mounted on the peaks. Not only the lightning rods but also the PV-generator frames are connected with each other. If skilfully laid out these electric lines can at the same time function as ring earth electrodes, to which maybe star-type earth electrodes or earth rods must still be added.

As the power electronics is mostly installed directly at the PV-generator in a small protection structure, a set of lightning arresters on the d.c. side is sufficient (figure 6). The lead between the power electronics and the pump is in most cases so long, that dangerous inductive coupling can damage both pieces of equipment. Therefore under consideration of the low additional costs, lightning arresters should be installed at least at the inverter output terminal and maybe also at the pump motor. Not only the power electronics but also the electric wires and the motor should be located within the protection zone of an external LPS respectively laid out sufficiently deeply in the earth.

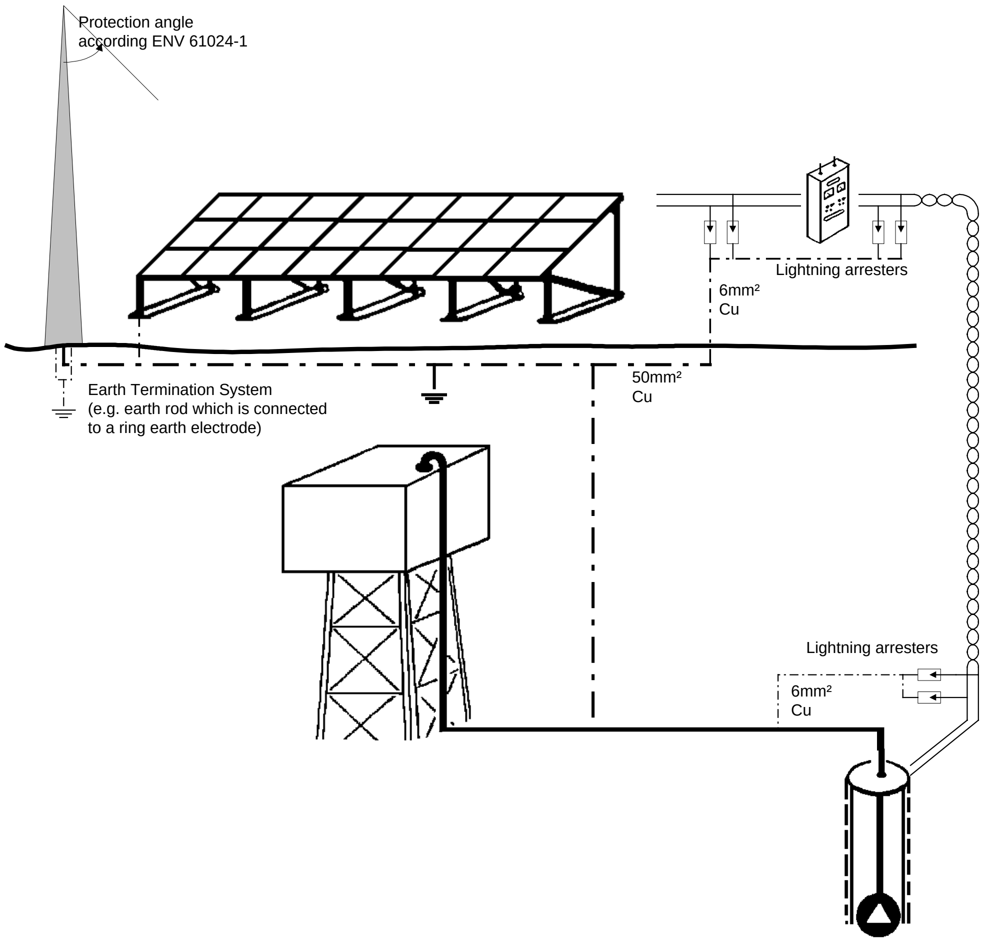

Fig. 6: Overvoltage protection of a PVPS

A further important aspect is the layout of the wiring itself. In order to minimise impact of inductive lightning the enclosed wiring areas should be kept small. This is due especially for the PV generator and the wiring to and from the pump / storage tank.

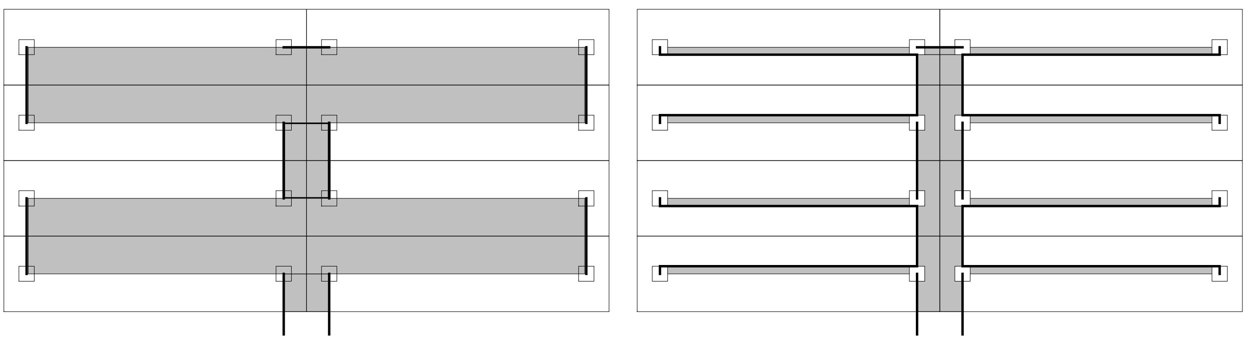

Fig. 7: Wiring of PV-generator (right side layout is better than left side layout)

The layout of the wires at the PV-generator should be in a way that the + and - cable are running in parallel wherever possible (figure 7). The enclosed area should be minimised. The same is valid for the complete PVPS (figure 8).

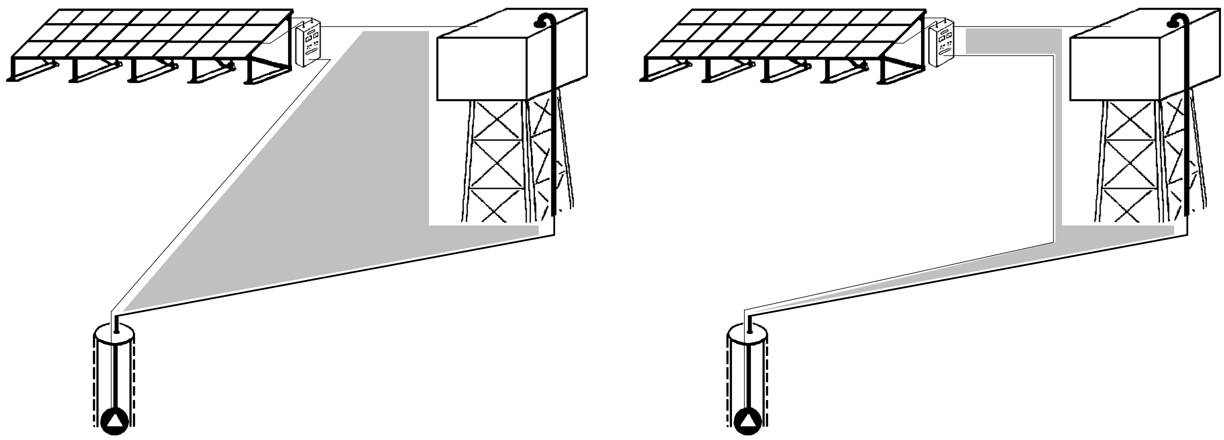

Fig. 8: Wiring of PVPS (right side layout is better than left side layout)

4. Reference:

”Lightning and Overvoltage Protection in Photovoltaic and Solar Thermal Systems”,
TÜV Rheinland, Hr. Becker, Apr. 2000

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