CONSIDERATIONS ABOUT THE LIGHTNING PROTECTION SYSTEM OF MAINS INDEPENDENT RENEWABLE ENERGY HYBRID-SYSTEMS – PRACTICAL EXPERIENCES

Prof. Dr.-Ing. Alexander Kern
a.kern@fh-aachen.de
Aachen University of Applied Sciences, Juelich
Germany

Dipl.-Ing. Frank Krichel
frank.krichel@gmx.de
Aachen University of Applied Sciences, Juelich
Germany

ABSTRACT: In the paper a lightning protection design concept for renewable energy hybrid-systems without power mains connection is described. Based on a risk analysis protection measures against direct strikes and overvoltages are shown in an overview.
The design concept is realized exemplarily for the hybrid-system VATALI on the Greek island Crete. VATALI, not lightning protected at that time, was a victim of a lightning strike in the year 2000 causing destructions and damages of some mechanical and electrical components with costs of approx. 60.000 €. The hardware costs for the protection measures were about 15.000 €: about 50% of the costs are due to protection measures against direct strikes, 50% are due to overvoltage protection.

Keywords: Lightning protection, renewable energy, hybrid-system, photovoltaic system, wind turbine.

1. INTRODUCTION

Independent renewable energy hybrid-systems generally consist of more than one renewable energy source, especially photovoltaic (PV-) systems and small wind turbine generators (WTGs), sometimes combined with solarthermic (ST-) and biogas systems. Those hybrid-systems are installed especially in regions with non-existent or low quality public energy supply, i.e. in regions with a low population density and in developing countries.

Lightning protection of independent hybrid-systems is a subject actually not widely investigated. Still those hybrid-systems are often research and development (R&D) sites, operated by educational and non-profit organizations. If in the near future more and more commercial activities are based on hybrid-systems, their availability will be an important item. Then also sufficient lightning protection is required.

For large WTGs in the past some R&D-projects were conducted showing existing problems in the WTG-design. Measures were determined to protect the entire WTG (here especially the rotor blades) against the mechanical destructions and the electrical/electronic systems against overvoltages (e.g. [1, 2]). The relevant state-of-standard is fixed in draft IEC 61400-24 „Wind turbine generator systems; Part 24: Lightning protection" [3]. The measures described herein, however, are useful especially for larger WTGs. For smaller WTGs their realization is hardly possible. Nevertheless, smaller WTGs are also strongly endangered to lightning strikes, if they are located on mountaintops. For those WTGs, usually used for hybrid-systems, the lightning protection measures described in draft IEC 61400-24 have to be modified in part.

For PV-systems a lightning protection standard does not exist. Often protection against direct lightning strikes is not sufficiently taken into account: e.g. air-terminations are not planned. Usually their lightning protection is focused only on a strike in a far away distance leading to comparatively low-energy induced overvoltages. Those overvoltages are limited by weak surge protective devices, like return-current diodes, bypass diodes or small varistors, being overstressed and therefore destroyed in case of direct and nearby strikes. In addition, both direct and nearby strikes may also lead to a weakening of the electrical strength of the PV-module isolation causing a locally, extremely high, heat development, up to the melting of glass (secondary long-term effect).

Protection against lightning strikes must be taken into serious consideration, if it is highly probable that a strike can occur. Therefore it is recommended, to evaluate the risk of a lightning incident for a given hybrid-system. The result of the risk analysis will be either that no lightning protection is needed, or a set of protection measures reducing the relevant risk. In this paper the procedure firstly is described generally and secondly based on a real case, VATALI.

2. DESCRIPTION OF THE HYBRID-SYSTEM VATALI

The center C.A.R.E. (Centre for the Application of Renewable Energies) in VATALI was founded by the University of Applied Sciences of Aachen (ACUAS), the Community Prasses, the Technological Educational Institute of Crete and the ITC-CIEA from Gran Canaria, to promote the development of the local agricultural community (fig. 1).

Fig. 1: Top view of the hybrid-system VATALI site.

The essential characteristics of the center are:

- International and interdisciplinary research and postgraduate centers;
- Research, demonstration and distribution of technologies to the local community;
- Technologies for renewable energy production and their benefits (photovoltaic, wind, biogas, water);
- Hybrid-systems for the decentralization of energy supply;
- Storage and processing of agricultural products;
- Water and waste technology;
- Building the network with cooperation partners in the Mediterranean area;
- Integral solutions for financial development of local resources (energy, water, agriculture, protection of the environment, nature balance restoration).

The center C.A.R.E. in the eastern Mediterranean region offers the capability for research, development, demonstration and distribution of renewable energy technologies and their applications. It sets up the infrastructure for subsequent projects with local and European partners from universities and enterprises. In cooperation with the local partners, C.A.R.E. enables numerous students of the Aachen University of Applied Sciences to fulfil their practical-semester or their graduate-work. A total of 135 students worked in C.A.R.E. during the past seven years.

The energy needed for the operation of a cheese-dairy and the total common electrical energy supply of the site comes from a hybrid installation that consists of a photovoltaic generator, two wind generators, one biogas generator and one diesel generator set. The disparate generators are connected to each other (fig. 2). The consumer with a voltage of 230 V must be supplied with an AC power source. The generated energy will be directed either directly to the cheese-dairy or the battery system with 1200 Ah capacity. An additional diesel generator only operates in the case of a power shortage. The energy consumption of the cheese-dairy is covered by the scant solar reserves and then it is preserved. The capacity of the battery can cover the energy consumption of the area for 2,6 days without recharging. One biogas tank exists as an additional reserve of biogas for the biogas generator to operate when the batteries are empty.

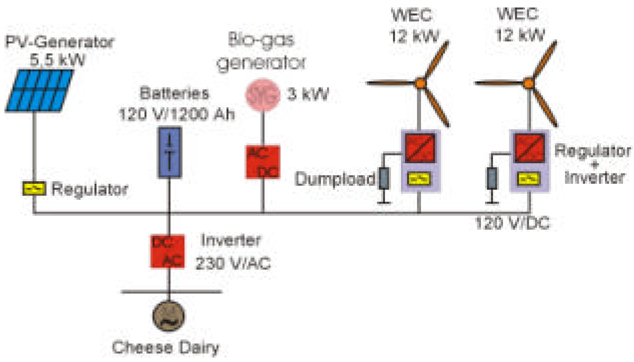

Fig. 2: Schematic diagram of the hybrid-system VATALI (extract).

A second photovoltaic generator of 3,8 kW exists for the electrical energy supply of an ice-storage, a third one with an output of 4,5 kW supplies the cold-storage house. The PV-modules operate at a voltage level of 48 V. The generated energy can be stored in two 800 Ah batteries.

3. RISK ANALYSIS

The first step regarding lightning protection of an independent hybrid-system is the decision, whether such protection is necessary, and if so, which kind of protection. Parameters which have to be taken into account are, for example:

- the area covered by the hybrid-system and their interconnecting cabling;
- the lightning flash density at the area;
- the components of the hybrid-system (WTGs, PV-systems, biogas systems, ST-systems, diesel generators, etc.) and their exposition;
- the costs of the hybrid-system;
- the danger for persons working or staying at the hybrid-system during thunderstorms;
- the necessity of the supplied consumers for an uninterrupted or only shortly interrupted electrical power supply;
- the possibility of a quick repair of damaged or disturbed components in case of a strike.

The list, of course, can not be complete due to the very special conditions of the individual independent hybrid-systems. A risk analysis going very deeply into detail is possible by using the new German standard DIN V VDE V 0185-2:2002 “Lightning protection – Part 2:Risk management; Assessment of the risk of damage for structures” [4]. This standard is mainly based on the draft IEC 61662 Edition 2 [5]. By using this standard, a very detailed calculation of the risk, individually for each special hybrid-system, is possible. With that the risk analysis directly leads to necessary protection measures.

For the further description of the risk analysis it is useful to underlay a real case. For the hybrid-system VATALI the risk analysis was performed to get the necessary protection measures. The relevant types of losses for VATALI are:

- Loss of human life (D1), because of the working people at the site, especially in the buildings;
- Loss of service to the public (D2), because there is no public energy supply at the site, taking over if the renewable energy sources are damaged;
- Loss of economic values (D4), because of the value of the hybrid-system (in comparison with the damage costs of the lightning strike in 2000).

The entire site of the hybrid-system VATALI was divided into four main parts, which were treated separately in the risk evaluation (fig. 3):

- appartement house/cold-storage house complex;
- electrical station;
- two wind turbine generators;
- three PV-systems.

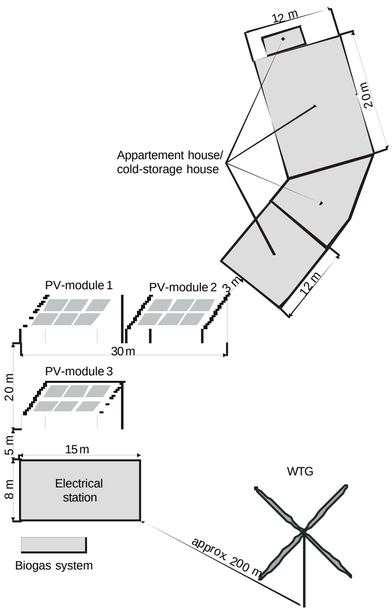

Fig. 3: Arrangement of VATALI’s main parts.

For each main part the whole risk evaluation was conducted individually, i.e. the equivalent collection areas (for the structures as well as for the cabels entering the structures), the probability and reduction factors and the damages factors were evaluated for every single case. Then the necessary proctection measures were selected separately. It would overstress this paper to describe all details of the risk evaluation; therefore only the results are shown for the four main parts in tables 1-4, namely:

- the relevant types of losses;
- the tolerable values R_a for those losses (for the economic losses D4 the same value 10^{-3} is defined as tolerable than for D2);
- the values for the risks without protection measures $R_{unprotected}$;
- the values for the risks with all necessary protection measures $R_{protected}$.

Table 1: Risks and risk values for the appartement house/cold-storage house complex.

Type of loss	R_a	$R_{unprotected}$	$R_{protected}$
D1	10^{-5}	$1,21*10^{-5}$	$0,29*10^{-5}$
D2	10^{-3}	$3,58*10^{-3}$	$0,70*10^{-3}$
D4	10^{-3}	$3,67*10^{-3}$	$0,72*10^{-3}$

The protection measures for the appartement house/cold-storage house complex necessary to fulfil the condition $R_{protected} < R_a$ are:

- Lightning protection system (LPS) type IV according to [6, 7];
- Overvoltage arresters: surge protective devices (SPDs) class II according to [8] for the power/data cables running to the electrical station.

Table 2: Risks and risk values for the electrical station.

Type of loss	R_a	$R_{unprotected}$	$R_{protected}$
D1	10^{-5}	$5,39*10^{-5}$	$0,24*10^{-5}$
D2	10^{-3}	$4,94*10^{-3}$	$0,71*10^{-3}$
D4	10^{-3}	$5,32*10^{-3}$	$0,73*10^{-3}$

The protection measures for the electrical station necessary to fulfil the condition $R_{protected} < R_a$ are:

- LPS type IV according to [6, 7];
- Overvoltage arresters SPDs class II according to [8] for the power/data cables running to the appartement house/cold-storage house;
- Overvoltage arresters SPDs class II according to [8] for the DC-power cables running to the PV-modules;
- Lightning current arresters SPDs class I according to [8] for the AC-power cables running to the WTGs;
- Lightning current arresters SPDs class I according to [8] for the AC-power cable running to the biogas system.

Table 3: Risks and risk values for the PV-modules.

Type of loss	R_a	$R_{unprotected}$	$R_{protected}$
D2	10^{-3}	$3,62*10^{-3}$	$0,45*10^{-3}$
D4	10^{-3}	$4,07*10^{-3}$	$0,90*10^{-3}$

The protection measures for the PV-modules necessary to fulfil the condition $R_{protected} < R_a$ are:

- LPS type II according to [6, 7];
- Overvoltage arresters SPDs class II according to [8] for the DC-power cables running to the electrical station.

Table 4: Risks and risk values for the WTGs.

Type of loss	R_a	$R_{unprotected}$	$R_{protected}$
D2	10^{-3}	$1,14*10^{-3}$	$0,19*10^{-3}$
D4	10^{-3}	$4,14*10^{-3}$	$0,74*10^{-3}$

The protection measures for the WTGs necessary to fulfil the condition $R_{protected} < R_a$ are:

- LPS type IV according to [6, 7];
- Lightning current arresters SPDs class I according to [8] for the AC-power cables running to the electrical station.

In case of the PV-modules and the WTGs the loss of human life (D1) is not taken into account, because lightning strikes to those components do not directly and remarkably endanger the people working at the site, being usually in the buildings during a thunderstom.

For VATALI the decision was made, to follow exactly the results of the risk evaluation, i.e. to realize only the protection measures mentioned above. One exception was defined: in case of the two buildings and the two WTGs a LPS type III according to [6, 7] should be installed.

Despite the real case VATALI in general two different main protection items can be distinguished, based on the need to handle direct strikes and/or to protect the installations against overvoltages. Some considerations about those two main items and corresponding relevant protection measures are discussed in the following two chapters.

4. PROTECTION MEASURES AGAINST DIRECT STRIKES

If the risk analysis leads to the result, that the hybrid-system has to be protected against direct strikes, the following items have to be investigated:

- Are the WTGs able to withstand a direct strike, i.e. do they fulfil the requirements of IEC 88/117/CD (Draft IEC 61400-24):1999-10 [3] ?
- Are the PV-modules, ST-systems and other installations not within buildings able to withstand a direct lightning strike ? Here especially at the possible points of strike small air termination rods are useful to prevent the metal frames of the PV-modules from damage [9].
- Are there any buildings or housings which have to withstand a direct strike ?
- Are there any additional installations (diesel generator, TV-tower, mobile phone-tower, etc.) which can be struck by lightning directly ?

If the installations mentioned above are able to withstand a direct strike due to their construction, there is no more need for additional air-terminations (fig. 4). However, the down-conductor system may have to be planned. In addition to that, the equipotentialization has to be carefully taken into consideration, so that no potential differences may occur between the individual components. Finally the earthing system has to be planned, including all possible earth terminations of the individual components and their interconnections.

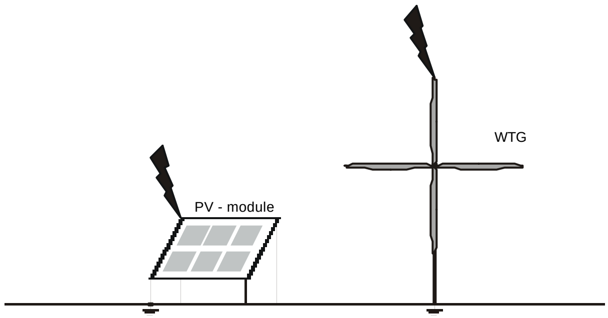

Fig. 4: Integrated LPS with direct strikes to the components (here: PV-module and small WTG).

If the installations mentioned above are not able to withstand a direct strike, and if an upgrading of the installations themselves also is not possible or does not seem to be meaningful, then an isolated lightning protection system (LPS) has to be installed [6, 7]. This often seems to be necessary in case of common PV-modules and in case of small WTGs with an electrical power output of only some kW.

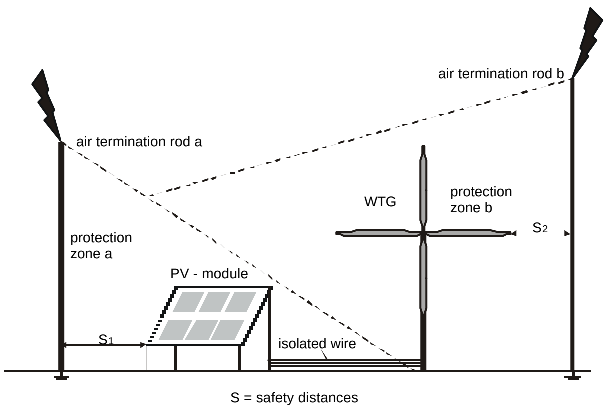

Fig. 5: Isolated LPS preventing the components from direct strikes (here: PV-module and small WTG).

Air-termination rods and wires and down-conductors have to be planned in such a way, that the lightning current can not affect the hybrid-system components (fig. 5). The most important items here are:

- the zones of protection given by the air-termination rods and wires are sufficient for all components which need to be protected;
- in case of PV-modules air-termination rods must be erected in such a way, that they do not cast a shadow upon the modules (otherwise a voltage reduction of the module or a damage of the shadowed module part may occur);
- the necessary safety distances have to be ensured between the air-termination and down-conductor

arrangement and the components of the hybrid-system.

Additional care has to be taken about the partial lightning currents distributed into the earth. Any galvanic coupling to equipotential wires and to system cables has to be avoided, i.e. the requirements of a "safety distance" have to be considered also at the earth surface. If buildings have to be protected by a common LPS, the typical requirements are given in the relevant and well-known standards [6, 7]. Therefore in this paper no additional considerations are necessary.

In case of VATALI the WTGs and the PV-modules (see fig. 1 and 3) are protected by isolated LPS against direct lightning strikes. This is necessary because both installations are not able to withstand a direct lightning strike. For the two WTGs 25m air-termination rods are erected in a small distance (approx. 5m). Taking the "rolling sphere"-method it can be shown, that the WTGs now are protected against direct strikes with lightning current amplitudes of i_{max} > 10 kA [6, 7], fulfilling the requirements of the risk analysis. In case of the PV-modules four 6m air-termination rods are erected around the installation, so that they do not cast a shadow upon the modules. The VATALI buildings are protected by common LPS tape III (for further details see [10]).

An alternative to the described protection measures is to have spare parts available within some hours. Then any damage (or disturbance) may be repaired within an acceptable time. This alternative „concept" may be useful in cases, where the damaged (or disturbed) components of the hybrid-system can be foreseen with a high safety and where the costs of the lightning protection measures related to the costs of the entire hybrid-system are comparatively high. This is a strategy probably for low-cost hybrid-systems like planned or even installed especially in developing countries.

5. PROTECTION MEASURES AGAINST OVERVOLTAGES

If the risk analysis leads to the result, that the hybrid-system components have to be protected against overvoltages (in addition to or without a protection against direct strikes according to chapter 4), the following items have to be investigated:

- Are there any existing surge protective devices at the components (e.g. at the PV-modules) ?
- Are there shielded cables running between the components ?
- Is the hybrid-system exposed to direct strikes ? If so, can the cables between the components be affected by partial lightning currents ?

In general three main protection measures against overvoltages for the interconnecting cabling (fig. 6) exist:

- In case of unshielded cables, and in case of direct strikes and with that the possibility of partial lightning currents along the interconnecting cables, the components can be protected by lightning current arresters SPDs class I [8].
- Shielding of the interconnecting cabling by cable shields for each single cable or by metal ducts, metal covers, etc. for a number of parallel cables [8]. Shielding is possible for both the case of direct strikes as well as for overvoltage protection only. In case of direct strikes and with that the possibility of partial lightning currents along the shield, a sufficient current carrying capability of the shield has to be ensured.
- In case of unshielded cables but with only the need to limit overvoltages, i.e. no partial lightning currents along the interconnecting cables have to be considered, the components can be protected by overvoltage arresters SPDs class II [8].

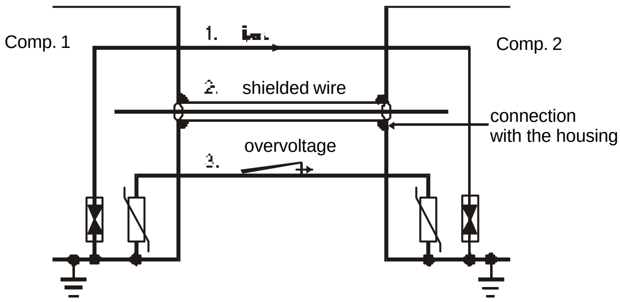

Fig. 6: General measures for the overvoltage protection.

All overvoltage protection measures have to be planned in detail. However, the recommendation can be given, that the passive measure of shielding should be used preferably, especially if partial lightning currents have to be considered. This is absolutely meaningful for DC-cables (e.g. from the PV-modules to the converters), because here SPDs class I are usually not applicable. So the protection philosophy should be applied as follows, both of technical and of economic reasons:

- Firstly use proper shields where necessary and possible;
- Secondly install SPDs class I where necessary (limit those SPDs class I to an absolute minimum);
- Finally install SPDs class II where necessary.

The use of shields is also advantageous from the EMC point-of-view, especially for the DC-cables from the PV-modules to the converters. If these cables reach a length of some ten meters, electromagnetic field emissions may occur in a wide frequency range. Those field emissions are reduced by the use of shielded cables (of course the reduction factor depends on the frequencies of the emissions and the quality of the shield).

For a further increase of the electromagnetic compatibility (EMC) of the hybrid-system and here especially the PV-system, it is recommended to ensure, that the converters are equipped at the AC-output (and, if needed, also at the DC-entrance) with line-filters reducing the line-emissions at the power-cables.

6. CONCLUSIONS

Due to the increasing number of renewable energy hybrid-systems without power mains connection worldwide and due to their exposed locations, the number of lightning strikes to those hybrid-systems and their components will increase also. If the hybrid-systems have no protection measures against lightning effects, more and more damages and destructions of important components will occur resulting in long fault times, because the repair is costly and needs specialized man-power. In some cases the hybrid-system may be lost totally. In addition the power supply of the consumers connected to the hybrid-systems is lost, sometimes for longer time periods. This may lead to serious consequences depending on the kind of consumers (waste of food, standstill of production processes, loss of infrastructure like computers, telecommunications, decreasing acceptance of renewable energy hybrid-systems).

It can be stated, that lightning protection of independent renewable energy hybrid-systems will become more important in the future. Therefore it is necessary to take into consideration technically/economically balanced protection measures. The installer, owner or user of such a hybrid-system has to decide whether it needs protection or not. Therefore usually the first step is a risk analysis. The risk analysis has to take into account the losses relevant for the hybrid-system and the specific parameters, values and circumstances, influencing lightning vulnerability and protection. The help of a lightning protection expert is very useful here.

For the hybrid-system VATALI at Crete, a victim of a direct lightning strike in year 2000, it could be shown exemplarily, that a technically/economically balanced protection against lightning strikes is possible with still acceptable costs and efforts. The hardware costs for the protection measures are about 15,000 €: about 50% of the costs are due to protection measures against direct strikes, 50% are due to overvoltage protection.

Of course, an upgrading or a new installation, resp. of a lightning protection system in case of an existing system is always more expensive than an earlier consideration of the relevant requirements during the installation of the whole system. Therefore the costs of the measures related to lightning protection will decrease in case of their installation for new hybrid-systems.

Hybrid-systems like VATALI may be used as a station for research and development expansions, i.e. new installations and modifications occur permanently, which have to be included in the lightning protection concept. To ensure this a periodical inspection of those hybrid-system seems to be useful. If necessary, the lightning protection measures should be maintained.

The authors of this paper are involved in some projects dealing with lightning protection of renewable energy systems (independent hybrid-systems, mains connected WTGs and PV-systems). Aim is the further development of simple design concepts which can be realized easily, worldwide and with limited costs for those systems.

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Prof. Dr.-Ing. Alexander Kern
Aachen University of Applied Sciences, Dept. Juelich
Ginsterweg 1
D – 52428 Juelich
Germany
Tel.: +49 - (0)2461 – 993042
Fax: +49 - (0)2461 - 993262
e-mail: a.kern@fh-aachen.de