Accepted version of paper published by in Proc. 32nd International Conference on Lightning Protection.

**Citation:**

DOI: [10.1109/ICLP.2014.6973451](https://doi.org/10.1109/ICLP.2014.6973451)
An Experimental Approach of the Transient Effects of Lightning Currents on the Overvoltage Protection System in MW-Class Photovoltaic Plants

Y. Méndez Hernández, D. Ioannidis, G. Ferlas, E. Giannelaki, T. Tsovilis, Z. Politis and K. Samaras
Raycap GmbH
Garching, Germany
Email: ymendezh@raycap.com

Abstract— the aim of this paper is to explore and disclose the experiences during the measurements of the effects of lightning transient currents injected by means of a surge generator on the DC overvoltage protection system on a real MW-Class photovoltaic (PV) plant.

The main motivation of this work is to explore the effects of the transient voltages and currents under real operation conditions in form of travelling waves within the PV plant, which may be characterized in its transient behavior during the interaction of its components, such as, PV-modules, mounting (racking) system, PV inverters and grounding (earthing) systems.

Further, simulation models were developed with the computational program EMTP-ATP in order to explore transient effects within the PV-plant with main focus on the overvoltage protection (OVP) system on the DC side of the electrical installation, taking the measurements of the real PV-plant as a reference for the validation of the models.

Finally, a recommendation a strategy for commissioning and/or energizing the PV-plant with central PV-inverters is disclosed.

Keywords- Surge Protective Device, SPD, Transient Voltage Surge Supressor, TVSS, Photovoltaic, Inverters, Lightning.

I. INTRODUCTION
Lightning and switching effects in form of overcurrent and overvoltages have to be considered in the design and reliable operation of photovoltaic (PV) systems.

The focus of this publication lies on the study and evaluation of the performance of the overvoltage protection (OVP) system on the DC side of the PV plant taking into consideration its complex structure and electrical topology. This study was conducted on a real 1.4 MW PV plant consisting of the following main characteristics (Fig. 1):

- Geographical location: northern Greece with clear sky conditions in winter during the season 2013-14 and low temperatures (below 5.0°C / 41.0°F).
- The PV technology: thin film frameless PV-modules, with 10 PV-modules per PV-String in order to reach the required nominal voltage of at least 700 V\text{DC} for the operation of the PV-inverters.
- 2 central PV-inverters (800 kW rated active power); with 6 Generator Connection Boxes (GCBs) or 9,000 PV-modules connected to a PV-inverter and the remaining 6 GCBs or 9,200 PV-modules to the second PV-inverter, respectively.
- The max. DC short-circuit current is 1,098 A and 1,122 for each PV-inverter with a total of short-circuit current of 2,220 A for the whole plant.
- Aluminum-based mounting (racking) system for the PV-modules with meshed grounding (earthing) system in order to minimize step- and touch-voltages with an additional grounded fence.
- An impulse- or surge generator (10/350\mu s), which was installed within the PV-plant in order to evaluate the response of the OVP system under real operation conditions.

The measurements during wintertime with the objective to explore the effects of the low temperatures in the early hours of the day on the current and voltages, which leads to elevated open-circuit voltages ($V_{oc}$) of the PV installation on the DC side.

Figure 1. PV-Plant 1.4 MW located in northern Greece (PV thin-film technology and frameless PV modules).
The $V_{oc}$ increase, depending on the ambient temperature may impose additional electrical stress into the system (Fig. 2); where different technologies are compared as an example; this condition may appear when the operation is resumed within the PV-plant.

The components of the PV-plant were modeled in form of concentrated elements and PI-Diagrams calculated at a frequency of 500.00 kHz using the program EMTP-ATP. The chosen time-step of the simulation was 0.01 $\mu$s. The models used are disclosed in the following subsections.

1) PV-Modules/PV-Strings and PV-Tables

The PV-technology analyzed was frameless thin-film PV-modules without by-pass diodes, which is already in operation in the real PV-plant.

Fig. 3 depicts the simulation model for a PV-table formed by 5.00 PV-strings with 10 PV-modules/PV-string each (50 PV-modules) in the frequency range from 150.00 kHz to 30.00 MHz. A floating open-circuit DC-source $V_{oc, String}$ is connected in parallel with a diode in order to represent an approximate model of the V-I Characteristic of the PV-string, with an open circuit voltage $V_{oc}$ of 845.00 VDC, as shown in Fig. 4.

The short-circuit resistance $R_{sc}$ with a value of 4.00 Ohm/GCB accounts for the limitation of the prospective short circuit current $I_{sc}$ expected for every GCB of approx. 160.00 Amps (with rated total solar irradiance $G_{PV}$ on the plane of the PV-generator of approx. 800.00 W/m²).

The PV-string capacitance $C_{PV}$ of the solar cells accounts for the space charge capacitance $C_{soc}$, the transition carrier capacitance $C_{t}$ and the diffusion capacitance $C_{d}$, which are intrinsic to the semiconductor material; for this frequency range a value of 18.00 nF for PV-string and 3.20 $\mu$F for a GCB was chosen [2]. A shunt diffusion resistance ($R_d$) of the semiconductor material with a value of 464.00 Ohm for a PV-string and 2.90 Ohm for the GCB is assumed [2]; these elements may introduce additional high frequency oscillations, which was the case observed in the experiments at the real PV-plant. The capacitance of the glass $C_{Glass}$ with a value of 6.20 nF of the PV-modules is considered, in order to reflect the floating condition of the solar cells with respect to the racking system [3].

![Figure 2](image2.png)

**Figure 2.** PV-String (10 modules in series): Open Circuit Voltage ($V_{oc}$) variation depending on the ambient temperature and normalized at the $V_{oc}$ at 25°C of each technology [4] and [5].

**Figure 3.** Model of one PV-String with mounting (racking) system and grounding resistances.

The mounting (racking) system is represented by resistances $R_{Back}$ and $L_{Back}$ with values of 1.00 mOhm and 3.00 $\mu$H respectively; it is earthed (grounded) with earthing resistances $R_{Earth}$ with a value of 10.00 Ohm corresponding to a low resistivity soil (<200.00 Ohmm). Fig. 5 shows a representation of 8 PV-tables (400.00 PV-modules or a quarter of a GCB). For simplification purposes on the modeling, only an equivalent DC-source for each GCB was connected in order to reduce overflow-problems in the calculation routine of the program.

![Figure 4](image4.png)

**Figure 4.** V-I Characteristic for the Diode modeling the PV-String (10 modules in series).

![Figure 5](image5.png)

**Figure 5.** Simulation model of 8 PV-tables (quarter of a GCB, 40 strings or 400 PV-modules), mounting (racking) system and grounding resistances.
(OVP) is depicted, with is modeled by a non-linear element and a capacitance connected in parallel with value of 6.50 nF per connection terminal; the curve of the OVP is showed on Fig. 7.

The model chosen for the cables connecting the PV-strings was a PI-equivalent calculated at a frequency of 500.00 kHz. The cables do have a cross-section of 50.00 mm² and are 2.20 m above the soil. The cables (central trunk), connecting the GCBs, have a cross-section of 250.00 mm² and are buried 0.25 m under the soil. The earthing cables were modeled.

The DC-Side of the central inverter was modeled with a surge impedance (resistance in series with an inductivity, with 2,500.00 Ohm and 3.00 nH respectively) as shown in the Fig. 8.

The surge generator consists of a capacitor bank in series with an inductivity in order to generate the surge current for the experiments (10–350 μs, charge voltage up to 20kV), as showed in Fig. 9.

III. EXPERIMENTAL APPROACH AND MODEL VALIDATION

Two operational conditions were evaluated in order to validate and calibrate the models developed in EMTP-ATP:

- Short circuit (Iₙ) transient response taking the GCB located far from the DC input of one PV-inverter (>100 m distance) and at an ambient temperature of 5°C and without DC overvoltage protection (OVP).
- Lightning surge condition (10/350 μs) using a real surge current generator in order to validate the models with DC overvoltage protection (OVP).

A. PV Short-Circuit Transient Response without OVP and without Surge Generator

A measured short-circuit current of approx. 160 A (steady state) on the terminal connection box of the PV-inverter DC-side (without connecting the PV-inverter) is depicted on Fig. 10.

Concerning the simulation models in EMTP an acceptable agreement for the measured transient condition is observed and depicted in Fig. 11, which shows a short-circuit from the...
beginning of the simulation time; especially for the prospective short circuit current of approx. 170A.

For validation purposes, the measured and simulated transient response of voltage and currents at the PV-plant is depicted in Fig. 13 and 14, where the yellow plot is the impulse voltage of the surge generator (with a pre-charge voltage of approx. 5.80 kV), the green line the current injected by the surge generator and the magenta line the total current flowing through the OVP (Surge generator + PV).

The simulation models in EMTP shows acceptable agreement for the measured transient condition as depicted in Fig. 14.

The lower frequency oscillation on the current and voltage are mainly dependent on the topology of the PV-plant, such as, the modeling of the grounding system and the length of the connection and grounding cables to the GCBs.

**B. PV Transient Response with OVP and Surge Generator**

In order to evaluate the highest demanding operation condition on the OVP in terms of transient current and voltages, a surge current of approx. 2.00 kA (10/350 µs) was imposed on the terminal connection box of the PV-inverter DC-side. The OVP was connected between the “PLUS” and “MINUS” and the additional PV-photocurrent of the farthest GCB was superimposed during the surge event.

For validation purposes, the measured and simulated transient response of voltage and currents at the PV-plant is depicted in Fig. 13 and 14, where the yellow plot is the impulse voltage of the surge generator (with a pre-charge voltage of approx. 5.80 kV), the green line the current injected by the surge generator and the magenta line the total current flowing through the OVP (Surge generator + PV).

The simulation models in EMTP shows acceptable agreement for the measured transient condition as depicted in Fig. 14.

**Figure 11.** Simulated short-circuit current from t=0 µs (magenta line) and voltage (yellow line) when the farthest GCB without OVP is connected (1,600 PV-modules @ 10 PV-modules/String, initial $V_{oc}$ of approx. 845 Vdc).

**Figure 12.** Simulated short-circuit current from t=50 µs (magenta line) and voltage scaled by a factor of 0.1 in order to fit it into the plot (yellow line) when the farthest GCB without OVP is connected (1,600 PV-modules @ 10 PV-modules/String, initial $V_{oc}$ of approx. 845 Vdc).

**Figure 13.** Measured impulse voltage applied to the OVP (yellow line), impulse current through the surge generator (green line) and total impulse current (surge + PV) through the OVP (Surge generator + PV).

**Figure 14.** Simulated impulse voltage applied to the OVP (yellow line), impulse current through the surge generator (magenta line) and total impulse current (surge + PV) through the OVP (magenta line) with the farthest GCB (1,600 PV-modules @ 10 PV-modules/String, initial $V_{oc}$ of approx. 845 Vdc).
system, the length of the connection cables to the GCB and the type of OVP (in this case a new innovative design for PV applications).

IV. EFFECT OF THE PV GENERATOR UNDER IMPULSE VOLTAGES

After validating the models on section III; a comparison of the influence of the GCBs of the PV generator was made, in order to explore its effect on the overvoltage protection OVP.

Fig. 15 depicts the two transient voltage plots of the simulation (with and without the PV generator connected); before the triggering of the surge generator, a transient overvoltage condition is observed (red plot) before and after the triggering of the surge event, which may cause additional electrical stress on the OVP or so-called pre-conditioning.

The PV-generator imposes additional stress in terms of the energy dissipated by the OVP; this condition is essential in choosing a suitable the OVP solution in terms of protection of the PV installation, especially when unexpected overvoltage conditions and possibly, uncontrolled electric arcs are to be avoided. Fig. 17 shows the two transient voltage plots of the simulation with one GCB and six GCBs connected respectively; previous to the triggering of the surge generator, a transient overvoltage condition is observed with one GCB (red plot), which may cause additional electrical stress on the OVP (pre-conditioning).

When additional GCBs are connected, the transient condition increases in form of voltage-oscillations, as depicted in Fig. 17 (green line) and additional GCBs reduce the oscillations before the surge event (grading-effect).

Fig. 16 shows the energy dissipated by the OVP with and without the PV-generator connected.

Fig. 18 depicts the energy dissipated by the OVP with one and six GCBs.
Considering the experimental surge topology evaluated for these experiments (Fig. 9) and in terms of energy dissipation, additional GCBs increase the energy dissipated by the OVP, hence additional DC-currents sources (GCBs) are injected (see Fig. 18).

V. REDUCTION OF OVERSHOOTING AND OVERVOLTAGES IN THE START-UP PHASE OF MW-CLASS PV-PLANT (START-UP SCHEME FOR GCBs)

An operation methodology is proposed in this section in order to mitigate overvoltage-effects during the commissioning or operation-resuming phase in MW-class PV-plants.

It consists of connecting the closest GCBs in the early phases and the farthest GCBs with some additional delay during the start-up process; in other words, avoiding that all the GCBs are connected simultaneously to the DC-Side of the central PV-inverter.

With this simple method, a reduction of the overvoltages is achieved (Fig. 19); by these means, every partial contribution and transient effect of each individual GCB is further reduced.

VI. CONCLUSIONS

The DC-Side of the PV-plant is a complex system, which requires further analysis and experimental research.

The OVP thrives and evolves with these type of studies combined with additional experimental testing, certification from recognized institutions and long-term field experience and applications, especially on DC applications.

Measurements and simulations by means of the recognized simulation software EMTP-ATP on a real MW-Class PV plant were performed in order to obtain an acceptable agreement between the simulation results and the measurements. However these models need to be continuously improved.

Taking into account, the especial topology discussed in section B and depicted in Fig. 9, the PV generator imposes additional electrical stress to the OVP in terms of surge voltage, current and energy, which may be defined as “pre-conditioning” and was the main objective of this research in to impose severe demanding conditions on the OVP.

A new method of energizing several GCBs in PV-plants with central inverters is proposed, which leads to a reduction of the overvoltages effects on the PV-inverter and OVP, thus reducing the pre-conditioning effects and extending OVP duty cycle.

ACKNOWLEDGMENT

The authors would like to thank gratefully Raycap for the support and facilitation of this scientific work.

REFERENCES