TRANSFORMERLESS INVERTERS AND RCD: WHAT'S THE PROBLEM?

T. Tran-Quoc[1], H. Colin[2], C. Duvauchelle[3], B. Gaiddon[4], C. Kieny[1],
C. LE Thi Minh[1], S. Bacha[5], S. Aissanou[5], G. Moine[6], Y. Tanguy[6]
[1] - IDEA – G2elab, BP. 46, 38402 Saint Martin d'Hères, France
[2] - INES/CEA, BP 332, 50 avenue du lac Léman, F-73377 Le Bourget-du-lac, France
[3] - EDF R&D - 1, avenue du Général de Gaulle – 92141 Clamart Cedex - France
[4] - HESPUL, 114 boulevard du 11 novembre 1918, F-69100 Villeurbanne, France
[5] - G2elab, BP. 46, 38402 Saint Martin d'Hères, France
[6] - TRANSENERGIE SA, 3D, allée Claude Debussy, 69130 Ecully, France

ABSTRACT: Considering the structure of PV systems, a stray capacitance can appear between the PV arrays and the ground. When transformerless inverters are used, this capacitance can cause leakage currents to the ground.
According to the French standards, a Residual-Current Device (RCD) has to be installed at the AC side of the PV installation, for the protection of individuals. Yet, when the value of the leakage currents reaches a threshold (30 mA in homes in France), the RCD may switch off and unintended disconnections of the PV installation occur with accompanying production losses.
Based on simulations and experimental tests, this project aims at giving information to PV system designers and inverter manufacturers about the best suitable type of RCD to use for several PV system configurations.
This issue is relevant for countries with TT grounded networks like France where many operations of PV systems with unexplained disconnections of RCD have been reported.

1 INTRODUCTION

When transformerless PV inverters are used, the stray capacitance between the PV arrays and the ground can cause leakage currents to the ground (Fig. 1):

- These leakage currents flow from the connection of the PV structure to the ground (necessary for safety reasons and to prevent lightning damages)
- The stray capacitance is formed from the module electrically active layers and the surrounding metallic structures [1], thus the capacitance magnitude will depend on parameters such as the module surfaces, the distance between the electric charges and metallic structures, and the nature of the insulation material
- The capacitive current is created from this stray capacitance and the alternating voltages of polarities
- Transformerless inverters do not isolate the DC from the AC side, and allow the current to circulate via the ground connections and through the inverter

According to the French standards, a Residual-Current Device (RCD) has to be installed at the AC side of the PV installation, for the protection of individuals. Yet, when the value of the leakage currents reaches a threshold (30 mA in homes in France), the RCD disconnects the PV installation.

TT grounding systems and RCD are topics that have not been explored in detailed so far. The purpose of this study, which is part of a research project funded by the French Agency for Environment and Energy Management (ADEME), is to fully characterise capacitive discharge currents that occur with transformerless inverters, in order to determine which type of RCD should be used to design safe and efficient PV systems.

This paper presents modelling that have been undertaken so far as well as details on experimental tests that have been done with the intention to have a better understanding on that issue, in particular:

- Theoretical: simulations investigating the influence of different parameters on the leakage current (topologies of inverters, types of PV modules, resistance to the ground, ...)
- Experimental: tests with different types of inverters and RCDs to quantify the leakage currents and study the disconnection actions.

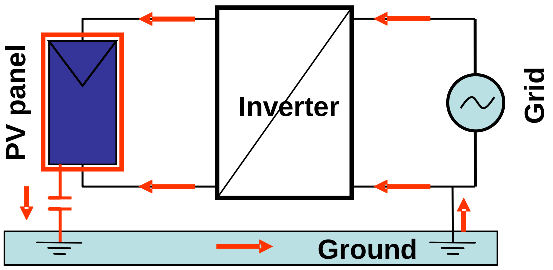

Figure 1: Schematic of leakage current according to the grounding system in France

2 WHY TO USE RESIDUAL CURRENT DEVICES

For a PV system, it is necessary to take two different measures of protection:

- Basic protection: protection against direct contacts,
- Protection against faults: protection in case of isolation fault between a live conductor and the ground (indirect contact).

In France, NF C 15-100 (or IEC 60479-1) standard requires the installation of protective devices that will cover those risks. The use of these devices will naturally lead the neutral grounding scheme. For a TT grounded networks (such as in France), this device is the basic unit of the protection of persons, its use is mandatory to ensure safety throughout the electrical installation.

The RCD is a protective device that monitors the residual current resulting from the vector sum of currents within conductors. In normal condition, the sum of the currents of all conductors (phase + neutral + ground) is zero [8].

The RCD is defined by the IEC 60755 international standard which provides different types of protections, as well as disconnection threshold or sensitivities:

- Class AC (sinusoidal alternating current)

- Class A (sinusoidal alternating current or pulsed DC component)
- Class B: this RCD is a device designed to protect networks with rectified alternation and filtered by capacitive load
- Class HI (High Immunity): RCD used for electronics or for sensitive devices.

3 APPROACH

This project aims at giving concrete answers to PV system designers and inverter manufacturers about the best suitable type of RCD to use for several PV system configurations. This issue is relevant for countries with TT network like France where many operations of PV systems with unexplained disconnections of RCD have been reported. This causes a loss of production, loss of financial benefit for the owner of the installation, loss of confidence in the PV technology and most of all a safety problem since system owners may be tempted to suppress the RCD or increase the disconnection threshold to a higher value, generating a potentially dangerous situation.

This problem of leakage currents has already been investigated in the literature [1-7]. Experimental tests done within previous research projects such as [9] concluded that the leakage current magnitude mainly depends on the inverter typology but without any recommendation concerning the type of RCD that should be used to make PV systems perform well and safe.

First, simulations have been performed with the help of EMTP-RV software in order to identify the factors that influence the leakage currents. Different types of inverters and modules have been designed in different configurations. The influence of stray capacitance value, capacitance distribution on both poles (DC+ and DC-) and the influence of the resistance of the neutral (impedance to ground) are also studied. Experimental tests have been then conducted on real components. Several types of inverters combined with different types of RCD (AC, A, B…) will be tested in order to measure the maximal admissible capacitance before the trigger action of the RCD and then to determine the best suitable type of RCD for each configuration.

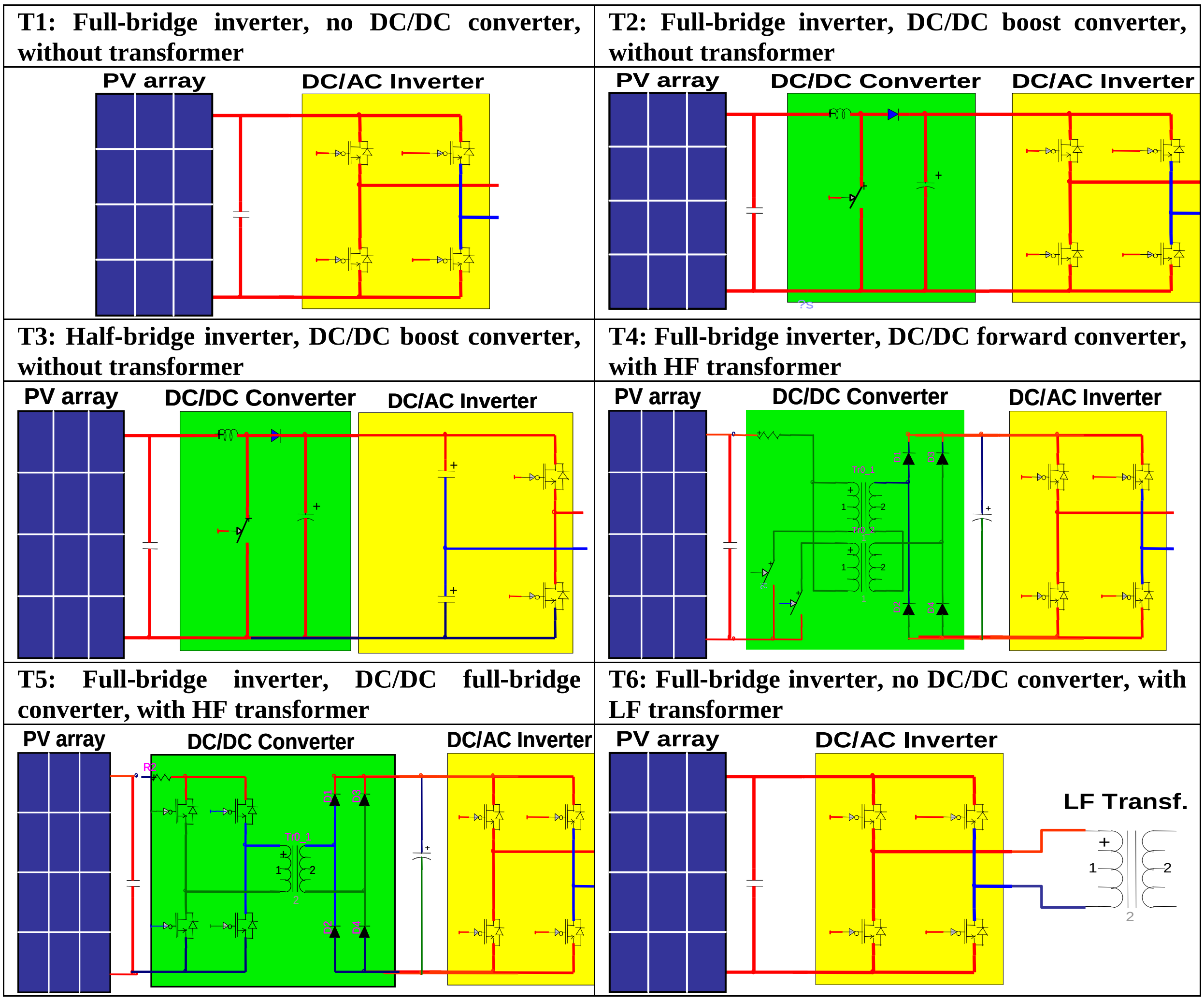

Figure 2: Different inverter models developed with EMTP-RV for studying the leakage current

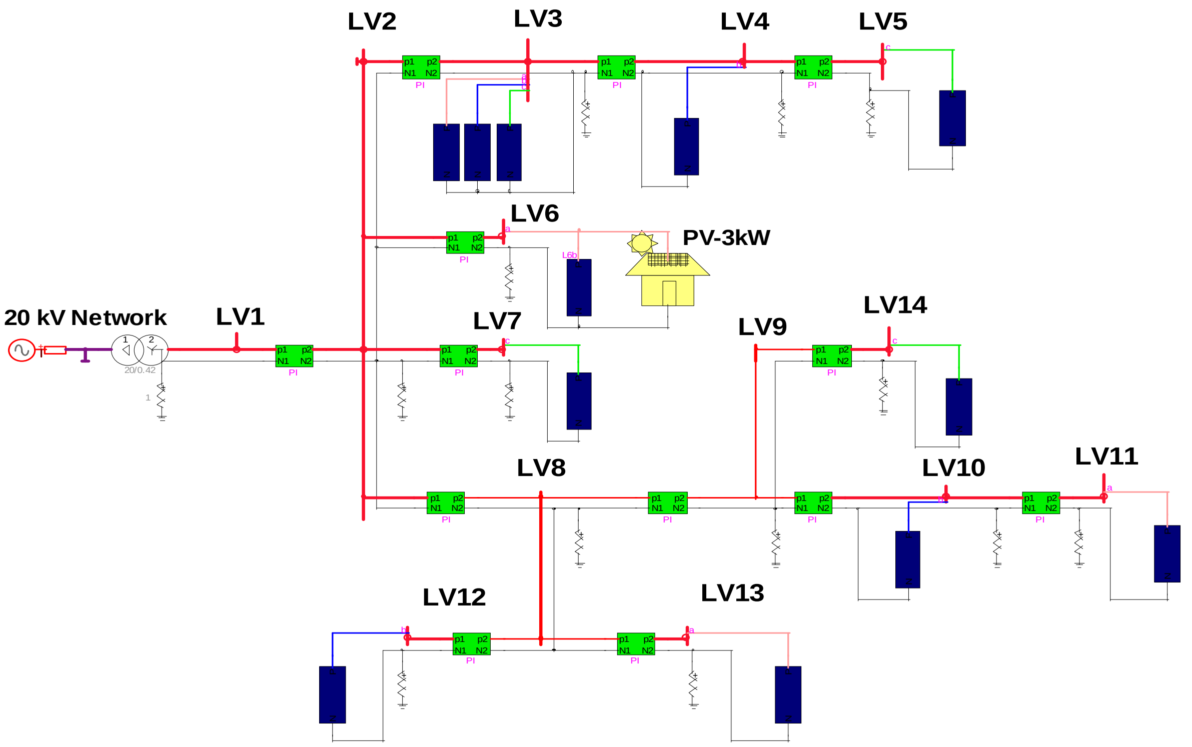

Figure 3: LV network with a single phase PV simulated with EMTP-RV

Finally, a solution that allows to differentiate the capacitance leakage current from the fault current is proposed. This solution can be used to avoid the undesirable disconnection of PV by RCD. Suggestions and solutions for reducing the current magnitude are also investigated.

4 MODELLING AND SIMULATION

4.1 Modelling

In this part, several models of inverter were developed in EMTP-RV in order to study the influence of inverter typology on leakage current (see Fig. 2):

- Full-bridge inverter, no DC/DC converter, without transformer (Typology T.1)
- Full-bridge inverter, DC/DC boost converter, without transformer (Typology T.2)
- Half-bridge inverter, DC/DC boost converter, without transformer (Typology T.3)
- Full-bridge inverter, DC/DC forward converter, with HF transformer (Typology T.4)
- Full-bridge inverter, DC/DC full-bridge converter, with HF transformer (Typology T.5)
- Full-bridge inverter, no DC/DC converter, with LF transformer (Typology T.6).

Then, a model of a real LV network with a PV system has been modelised (Fig. 3). This LV network is supplied by a 20/0.4 kV transformer of 160 kVA with 14 buses, 10 loads and 1 PV system (3 kW). A three phase load is connected at bus 3 and single phase loads are connected to other buses.

The influence of stray capacitance values, capacitance distribution on both poles (DC+ and DC-) and the influence of the resistance of the neutral network (impedance to ground) on the leakage current are studied.

4.2 Simulations

Table I: Leakage current magnitude according to inverter typology (Module capacitance: 1µF and R_earth = 30 Ω)

Topologies	Leakage currents (mA)
T1 : Full-bridge inverter – no DC/DC converter- transformerless	38
T2 : Full-bridge inverter – DC/DC boost converter - transformerless	39
T3 : Half bridge inverter – DC/DC boost converter - transformerless	9
T4 : Full-bridge inverter – DC/DC Forward converter – HF transformer	0
T5 : Full-bridge inverter – DC/DC full-bridge converter –HF transformer	0
T6 : Full-bridge inverter – no DC/DC converter – LF transformer	0

The simulations show that for a 3 kWp PV system using a transformerless inverter, the leakage current could reach 39 mA (Table I and Fig. 4), according to the hypothesis defined.

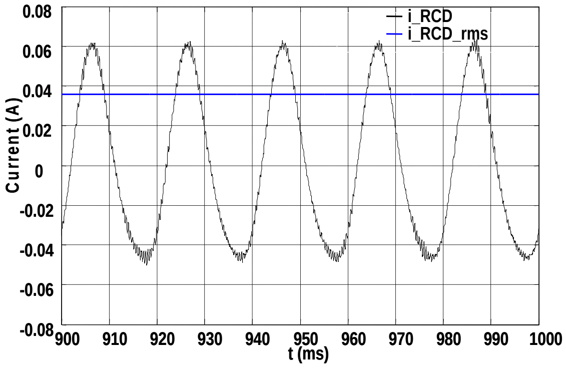

Figure 4: 39 mA leakage current obtained by simulation for T2 typology

Results obtained from simulations indicate that the leakage current strongly depends on the inverter typology:

- for inverter with transformer, leakage current is negligible (Topologies T4 to T6);
- for transformerless half bridge inverter, leakage current is very small (9mA, T3) - So we note that leakage currents are not necessarily linked with all transformerless inverters, indeed a proper choice in the inverter typology will strongly reduce this current. This comes from the reduced voltage variation amplitude of the polarities.
- for transformerless inverter, with a PV array capacitance of 0,8 µF , the leakage current can cause the trigger actions of the RCD (Table II).

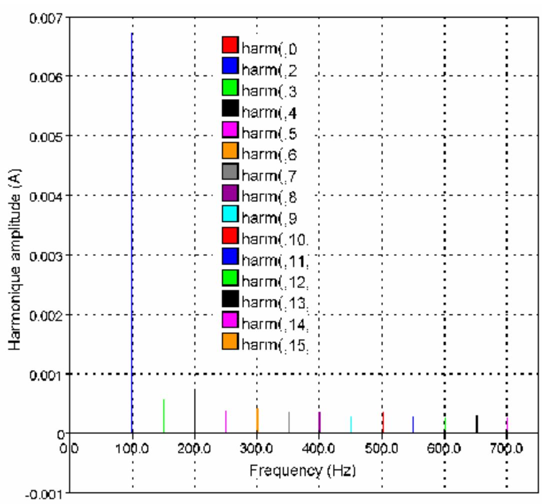

Figure 5: Harmonics of leakage current

Fig. 5 shows the result of the harmonic analysis (FFT) for a wave form of the leakage current shown in Fig. 4. It shows that the fundamental component (50Hz) is very important while other harmonics are very small. Fig. 6 shows the voltage on both poles of DC part of a transformerless inverter (DC+ and DC- ; output of PV arrays for T2 typology – see Fig. 2). We can notice that we have an important fundamental component while this current is direct. The other harmonics are due to the RLC circuit in the system. As the leakage currents have just little DC components, standard AC RCD type should correctly protect transformerless-based PV systems.

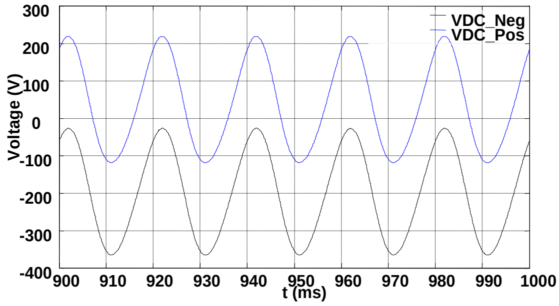

Figure 6: Voltage on DC+ and DC- of a transformerless inverter

The leakage current does not depend on the distribution of capacitance on both positive and negative polarities (Table III). This current depends on the grid grounding system resistance: in damp weather conditions this resistance reaches very low values, and this can lead to the disconnection of the RCD. In our simulations, this variation is relatively small (10% variation when the earth resistance varies from 1 Ω to 30 Ω). But sometimes, this variation is significant and can lead to a disconnection of the PV system. Simulations have been carried out with a constant 0.7µF capacitance and with several earth resistance values. While a 10 Ω earth resistance doesn't generate any critical leakage current, an earth resistance value lower to 1 Ω generates a leakage current upper to the limit of 30 mA (see Table IV).

Table II: Influence of PV module capacitance

C (µF)	i_leakage (mA)
1	39
0.8	31
0.6	24

Table III: Influence of repartition of PV capacitance on 2 polarities

C (µF)	i_leakage (mA)
V_{DC+} (0.5) & V_{DC-} (0.5)	39
V_{DC+} (1) & V_{DC-} (0)	39
V_{DC+} (0) & V_{DC-} (1)	39

Table IV: Influence of the neutral earth resistance (0.7µF)

R_earth (Ω)	i_leakage(mA)
30	27
10	28
1	30

4.3 Conclusion of the simulations

The simulations show that in general cases, there is no problem of leakage current; this is why the probability of disconnection of RCD is very small.

In case where the leakage current is important (> 30 mA), following solutions can be carried-out:

- Using inverters with transformer or transformerless half bridge inverter
- Using PV mono or polycrystalline modules (these modules with small tray capacitance)
- Using an advanced control mode inverter.

5 EXPERIMENTAL TESTS

Based on the theoretical results obtained so far, several experimental tests have been conducted with real system components (inverters and RCD) in order to have a concrete evaluation of leakage currents and see how RCD operate in a PV system.

Such experimental tests took place in a laboratory facility equipped with different types of transformerless inverters available on the market and most common RCD types : AC, A, B, … (Fig. 7). Three types of transformerless inverters are used for these experimental tests:

- Inverter # 1: the same as T1 in Fig. 2
- Inverter # 2: the same as T1 in Fig. 2 with H5 topology
- Inverter # 3: the same as T2 in Fig. 2.

Tests are undertaken to give empirical answers on 3 topics :

- The RMS leakage current value for different transformerless inverters with regard to the power delivered,
- The behaviour of several types of RCD in case of capacitive leakage current,
- The impact of using a high immunity RCD on human safety in case of direct contact with a live conductor.

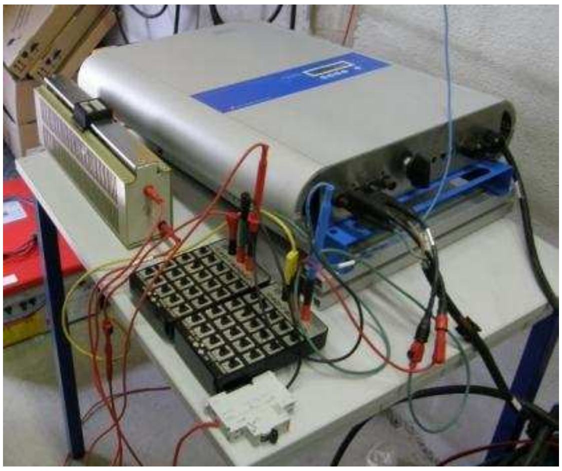

Figure 7: Inverter under test with capacitance between the positive and negative poles and the ground to increase the leakage current

5.1 RMS leakage current

The objective of this experimental test is to quantify the RMS leakage current value of three transformerless inverters available on the market.

All inverters were supplied by a 5 kWp PV array of polycrystalline type. Their nominal power is ranging from 3,8 to 4,6 kVA.

The results presented in Figure 8 show in this system configuration and the available test conditions that:

- The leakage current value is rather proportional to the inverter power (1 to 2 mA/kVA),
- Extrapolated value for nominal power lead to a maximum of 9,4 mA for inverter #2:

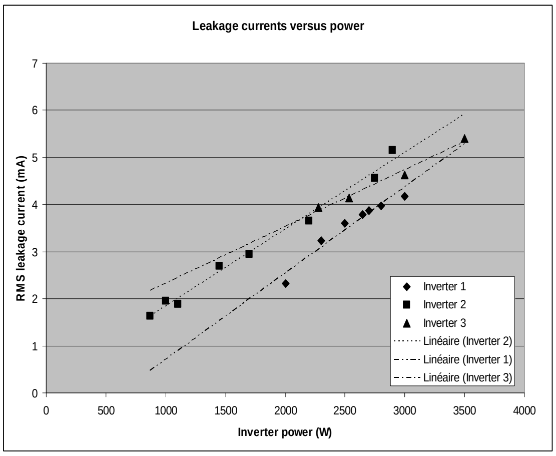

Figure 8: Leakage current versus inverter power

5.2 Behaviour of RCD

The objective of this experimental test is to analyse the behaviour of most RCD types available in case of leakage current.

For this test, 4 different RCD types are connected in string to see which RCD first trips for different levels of leakage currents (see Fig. 9).

The value of the leakage current is set by increasing manually the capacitance value (see Fig. 7).

Figure 9: Several RCD types under test

First results show that:

- The order of disconnections of the RCD may vary (according to the conditions of testing),
- RCD’s behaviour strongly depends on the inverter: for instance, inverter #3 is very sensitive and disconnects before any action of a RCD; for the two others, the disconnection sequence is different from each other.

5.3 Leakage current and human safety

The third test deals with human safety. The inverters are tested with the most immunised RCD (i.e. the one disconnecting for the highest value of current). A virtual direct contact is simulated with the help of a resistance placed in series with the variable capacitors (set to the highest value before tripping), either on DC+ or DC- pole, to check if the operation and tripping of the RCD complies with human safety requirements.

Here as well, results depend on the inverter type: with inverter #3, which detects the default, RCD trips in case of direct contact and would thus perform its duty; with inverters #1 and #2, RCD's behaviour differs depending on whether the resistance is connected on DC+ or DC-: in a particular situation no action is observed, which would endanger human safety.

6 CONCLUSIONS

This study aimed at giving some hints to PV system designers and inverter manufacturers about the best suitable type of RCD to use for several PV system configurations.

This issue is relevant for countries with TT grounded networks like France where many operations of PV systems with unexplained disconnections of RCD have been reported.

The simulations made within this project showed that in general cases, there is no problem of leakage current; this is why the probability of disconnection of RCD is very small.

In case where the leakage current is important (> 30 mA), following solutions can be carried out:

- Using inverters with transformer or transformerless half bridge inverter
- Using PV mono or polycrystalline modules (these modules have small stray capacitance)
- Using an advanced control mode inverter.

The first experiments clearly showed the complexity of the study as results depend on inverter types and testing conditions. They also emphasized the relevance of this topic regarding production sustainability and safety.

In the continuation of the project, further experimental tests will be carried out in order to complete the first results.

7 REFERENCES

[1] J.C Hernandez, P.G. Vidal, A. Medina, "Characterization of the insulation and leakage currents of PV generators: Relevance for human safety", Renewable Energy, ELSEVIER, No. 35, 2010

[2] Lin Ma, Fen Tang, Fei Zhou, Xinmin Jin and Yibin Tong, "Leakage current analysis of a single-phase transformer-less PV inverter connected to the grid", IEEE Conference, 2007

[3] Roberto González, Jesús López, Pablo Sanchis, and Luis Marroyo, "Transformerless Inverter for Single-Phase Photovoltaic Systems", IEEE Transaction on Power Electronics, Vol. 22, No. 2, March 2007

[4] Roberto González, Eugenio Gubía, Jesús López, and Luis Marroyo, "Transformerless Single-Phase Multilevel-Based Photovoltaic Inverter", IEEE Transaction on industrial Electronics, Vol. 55, No. 7, July 2008

[5] Kerekes, T.; Teodorescu, R.; Borup, U "Transformerless Photovoltaic Inverters Connected to the Grid", APEC 2007 conference, February 2007, Anaheim, California USA

[6] Oscar Lopez, Francisco D. Freijedo, Alejandro G. Yepes, Pablo Fernandez-Comesana, Jano Malvar, Remus Teodorescu, and Jesus Doval-Gandoy, "Eliminating ground current in a transformerless photovoltaic application", IEEE Transaction on power conversion, Vol. 25, march 2010

[7] "Courants de décharge capacitifs - Remarques concernant la conception des onduleurs sans transformateur", Information technique, SMA

[8] Schneider Electric, "La protection différentielle dans les installations électriques basse tension", Inter Sections, magazine de Schneider Electric de l'enseignement technologique et professionnel

[9] DISPOWER project, "Identification of general safety problems, definition of test procedures and design-measures for protection", 2006