PV in Urban Policies- Strategic and Comprehensive Approach for Long-term Expansion

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WP4 – Deliverable 4.1:

STATE-OF-THE-ART ON DISPERSED PV POWER GENERATION:
Publications review on the impacts of PV Distributed Generation and Electricity networks

ANNEXES

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1 IMPACTS OF PV-DISTRIBUTED GENERATION ON DISTRIBUTION NETWORKS

1.1 Voltage rise and voltage fluctuations	*References*
DESCRIPTION:	
* VOLTAGE RISE	
In a classic electrical distribution system, the generated power is assumed to feed into the system at the highest voltage level and the power is consumed at the lowest voltage level. Thus, the power direction through the system is expected to be from the higher voltage level to the lower voltage level. The only exceptions from this are step-up transformers used to maintain voltage within acceptable values at the different voltage levels.	
The electricity supply companies must fulfil certain obligations when supplying electric power to the customers. Some of these are the requirements to power quality at the delivery point, e.g. voltage limits, voltage fluctuations, interruptions and harmonics. The supply voltage at the delivery point must lie within ±10% of the nominal value for European LV networks (EN 50160). Stricter limits apply nationally, both in Europe and elsewhere, with accepted voltages typically lying between 90% and 106% of the nominal voltage.	*1, 2*
Voltage variation in distribution systems is partly caused by load variations. In this sense, the voltage drops through the power lines are reduced when the load is reduced, e.g. during nights or summer holidays. To avoid the grid voltages surpassing acceptable limits at the MV distribution levels, it is common to perform automatic voltage regulation by means of step-up transformers that change automatically their transformer ratios when the voltages change on their secondary side. The automatic tap changers fix the voltages on the secondary side as close as possible to the nominal system voltage (maximum deviation from the nominal system being typically ±1.5%).	*3*
Other measures used to regulate voltage on distribution lines consist of installing voltage regulators on the line at mid-point of the lines, with the secondary voltage of the regulator set higher than the primary voltage. This voltage ratio is thus automatically changed as the line voltage fluctuates.	
At the LV distribution level voltage regulation is not performed automatically, but through the use of manual off-loads tap changers in the MV/LV transformers. Typically, these tap changer positions are set once and never changed again except when the networks are extended or modified. The manual tap changer settings must be chosen so that the voltage is always below maximum accepted level (e.g. 106% of nominal) at minimum load, and always above minimum acceptable level (e.g. 90%) at maximum load.	
With the growth in Distributed power Generation (DG), the power flow has become more complicated, with combined heat and power plants and wind turbines feeding directly into the Medium Voltage (MV) networks, and PV	

systems also to the Low Voltage (LV) networks. Undesirable overvoltage situations in the LV distribution system might occur under particular circumstances of relative size of the load and power generation (for example, low load demand coincident with considerable DG generation). In the Netherlands, for example, implementation of DG is possible to 70% of the nominal power of the distribution transformer (MV/LV) in most situations due to the increased upper limit of the voltage level (from 242 V to 253 V).	*4*
* VOLTAGE FLUCTUATIONS The output of PV power generation fluctuates with hourly changes of solar radiation. Solar radiation varies in second order owing to the movement of clouds except for on completely clear days and completely cloudy days. The hourly fluctuation in output of the PV power generation causes fluctuation in power flow, or fluctuation in voltage, in the connected distribution line. For PV power generation of a concentrated arrangement in a limited area, the output of each system could fluctuate simultaneously compared with the load. Accordingly, the hourly fluctuation in voltage in the distribution line due to PV power generation could become larger than the fluctuation induced from the load. Such kind of fluctuation might become a technological issue affecting future introduction of PV power generation systems.	*5*
THEORETICAL EVIDENCES: * VOLTAGE RISE If a large number of PV power generation systems are connected to distribution lines which are controlled by adjusting the transformer taps or by voltage regulators installed on the lines, the voltage at the customers' terminals may increase because of reverse power flow (the increase will depend upon the relative sizes of the load and the power generation): - If the distribution transformer is used to perform voltage regulation (automatic change of transformer taps), since the sending voltage on the secondary side of the distribution transformer is typically set at a value higher than the standard voltage under current operating procedures, the voltage at the end of a distribution line could exceed the upper limit even with slight reverse power flow, possibly created by the PV system during light-load hours in the daytime. - If distribution lines are provided with voltage regulators, they might operate frequently because of the voltage changes corresponding to solar irradiance changes. As a result, their service life-time might be shortened. Three possibilities are identified to overcome this effect: - One is to limit the effective output of the PV system when overvoltage occurs. - Demand supply management with battery storage is another option to prevent overvoltage, while fully benefiting from the power generated by	*6*

the sun - The third option is to operate the PV system at the leading power factor. Leading power factor operation has the advantage of controlling the voltage without restricting the effective power output of the PV system. However, the effectiveness of this method depends on the ratio of resistance to reactance of the distribution line impedance. If the resistance component of the impedance is very large in comparison to the reactance, a large reactive power is required to maintain the proper voltage value. Attention must be paid to this factor because a large kVA inverter would be necessary when the line resistance is large. The power factor of the entire distribution line might also be degraded if every PV system on the line supplies a large reactive power. A combined approach could be to turn the inverter to leading power factor operation as soon as the upper voltage limit is reached, and then to limit the effective power output of the inverter when the voltage rise cannot be suppressed with the leading reactive power supply within the capability of the inverter. Another measure that could be used to limit overvoltages would be to limit the amount of generation allowed by each customer. Similarly as it is currently done in distribution systems design, where a typical “After Diversity Maximum Demand” (ADMD) is used for sizing the distribution transformers, a similar factor could be used for PV systems, reflecting the total number of consumers likely to have PV systems. In this way, both the transformer overload and voltage rise effect could be solved.	
Theoretical studies have been conducted under the International Energy Agency – Photovoltaic Power Systems Programme (IEA-PVPS Task V) for a typical configuration of a MW/LV power system (open MV ring configuration with five MW/LV transformers and five LV lines per MW/LV transformers —total 25 LV lines). Typical average values were chosen for line impedances, line lengths and tansformer sizes. The minimum load was set to 25% of the maximum load. Three cases of high PV penetration were investigated: 1) Penetration from a single LV line (in the order of 30-80 kWp); 2) Penetration from all the LV lines connected to a single MV/LV transformer (in the order of 200-400 kWp); 3) Penetration from all the MV/LV transformers connected to a 10 kV ring (in the order of 1-2 MWp); [Note: The referenced report does not mention the operation conditions, namely irradiance and PV generators position. It is assumed that these refer to Denmark (report authorship) and optimal position (maximum production).] Main results were the following: - In principle, no PV penetration was acceptable at minimum load. The excess voltages for PV penetrations up to the minimum load were,	*3*

however, rather limited: between 106% and 107% for the cases considered. Obviously, the restrictions at minimum load are only a problem if the power generation from the PV systems coincides with minimum load situations (not at night times, holidays periods however could be the case).

- Only a small increase in the load from the minimum load opens up for a considerable amount of PV (linear increase). This is especially the case if PV power only penetrates from a single LV line (case 1, 158% of load under maximum load conditions; cases 2 and 3, 120% and 75% respectively). (Note: limiting of PV penetration to 75% of maximum load for case 3 is due to the fact that the MV/LV is not supposed to be designed for a total no-load situation).

Measures were also listed to increase the amount of PV penetration, to be used only if large power production from PV coincides with minimum load situations (during the summer holidays in many countries, especially if the use of airconditioning is limited):

- A conservative way to avoid over-voltages from PV penetration would be to build separate reception networks for PV systems (i.e. PV networks separated from the consumer networks), such as the ones often seen in the open country with high concentrations of wind power. This measure would imply neglecting one the big advantages of PV, which is in fact to connect to the existing power networks as well as to use the existing buildings for mounting. The costs of PV systems would also increase to unacceptable levels, especially if the problems only occurred a few times per year.

- Another way to avoid over-voltages could be to let PV systems reduce their power generation in case of over-voltage. Such a measure would add unacceptable costs to PV systems, especially if the measure is not needed in the majority of cases. In addition, over-voltage monitoring systems would make PV more sensitive to short-term disturbances in the network.

- A more feasible solution to allow for more PV penetration at minimum load is to change the MV/LV transformer tap changer positions in the period when maximum load situations are not expected. Such a measure would require an interruption of the electricity supply a few times a year (twice, should the summer days be periods of low load, such as it is the case in northern countries) for adjustment of the off-load tap changers. The costs of this measure are likely to be rather limited.

- One of the most efficient measures to allow for more PV is perhaps the customers' own changes of behaviour. Experience with PV systems in Denmark shows that the customers change their consumption behaviour when at the same time they become power producers. In this sense, many customers who have PV installed endeavour to move their consumption to moments with high PV power production. This tendency is especially noticeable if the customers experience different buying and selling prices of electricity.

Other relevant concluding remarks were: - PV is considered unlikely to present conceptually novel issues requiring fundamental additional investments in the power systems. In the longer term, it is expected that more flexible and accommodated consumption will remove the barriers of limits to PV penetration. It is essential that PV —together with other elements of distributed generation— is considered in the future network planning. - PV is likely to offer benefits (for example, reduction of the peak power demand from the network if high generation coincides with peak demand situations, such as in areas with significant use of airconditioning) that far exceed the limited costs of PV penetration.	
Simulations have been done within the DISPOWER project in a weak network scenario (rural area), in order to identify ways to increase the penetration of Distributed Generation provided by wind technology (penetration limited by voltage rise coming from wind generation exceeding the normative levels during minimum load conditions). Results show the benefits of using load management, namely: - If the load management system is used to control 20% of the total load, the maximum size of the wind turbine would be 3 times greater than that without using load management. - Further benefits would arise from controlling 50% of the total load, with the maximum size of the wind turbine being 5 times greater than that without using load management. This possibility is seen however less realistic, due to the difficulty of finding a large amount of controlled loads (>20%). The results of the study prove that load control is an effective strategy for mitigating voltage rise on weak rural networks, in order to facilitate connection of an increased capacity of Renewable Distributed Generation.	*7*
Theoretical studies have been carried out in the U.K. with the aim of providing a defined path for maintaining quality of supply to all customers as Distributed Generation penetrates the distribution system. - Computer modelling and simulations were done to review the impact of a generator on the voltage control scheme, using existing equipment. The studies revealed some problems due to the interaction of DG with Automatic Voltage Control (AVC) schemes. For example, typical problems include the failure of compounding to provide the correct voltage boost, operation at poor power factors or interference with the ability of schemes to keep transformers in step. It was concluded that the correct strategy for managing voltage regulation in the presence of DG depends on the operating mode of the generator (power factor or voltage control) combined with a complementary operating mode for the AVC scheme and selection of the correct relay characteristic/algorithm.	*8*

- A range of alternative/new voltage techniques were described with comments concerning their costs and benefits. A new distributed sensing voltage control technique utilising a PSTN/GSM (Public Switched Telecommunications Network / Group Special Mobile) interface was proposed. Scheduling embedded generation to improve voltage control was also considered together with a summary of costs and benefits.	
Another theoretical study (computer simulations) done in the U.K. to investigate the effects upon a typical 11 kV network from various DG technologies (small scale hydro, landfill gas and wind power), networks design influences and management issues. Regarding voltage regulation through the use of transformers tap changers, it was concluded that the ability for generators to actively control and change on line tap settings could assist in the control of network voltage levels when encompassing DG.	*9*
Similarly, other U.K. studies assessed the potential benefits of changing the traditional operation philosophy of distribution networks from passive to active management in order to accommodate DG.	
- In one case results showed that an area-based control of On Load Tap Changing Transformers with respect to amount of DG that can be connected and the amount of reactive support required was likely to bring the largest benefits in terms of increase of DG that can be connected, especially to weak distribution networks.	*10*
- In another study, a relatively simple solution is proposed, providing there is a similar DG at times of high and low load demand (it may be either the same DG technology or different), namely by lowering the voltage set point at the primary substation or “permanently” altering the tap positions of fixed MV/LV transformers.	*11*
- In another study covering load flows and fault analysis at the LV level, voltage control problems increased steadily with increasing levels of DG. Introducing some form of active voltage control into the LV network was considered to be necessary.	*12*
A theoretical study (simulations) done also in the U.K. on the unbalanced load flows that can result from single phase PV generator connections showed that the local voltage increases can be worse than predicted by a balanced load flow model, such as it is usually employed by distribution companies.	*13*
A theoretical study has been carried out in France in order to assess technical factors that could limit the penetration of DG in the low voltage grid for 3 types of LV grids (urban, semi-urban and rural). - For the urban grid, DG has very little impact on the grid voltage. In this kind of grids, the penetration of DG is limited by the maximum current of feeders. - For semi-urban and rural grids, the penetration of DG is limited by the voltage grid, especially at weakest point of the grid, which is the location at which the voltage varies significantly when the consumption is	*14*

maximum without any generation.	
* VOLTAGE FLUCTUATIONS Theoretical studies have been conducted in Japan within the framework of the International Energy Agency – Photovoltaic Power Systems Programme (IEA-PVPS Task V), to develop a method of evaluating the output fluctuation in view of the magnitude and time of fluctuation when many PV power generation systems are connected to a distribution line that is densely located in an area such as a residential zone. The model was tested with actual data from a Test field for Photovoltaic systems in Japan, using an experimental facility in which about one hundred 2 kW PV systems were connected to a simulated distribution line having a line constant (inductance and capacitance) equivalent to 10 km. Total area occupied by the PV systems (including clearances between PV generators) was 9350 m^2. All PV systems had the same orientation and tilt angle. Main conclusions were the following: - It is difficult to measure the actual speed and magnitude of output fluctuations of multiple interconnected photovoltaic power generation systems. It was found that the value measured by a pyrometer having a slow response is similar to the actual values of the speed and magnitude of output fluctuation of multiple interconnected photovoltaic power generation systems. Therefore, the speed and magnitude of total output fluctuation can be measured with a pyrometer having a slow response. - In the case when many PV systems are connected uniformly along the distribution line, even if the output fluctuation of each PV system is large, both the magnitude and speed decrease and level off for the whole system. Accordingly, the distribution voltage fluctuation due to output fluctuation also decreases. Local voltage fluctuation for the case of distributed and concentrated installation of PV system should be examined in future works.	*5*
Another evaluation method to determine the fluctuation characteristics of PV systems has been proposed in Japan, by using frequency analysis. Irradiance was measured in 9 different locations scattered on a 3.2 x 3.9 km^2 area over more than 2 years. Preliminary results show that the more the irradiance fluctuates, the more the smoothing effect is effective. In future work the authors will perform further simulations to consider the smoothing effect in actual networks including area size, the distance to distribution stations, and the number of PV systems.	*15*
Theoretical studies have been carried out on the effect of a high level of penetration of grid connected PV systems installed at household level, in distribution networks (Medium Voltage level, 20 kV). Simulations have been done with more than 150 different case studies, including two geographical locations (Helsinki at 60ºN latitude, and Lisbon at 39ºN) and three different domestic electricity consumption profiles based on publicly available data, representing apartment houses: typical finish blocks of flats, Portuguese without air-conditioning, and Portuguese with 50% of load assumed to be air-conditioned. Three different distribution networks were considered: a multi-	*16*

branched tree type (radial, corresponding to a urban environment), a comb-type (radial, linear type) and a loop-type network. Concerning the PV systems, different orientations were considered, accounting for different town planning cases: all PV modules oriented to the south; 50% to south, 25% east and 25% to west; 50% to south and 50% to west; and 50% to east and 50% to west. Shading effects were also taken into account, as well as different PV penetration levels. Voltage rise levels were considered acceptable within the range 0.975 and 1.025 p.u. (i.e., ±2.5% related to nominal value); the limits were selected as a compromise of rural (5-15%) and urban (0.2-2%) voltage rise recommendations in Finland. Main results were the following: - For the lowest penetration level (5% of all the nearly 10,000 households having a 1 kWp system), equivalent to 50 Wp/hh (hh=household), positive effects to the network were obtained in all cases (reduction of network losses). - For a 50% penetration level, equivalent to 0.5 kWp/hh, only modest voltage rises occurred at some of the network tail sections, in all cases below 0.7% of the nominal voltage value. - For 100% penetration level, equivalent to 1 kWp/hh, higher voltage rises were obtained in all the network types. For south oriented PV modules and the multi-branched network, voltage rise over nominal value reached 2.5%, while the comb-type network experienced voltage rise up to 1%. - For 200% penetration level, equivalent to 2 kWp/hh, most of the network cases topped the 2.5% voltage rise limit except for the comb-type network (2%) - In all the cases, highest voltage rises where reached with the PV modules south oriented. Comparison between the different network types showed that the comb-type network could absorb the highest PV penetration rate. On the contrary, the highest voltage rises were experienced with the tree-type networks.	
EXPERIMENTAL EVIDENCES: * VOLTAGE RISE Commercial inverters in Japan incorporate a voltage regulation functionality that prevents overvoltages at the Point of Common Coupling by reducing the PV generator output (shift of its working voltage towards the open circuit point). Experimental research has been done in a residential area with more than 200 clustered PV systems integrated on top of roofs (total enclosed area smaller than 1 km^2). Detailed measurements during one spring month showed that the implemented functionality worked properly; the effect on the PV systems performance ratio was a reduction of 16% compared with the expected no power-limitation case.	*17*

* VOLTAGE FLUCTUATIONS Experimental tests were carried out in a 200 kWp Test field for Photovoltaic systems in Japan. It was confirmed that the speed of output change corresponding to the change of solar irradiance is relatively slow even when a large number of PV systems are interconnected and dispersed over a wide area. However, the gross magnitude of the change increased in proportion to the number of PV systems involved, a factor which increased the distribution line voltage variation. Particularly with low voltage distribution lines, the proper voltage range might be exceeded if no countermeasures are provided.	*18*
NEEDS FOR STANDARDIZATION: For PV inverters to perform voltage regulation functions to limit overvoltages, product standards should incorporate the relevant requirements, both for the products development and testing. **TIME FRAME:** Short / Medium	
NEEDS FOR RESEARCH AND DEVELOPMENT: More studies and measurements are needed on the effect of widespread application of PV systems on distribution line voltages, for different network configurations (urban, rural areas; different countries), in order to provide methods of assessment of maximum (/optimum) PV penetration in distribution systems. Multiple generator modelling studies are also considered necessary, in order to identify and correct eventual problems arising from the operation of small multiple generators. Moreover, R&D on new voltage control techniques are necessary, which enable to maintain network voltage control with Distributed Generation technologies. **TIME FRAME:** Short / Medium	

References - Voltage rise and voltage fluctuations

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1.2 Current harmonics	***References***
DESCRIPTION:	
The grid voltage in public supply systems is never a pure sinewave. Disturbances in form of harmonic and interharmonic voltages superposed on the grid voltage are some of the main steady state power quality phenomena. Voltage and current harmonics are defined in terms of the spectral components over a defined range of frequencies:	
- Harmonics (IEEE P1-433-A) are sinusoidal voltages or currents having frequencies that are integer multiples of the frequency at which the supply system is designed to operated (termed the fundamental component, usually 50 Hz or 60 Hz);	*1*
The main sources of existing harmonics in the networks are nonlinear loads, mainly present in the MV and LV levels of the power system. Harmonic voltages superimposed on the fundamental grid voltage have their origin in the harmonic currents drawn by these loads. The harmonic voltages then propagate around distribution systems and branch circuits not concerned with carrying the harmonic current. Examples of sources of harmonic currents in the networks are: switch mode power supplies, gas-discharge and fluorescent lamps, variable speed drives, uninterruptible power supplies, cyclo-converters, phase angle controlled loads, arc furnaces, static VAR compensators and transformers. Also, linear loads (consisting of resistors, capacitors and/or inductors) may become source of harmonic currents when they operate under distorted voltage conditions. The distortion in the current can be much higher than the distortion in the voltage. Total Harmonic Distortion levels above 100% occur often for single phase loads, but harmonic voltage distortion above 8% is very unlikely.	*2* *3*
Harmonics have a wide range of impacts on the network components and the customer side of the system (including loads and generators). Typically associated problems are variations in RMS voltage and flicker, thermal effects on transformers, rotating generators and motors (increased losses), disturbances of electronic equipment, acoustic disturbances, overloading of passive filters, disturbance of protection systems and protective relays, interference with communication systems (telephone, control and data transmission signals), stress on insulation materials, transformer saturation and system resonances.	*4, 2*
Inverters to be used in grid-connected PV systems (or by any other Distributed Generation technology) are not covered by specific standards. Generic standards for electrical equipment are generally applied. For example, for inverters operating in Low Voltage (LV) networks with output rated currents up to 16 A per phase the international standard IEC 61000-3-2 is used (with inverters falling under the class A equipment), which requires Total Harmonic Distortion (THD) of the current to be less than 5% and places limits on the size of any one current harmonic. Different requirements exist, however, in some countries.	*5* *6, 7*
According to manufacturers information of commercial inverters (1998) with powers ranging from 700 W to 50 kW (most of them based on PWM	*4*

technology), typical achievements were found to be less than 5% THD with any one harmonic less than 3%, For electrical equipment with higher currents operating in LV networks, no international consensus has been reached in order to have an international standard, so a Technical Standard exists (IEC/TS 61000-3-4). The same applies for MV and HV loads.	*8, 9*
THEORETICAL EVIDENCES: It is possible to make a “harmonic fingerprint” of devices in general and DG-systems in particular. With this harmonic fingerprint harmonic voltages and current can be predicted. Harmonic problems occur as the inverters have a too high capacitance. Applying a lot of these systems will bring the resonance frequency to a level where in general already is a background harmonic voltage. Resonance problems will then occur leading to high harmonic currents and voltages.	*10, 11, 12, 13* *14*
EXPERIMENTAL EVIDENCES: Experimental measurements were carried out in a Danish residential area with 60 kWp of PV systems (60 systems of 1 kWp each) at 29 existing private single houses (80% of neighbourhood total), connected to a distribution transformer (200 kVA,10/0.4 kV) via 2 of its 5 feeders. Objectives were, amongst others, to assess the overall impact of the PV systems on the voltage quality via the current harmonics produced by the inverters. Measurements included currents, voltages and powers, and harmonics (individual and total distortion of currents and voltages) during one year. The impact of current harmonics on voltage quality was assessed through the correlation between Total Voltage Harmonic Distortion and the weighted sum of harmonic currents. Results led to conclude that the most important part of the voltage distortion in the local network comes from external sources (local cogeneration plants). At the same time the most significant part of the current harmonics produced in the neighbourhood is caused by TV sets and only to a limited extent by the PV installations. This conclusion was also confirmed by measurements realised at individual consumers with PV installations where there have been detected no differences in the voltage distortion of phases with and without energy produced by the installations. The authors consider the results are representative of a high concentration of PV systems for a geographically limited residential area. The risk that a similar concentration of PV systems in other confined areas would give an unwanted impact on the voltage quality cannot be excluded, if the grid in that area had a significantly lower short-circuit power than it is the case analyzed.	*4*
Experimental tests were carried out in a Test field for Photovoltaic systems in Japan, on the harmonic distortion arising from the operation of multiple PV systems connected to the same distribution. To that aim, four or five 2 kW PV systems were connected to the same phase of the secondary side (single-	*15*

phase, three wires) of the 30 kVA pole transformer. Harmonic distortion was measured both at the transformer secondary side, as well as at each individual inverter output. The tests were carried out under a no-load condition to remove the effect of harmonic current from loads. The inverters were all self-commutated, both of the voltage controlled (7) and current controlled (2) types, in all cases with isolation transformers. The tests included the operation of inverters of the same manufacturer only (same control scheme), and of different manufacturers (different control schemes). From these measurements, it was concluded: - Third and fifth harmonic currents from inverters had almost the same phase displacement, and the total harmonic current could be superimposed (increase with the number of connected units). This phenomenon was considered to be caused by the excitation current of the inverters isolation transformers. - Higher harmonics had in general different phase displacement even if the same control scheme was employed, so that the total harmonic current could be cancelled.	
Experimental measurements done in the U.K. on the cumulative effect of harmonics when different inverters operate simultaneously showed that the higher frequency harmonics tend to be attenuated quickly. For the lower frequencies the situation is more complex, depending on the nature of the inverter control and the strength of the grid. In a strong grid, the total harmonic distortion is more constant, while in a weak grid it tends to increase as the number of inverters increases. The effect is expected to be less noticeable with significant impedances in the lines between the inverters.	*16*
Experimental measurements done in France on a 13 kWp PV system composed of 4 inverters with transformers and 2 transformerless inverters showed that the PV system generates very little current harmonics except for the H6 and H8 current harmonics which were higher than the upper limit set by standards IEC 61000-4-7 (related to harmonics and interharmonics measurements), and compatibility levels for low-frequency conducted disturbances). In the 0-2 kHz range, the Total Harmonic Distortion of current (THDI) value was 4.94% while in the 2-9 kHz frequency range, the maximum Frequency Distortion of current measured (FDI, or ratio between the effective values of all currents in the frequency range considered, and the nominal current at nominal power) was 0.643%.	*17* *18, 19*
NEEDS FOR STANDARDIZATION: An international standard for inverters with currents higher than 16 A per phase operating in LV networks is needed; the same applies to electrical equipment. **TIME FRAME:** Short	
NEEDS FOR RESEARCH AND DEVELOPMENT: Cumulative effect of harmonics when multiple inverters operate simultaneously	*4*

is an issue not covered in the standards. Although the devices individually comply with existing standards, the knowing of the power system total distortion is not an easy task (many influencing factors, both on inverters design and level of background distortion in the network). More research on the understanding of harmonics is needed in this respect, as well as measurements on real projects. **TIME FRAME:** Short / Medium	

References – Current harmonics

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1.3 DC from inverters	*References*
DESCRIPTION:	
Requirement of isolation transformers for PV grid-connected systems for safety reasons varies amongst countries. Whereas in some they are compulsory required, in others the requirement depends on technical features of the devices (e.g. DC currents monitoring scheme) or specific utility technical requirements.	*1* *2, 3*
Many commercial inverters employ transformers; these suppress any DC component by design. However, transformerless inverters have gained over the last decade an increasing importance due to technical and economical advantages (higher efficiency, lower weight, volume and costs).	
PWM-controlled converters can produce DC-components when even order harmonics are contained on the voltage waveform and, in general, when a positive-negative imbalance exists on the network voltage waveform. When the network voltage contains harmonics, a percentage of these will also be contained in the reference waveform used by the inverter. This distortion of the reference waveform will be higher especially in the case where the synchronization of the inverter with the network voltage is done by taking as reference the zero-crossings of the voltage.	*4*
Even harmonic currents are injected by loads that exhibit asymmetrical i-u characteristics (i.e. i(u) ≠ -i(-u)). Possible sources of even harmonics in the networks are: three-phase half-controlled bridges, AC arc furnaces, converters (e.g. three-phase rectifiers supplying DC/DC converters, six-pulse cyclo-converters), and half-wave rectifiers. Current distortion propagates through the distribution system and results in voltage distortion due to the system impedances.	
Regarding DC currents in networks, the following distinction is to be done (at present not considered in the relevant standards):	
- “Symmetrical” DC current is acomponent flowing in live and neutral conductors. It can be generated, for example, by loads using half-wave rectifiers (such as light dimmers, high frequency ballasts within fluorescent lighting loads and switch power supplies for household appliances) or PWM inverters.	
- “Unsymmetrical” DC current is a residual component that can be generated by earth faults in DG installations using DC sources and inverters without galvanic separation, or by earth leakage currents in the DC circuit of the inverter.	
Currently, there are no limits for DC harmonics defined under the standard EN61000-3-2, and additionally equipment consuming less than 75W do not have any harmonic limits defined at all (exceptions under clause 7). Hence for some household equipment, such as mobile phone chargers, it is not known whether any DC current component is produced. In principle, the likelihood of the occurrence of high levels of DC injection (e.g. above 20mA), is possible by aggregation of smaller DC injection levels from a number of devices.	*5*

Additionally there remains the possibility for a certain degree of cancellation due to opposing DC polarities, and the nature and connection of system components in a particular scenario. Impact of DC currents on network equipment mainly concern distribution transformers, Residual Current Devices (RCD), current transformers, energy meters, pipelines and metallic structures. Of these, critical effects (and lack of detailed information and experiences) are on: - RCD's safety function: AC trip exceeding the nominal value due to the presence of DC currents) - Distribution transformers: harmonic distortion increase, losses increase, heating increase and noise increase, associated to half-cycle saturation (induced by a DC offset in the transformer core magnetisation). Saturation can cause high primary current peaks, which might trip the input fuse and thus cause power outages.	*1*
THEORETICAL EVIDENCES: * DC-VOLTAGE COMPONENT OF VOLTAGE SOURCE INVERTERS: Simulations have been done within the DISPOWER project in order to quantify the amount of DC voltage that PWM voltage source inverters might generate under particular conditions. Different converter topologies (2-level, 3-level and 5-level), parameters of PWM pattern (Modulation Frequency and Modulation Amplitude indexes) and harmonics contained in the grid voltage waveform (Harmonic Orders 2nd, 4th, 6th, 8th and 10th; Harmonic Percentage of the voltage waveform between 1 and 10%; Harmonic Angles ranging from 0 to 162º) were analyzed, in order to cover a wide range of possibilities. Most relevant results were the following: - The level of DC-voltage component is directly related with the Modulation Frequency (MF) index. In general, for MF indexes up to 33, as the MF index increases the DC-component decreases. MF index of 21 gives the highest level of DC-components for every Harmonic Percentage value considered. - There is no clear connection between the DC component and the Modulation Amplitude (MA) index. The same applies to the Harmonic Angle (HA). - Highest DC components were obtained for 2-level converters, with values between 0.6 and 9.5% of the fundamental component of the line voltage. 3-Level converters produced the lowest DC components (between 1 and 2.5%), similar to the ones produced by 5-Level converters (between 1.8 and 2.2%). - For high MF indexes (MF≥45), the level of DC-voltage component was low in all the cases (<1%). Furthermore, analysis of typical measures used to eliminate DC- components in	*4*

PWM inverters were carried out. The following are not recommended due to their drawbacks: - Provision of filters to remove harmonics from the measured network voltage. Although this would prevent even harmonics to enter the reference voltage waveform, such a filter could delay the time response of the control system in the event of a system fault (and therefore not be able to prevent overcurrents). - Increase of the Modulation Frequency to eliminate DC-component on the inverter output voltage. This results in higher switching losses and lower efficiency of the inverter. A minimum value should be used, for which the DC-component is low and inverter efficiency is high.	
* EFFECTS OF DC-CURRENTS ON DISTRIBUTION TRANSFORMERS: A study has been done in the United Kingdom on the impact of injected DC currents on harmonic distortion of distribution transformers, based on simulations of a 500 kVA 11/0.433 kV transformer (loading of 50 % and unity power factor considered). As criterion for admissible DC injection, a limit is proposed leading to 5 % Total Harmonic Distortion for the phase current has been proposed. In particular, for a typical 500kVA distribution transformer a 40mA DC injection per small-scale DG was proposed to a Distributed Generation Coordinating Group, to be considered as a starting point for later work on planning standard levels for low voltage DC injection. Another DC injection limit of 0.5% the nominal phase current has been proposed by the U.S. National Rural Electric Cooperative Association, based on existing standards (IEEE 1547).	*6* *7, 8*
* EFFECTS OF DC-CURRENTS ON RESIDUAL CURRENT DEVICES: Theoretical studies done in the United Kingdom conclude that RCD's are unlikely to be adversely affected (i.e. prevent tripping under a fault condition) by the presence of dc arising from inverters used in conjunction with embedded generation plant, nor is there any evidence to suggest any increased safety risk. The issue of nuisance tripping (i.e. tripping not under fault conditions), whilst being an inherently safe option, may nevertheless become more of an issue and should be investigated.	*6*
* EFFECTS OF DC-CURRENTS ON CORROSION OF PIPELINE AND CABLE NETWORKS: In the previously mentioned study it was also mentioned that a large volume of evidence exists of corrosion risks associated with dc currents in pipeline and cable networks (and in particular with regard to stray current corrosion in dc traction systems). Whilst such failures may lead to minor utility service disruption, more catastrophic failure can also occur with severe consequences. Therefore, some upper limit should be set, the main difficulty being the influence of earthing conditions in the local networks on corrosion problems, which suggests that a wider discussion on corrosion issues is necessary.	*6*

EXPERIMENTAL EVIDENCES: * DC-CURRENT COMPONENT OF CURRENT SOURCE INVERTERS: Experimental tests have been carried out within the DISPOWER project on state-of-the art inverters representative of the European domestic market (12 single-phase units with different design concepts: low-frequency transformer, high-frequency transformer and transformerless). Test voltages with various harmonic levels were used, based on European standards (EN 61000-4-13, class 2 for points of common coupling), corresponding to the levels that can be typically found in public networks. Voltage harmonic orders 2nd, 4th, 6th and 8th were applied in the tests. Main results were the following: - In 67% of the cases DC-currents measured were below 100 mA. In the remaining cases DC-currents were smaller than 600 mA. - The amount of DC component did not increase in the presence of even voltage harmonics. - Comparing the voltage test levels used and the levels which can be expected on public networks, it can be concluded that state-of-the-art grid connected inverters do not produce relevant DC current components.	*4* *9*
* EFFECTS OF DC-CURRENTS ON DISTRIBUTION TRANSFORMERS: Experimental measurements carried out in a dense urban German settlement with 50 kWp of PV systems (25 systems of 2 kWp each; line commutated transformerless inverters feeding in the same phase) found typical DC currents between 0 and 5% of fundamental current for a single inverter, with a maximum total DC current of about 4 A for all the inverters. During one year of testing, these DC components did not cause any disturbance in the network.	*10*
Laboratory tests carried out in Germany with a toroid transformer (1:1 transformation ratio; 3 kVA) under different load conditions (DC and AC) showed the following results: - Without any AC load at the secondary side, pulsed DC current load of up to 50% of transformer rated current (both in rms values) did not cause any hazard of a local blackout due to the action of the transformer primary fuse. - Operation under high constant AC load (85% of nominal rating) and variable DC loads (similar conditions of a utility transformer) showed that the DC component caused a distortion of the transformer primary current. For DC currents of up to 13% of the transformer nominal current no hazard situations occurred. Experiments were repeated for a different transformation ratio (2:1). Results were similar, the only differences being the calibration factor for the primary	*1*

current, reduced by the new transformation ratio.	
Experimental tests were carried out in a Test field for Photovoltaic systems in Japan, with 2 simulated high voltage overhead distribution lines (transformer capacities of 500 kVA and 2000 kVA respectively), each line consisting of 10 blocks equivalent to a total length of 10 km, with 2 pole transformers (of 10 to 30 kVA) mounted in every block of the distribution lines. Single-phase PV systems were connected to the Low Voltage side of the pole transformers: in line 1, 100 units with a capacity of 2 kWp each, total 200 kWp; in line 2, 100 units with capacities of 2, 3 and 5 kWp, total 300 kWp. Inverter types used were voltage-controlled (50% of those connected to line 1) and current-controlled type (50% of line 1 and 100% of line 2). All inverters had insulation transformers. An experimental AC-DC mixing fault was induced by directly connecting the output terminal of a PV array (4 parallel strings of 7 series connected PV modules each) directly to the AC circuit of a 10 kVA transformer. Measurements showed both the exciting current of the transformer and harmonics of even orders increase on the high voltage side of the transformer (the exciting current waveform being the cause of distortion due to magnetically deflection by the DC currents). However, even when DC current equivalent to 10% of the transformer rated current was induced, no problem such as overheating was observed. The effect of the previous AC-DC mixing fault in other parts of the distribution line was also investigated. Measurements showed that: - Distortion of the current waveform was seen in other PV systems connected to the same low voltage distribution line where the AC-DC mixing fault occurred (DC magnetic deflection phenomena in the inverters insulation transformers). This phenomenon did not have any effect on these PV systems, such as stopping power generation. - Distortion of the current waveform caused by an AC-DC mixing fault was seen in other pole transformers connected to the same high voltage distribution line. This was particularly noticeable in pole transformers located on the power supply side from the pole transformer generating the AC-DC mixing fault, but not in pole transformers located on the load side from the pole transformer generating the AC-DC mixing fault. - No effect was observed in PV systems connected to the low voltage side of pole transformers located in the vicinity of the pole transformer generating the AC-DC mixing fault. Thus, there was little detrimental effect such as overheating of pole transformer caused by mixing faults of PV systems which continued for several minutes.	*11*
Experimental tests have been carried out within the DISPOWER project on two 400 kVA distribution transformers, in order to identify and quantify the effects of DC injection and to determine immunity levels: one representative of 1970's technology, rather inefficient, and one representative of 2005 technology, rather efficient (class of transformer with the lowest losses and very low excitation current). Assumption was made that the installed DG capacity represents half of the transformer rating.	*4*

Electrical effects of DC injection on the current harmonic distortion (limiting factor, 5%), no-load losses (limiting factor, 200 W) and noise levels (limiting factor, sound pressure increase < 6 dBA) were investigated. Main results were the following: - Of the 3 effects investigated, noise level increase due to DC currents is the most limiting, particularly for the modern transformer. A translation of this transformer immunity limit into emission limit for DG is proposed: o Maximum DC injection: 0.5% of the transformer rated current, with an exception of small/micro distributed generation; o Maximum DC injection for small/micro distributed generation: 100 mA per unit. - The previous values are to be considered rather conservative (the limits being set on the basis of a small increase of noise level on a modern transformer with very low excitation current), meaning that respecting these values should not lead to any problem for the whole population of distribution transformers. As a conclusion it was stated that the injection of DC current by inverter-based generators seemed not to be really a decisive issue for the integration of Distributed Generation. With proper design of the inverter control, as it is the case for most current products, DC current levels are low in comparison to the meaningful limits proposed above.	
* EFFECTS OF DC-CURRENTS ON RESIDUAL CURRENT DEVICES: Research done in the United Kingdom and Austria on the effect of "symmetrical" DC currents on Residual Current Devices (RCD) which may be affected by DC currents (type "AC" for sinusoidal AC currents, and type "A" for pulsed currents) concluded the following: - "Symmetrical" DC currents do not have any worth mentioning impact on the operation of RCDs. Even with DC current levels of several Amps, the trip function is still operating properly. - "Unsymmetrical" DC currents have a noticeable effect on RCDs of type AC and A. For this reason, and in order to prevent safety problems, RCDs of type B (all-current sensitive RCDs) should be used in connection with generators which could present DC residual currents.	*6, 4*
* EFFECTS OF DC-CURRENTS ON MEASUREMENT SYSTEMS: Research has been done in the U.K. on the effects of DC components on measurement systems: - Concerning the impact on current measurement transformers, according to manufacturers' information DC currents up to 10% of rated current should not cause inaccuracies. Considering the lowest rating of Low Voltage Current transformers (typical 50/5 A, class 0.5 metering current transformer), a level of DC current of 5 A would be required to influence	*6*

accuracy, a value certainly too high to be considered as limiting for DG. - Regarding electricity meters (watt-hours), while for new meters compliance with existing standard (IEC 62053) ensure reliable and accurate operation under DC, electromechanical meters are seen as susceptible to present measurement deviations in presence of DC components. This issue is in fact not specific to inverter-based DG, since effects may also be expected for loads drawing DC currents.	*12*
NEEDS FOR STANDARDIZATION: * LIMITS ON DC CURRENT INJECTION BY DISTRIBUTED GENERATORS: - PWM inverters may in principle generate symmetrical DC currents during normal operation in the presence of even harmonics in the grid voltage. Currently, the distinction between symmetrical and unsymmetrical DC currents is not made in the applicable standards. This point should be addressed in future standardization activities. - The DC injection limits currently specified in interconnection requirements are very diverse, ranging from 20 mA (UK-G83/1) to 5 % not exceeding 1 A (IEEE 1547). Meaningful limits such as the ones proposed by the DISPOWER project should therefore be uniformly adopted. Too severe limits might result in unjustified constraints for equipment manufacturers, and therefore lead to significant barriers. **TIME FRAME:** Short	*13, 8*
NEEDS FOR RESEARCH AND DEVELOPMENT: * DC CURRENT INJECTION BY INVERTERS: State-of-the-art inverters without galvanic separation and with appropriate control designs are able to regulate the (symmetrical) DC component to very low values, even in case of presence of even harmonics on the grid voltage. No specific R&D needs on this subject are needed, except improvement of inverters control techniques for operation in highly distorted electrical environments. **TIME FRAME:** Short / Medium	
* EFFECTS OF DC CURRENTS IN THE NETWORKS: Further research, especially of experimental nature (testing) should be devoted to effects of DC currents on transformers, RCDs (to determine upper limits to nuisance tripping rather than maloperation, i.e. failure to trip), electronic and electromechanical energy meters. Measurements on fluorescent lighting ballasts and switched mode power supplies, including Class D devices (e.g. mobile phone chargers) should be also carried out in order to quantify any DC current components coming from these devices. **TIME FRAME:** Short / Medium	

References – DC from inverters

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1.4 Ground faults

References

DESCRIPTION:

System and equipment grounding are two complementary measures widely used in PV systems to provide safety. System grounds, when used, generally provide the ground paths using the intended current-carrying conductors, whereas equipment grounds provide the ground paths for the metallic surfaces that might be unintentionally energised and ensure that those surfaces remain at or near ground potential.

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System and equipment grounding practices and requirements vary widely with applications and among the countries, resulting from the historical evolution of elctrical codes to address safety and grounding techniques for electrical generation and distribution systems. For example, codes in the USA require equipment grounding of all PV systems, and system grounding for systems with voltages over 50 volts (open circuit module voltage). European and Japanese codes require equipment grounding, but do not require system grounding and most of their PV systems do not have grounded current-carrying conductors on the DC side. Both approaches entail advantages and disadvantages, namely:

- The ungrounded system provides the best fire hazard reduction (multiple ground faults are needed to create a fire hazard) and allows easy ground fault detection.
- The grounded PV system generally provides the best personnel protection from electrical shock because the voltages to ground are well defined and stable (the distributed capacitances of PV modules and wiring to ground do not build static charges)

Notwithstanding the previous comments, with proper design, both grounded and ungrounded PV systems can achieve good personnel, fire and equipment safety. An important consideration for grounding PV systems is to determine the compatibility of the PV system ground with the interconnected utility.

Due to the electrical nature of PV systems and their particular operation conditions (exposed to outdoor meteorological conditions as well as to eventual faults coming from the distribution network or the electrical installation itself), the following insulation faults might occur:

- Insulation failures between current-carrying conductors of opposite polarity, causing bolted (line-to-line) faults. The current flow into bolted faults can be from PV modules in the faulted circuit, from modules connected in parallel with the faulted circuit, or from external sources such as batteries or inverters. Blocking diodes have failed on many occasions in PV installations and have allowed multiple PV strings to contribute to ground fault currents. Some inverters, even under normal operating conditions, can feed AC utility currents into faults in the PV array wiring (“backfeeding”).
- Insulation failures between current-carrying conductors and ground, known as ground faults. Ground faults can develop within the PV array,

in circuits that have electrically combined the array or in switches and inverters. Ground-fault detectors must be used to sense ground faults in both grounded and ungrounded PV systems. The detectors to be used in ungrounded systems should be more sensitive to protect personnel, than for grounded systems. The practical limit for ground-fault sensitivity is limited by wet-weather leakage currents.	
THEORETICAL AND EXPERIMENTAL EVIDENCES: Installed PV systems rarely perform exactly in the manner indicated by electrical schematics. Accumulative leakage currents associated with the large PV array, long runs of wiring, surge protection, diodes, junction boxes that collect moisture, and conduit often make actual ground-fault detection difficult. Leakage currents in early PV systems were often sufficient to cause false indications of ground faults and contributed to many hours of system down time. The leakage currents associated with all of the distributed PV source components and wiring also pose unseen and unfamiliar hazards to personnel, or might contribute to ground faults that increase fire danger and personnel hazards. The increasing penetration of building-integrated PV systems using DC wiring circuits and inverters will require ground-fault detection and PV array disable devices for fire and personnel safety. There is however no consensus yet regarding ground faults coming from the DC side of PV systems, an example of which can be seen in the relevant international standard (IEC 60364-7-712), where it is stated that “protection by automatic disconnection of supply on the DC side requires special measures which are under consideration”. The particular interaction between the PV system, the buildings (including their users) and the electricity networks makes this an important matter to deal with.	*1* *2*
NEEDS FOR STANDARDIZATION: Present international standard (as well as many national codes) covering PV power systems installed in buildings (IEC 60364-7-712) are incomplete regarding fault protection by automatic disconnection of supply on the DC side of PV systems. The fact that there are many PV systems integrated in buildings already under operation worldwide brings the necessity to address this topic. **TIME FRAME:** Short / Medium	*2*
NEEDS FOR RESEARCH AND DEVELOPMENT: Experimental measurements of ground faults currents in grid-connected PV systems (especially if installed in buildings or public places) should be carried out on a long time basis, in order to gain further experience and produce technical recommendations (monitoring, disabling) as well as input for relevant standards. **TIME FRAME:** Short / Medium / Long	

References – Ground faults

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1 IEA PVPS Task V, report IEA-PVPS T5-01: 1998, “Utility aspects of grid connected photovoltaic power systems”.

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1.5 EMC – Capacity leakage of PV systems with transformerless inverters	***References***
DESCRIPTION:	
When running PV grid-connected systems, operators have occasionally reported about triggering Residual Circuit Devices. In other cases, window cleaners have sensed a tingling when cleaning PV facades. Capacitive leakage currents in PV systems with transformerless inverters could produce such effects.	*1*
There are various concepts of transformerless inverters. For the most part, the inverter conducts a reversion of polarity of the solar generator relating to the earth potential, either abruptly or continuously according to a specific time function. (Note: a few designs avoid the above mentioned polarity reversion by using built-in DC-DC converters or special topologies).	
When AC voltage components lie across the capacities appearing in the solar plant, leakage currents flow over these capacities, the amplitude of which is dependent upon the size of the capacity, upon the amplitude and harmonic content of the AC voltage and upon the frequency. Capacities are related to:	
- PV generator. Although capacities are small when individual PV modules are considered (as required by standards such as IEC 61215), total capacity of a PV generator consists of the electrical association of modules and mounting structure (i.e., of their respective capacities). If an AC voltage lies across this capacity, a residual current will flow. Also, a touch of the PV generator (especially on the back side of glass-foil PV modules) can, under certain circumstances, cause non negligible current leakages.	*2* *3*
- EMC filters used at the inverters input and output sides, which contain, amongst others, Y capacitors (“Line-to-ground” type). These capacities induce common mode leakage currents on the ground (protective) wire that might trigger Residual Circuit Devices under certain circumstances or induce undesirable effects.	
Ground wire currents load the ground wire, which normally should be free of current (it should conduct current temporarily only in case of an error). If the leakage currents from several devices add up in the ground wire, in case of an error (interruption of the ground wire) a danger can arise if it is touched. If the sum of the ground wire current is too large, a larger cross-section of the ground wire can be necessary.	
THEORETICAL EVIDENCES:	
* CAPACITIVE LEAKAGE CURRENTS ON PV GENERATORS:	
Research done in a German R&D project (SIDENA) on PV modules and generators connected to transformerless inverters enable to calculate (simulate) the form and size of the leakage currents by means of the ascertained earth and hand capacities. It can be seen that due to their capacitive behaviour, the	*2*

voltage jumps might cause high leakage currents.	
EXPERIMENTAL EVIDENCES: * CAPACITIVE LEAKAGE CURRENTS ON PV GENERATORS: Experimental measurements have been carried out within the DISPOWER and SIDENA projects on insulated (not grounded) PV generators of two different technologies (glass-glass and glass-foil type PV modules) connected to transformerless inverters. Over several months and with different weather conditions, touch conditions were induced in the front and back side of the PV generators using surfaces equivalent to a human hand. Main results were the following: - Leakage currents on the glass-glass PV generator were the same when the touch was on the front or back side. - Leakage currents on the glass-foil PV generator were the 1.5 times higher when the touch was on the back side (foil) compared to the front side. Leakage currents in this last case were comparable to the glass-glass PV generator. - The leakage currents flowing through the inverters over a period of two months (back side touch condition) were independent of the fed-in power, which means that the amount of the leakage current is independent of the irradiation strength. No apparent correlation could be either identified from evaluating the influence of other meteorological variables such as wind, humidity, atmospheric pressure or rainfall. - Contact pressure and, above all, the inverter topology have greater influence on the amount and the curve form of the leakage currents. * CAPACITIVE LEAKAGE CURRENTS ON PV SYSTEMS WITH TRANSFORMERLESS INVERTERS: Experimental measurements have been carried out within the DISPOWER project on 11 single-phase transformerless inverters connected to PV generators of two different technologies (glass-glass and glass-foil type PV modules). Touch conditions were induced in the back side of the PV generators using surfaces equivalent to a human hand. Main results were the following: - Leakage currents measured were higher in the glass-foil PV generator, compared to the glass-glass one (1.2 – 1.5 times). - Whereas the measured leakage currents were not directly dangerous when a PV module was touched, however a dangerous reflex movement could be triggered by the noticeable electric shock. In contrast, the PV generators leakage currents for certain inverters were in such a magnitude that they present a real potential for danger if the mounting structure earthing were interrupted with the potential equalisation. - During the tests, there were repeated undesired shut-downs from Residual Current Devices when a specific number of inverters were put	*1, 2*

in operation. Effective values of the ground wire current at a load of 1 kΩ (simulates human body resistance) varied between 1 and 15 mA for the different inverter topologies. - The measurement results show that the problematic of ground wire currents has to be kept in mind when PV systems with many inverters are planned (partially also for each individual device), since the currents can add up to values that can exceed the given limit values, or that can represent a potential for danger when the line is interrupted.	
NEEDS FOR STANDARDIZATION: Design of transformerless inverters for PV systems should pay close attention to the potential leakage currents. In the requirement for fix electrical devices of the DIN EN 61140 safety class 1, leakage currents of up to 10 mA (corresponding to a capacity of up to 135 nF in the AC side of the equipment) are permissible. However, there are no equivalent limit values for the DC capacity. Product standards for transformerless inverters should consider this issue, since AC voltages with a large harmonic content across earth are often injected into the DC side of transformerless inverters. **TIME FRAME:** Short	
NEEDS FOR RESEARCH AND DEVELOPMENT: Experimental measurements of leakage currents in PV systems with transformerless inverters should be carried out on a long time basis, in order to gain further experience and produce technical recommendations for the inverters design. **TIME FRAME:** Short / Medium	

References – EMC – Capacity leakage of PV systems with transformerless inverters

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1.6 Contribution to short-circuit capacity	*References*
DESCRIPTION: It is generally considered that PV generators interconnected to distribution systems do not supply short circuit fault current to the system in case of a short circuit fault on the distribution system side. This is so because the short circuit current of a PV array is 10 to 20% more than the rated maximum output current at most, inverters are normally equipped with an Under Voltage relay, and current controlled type inverters mainly used for PV Distributed Generation have an over-current limiting in case of a disturbance on the distribution system side. It is therefore considered that if the number of interconnected PV systems remains small, their effect on the distribution line would be negligible. However, if the number of PV system increases, the short-circuit capacity of the whole distribution system (including PV systems) might be also increased and the fault current during the short-circuit can reach more substantial values. If the value of short-circuit current exceeds the rupturing capacity of the over-current circuit breakers installed at the customers end, they might become incapable of clearing faults at the customers premises. In distribution networks, protection against short-circuit faults on the lines is provided by means of over current relays and/or fuses coordinated with the protection devices of the distribution feeders. A concern exists that under high penetration of PV DG and certain conditions (e.g.if it occurs at the end of a long distribution line with a high resistance), the PV systems may be unable to detect a fault and supply a significant fraction of the fault current, causing miscoordination of the overcurrent protection of the distribution system (fuse-breaker), excessive fault currents, nuisance fuse operation and hamper fault detection. For example, normally it will take five to six cycles for the upstream breaker using an instantaneous trip setting to clear a fault, hence a fuse needs to be sized so that its minimum melt time is longer than the total breaker fault clearing time (must be at least six cycles plus some margin time). If the fault current increases due to DG contribution to the fault current, its minimal melt time may be significantly shorter than six cycles and it will no longer coordinate with the circuit breaker. The coordination of the fuse and the time overcurrent relay at different fault current levels is therefore critical to the power system protection. Not withstanding the previous comments, it should be also considered that in some countries, the LV fault levels are such that even at high penetration levels, the potential current contribution of PV DG may be much less than that from the distribution system. For example, with a fault current from a 500 kVA substation in the range 5000-15000 A, and a contribution from say 500 kW PV Distributed Generation at around 1000 A, operation of a typical fuse protection would not be significantly affected.	*1* *2* *3*
THEORETICAL EVIDENCES: A theoretical analysis has been carried out in the U.S. to determine the mutual impact of Distribution Generators and power systems performance, the primary focus being inverter-based devices.	*2*

Regarding the impact of DG on fault currents, fault current contributions of current controlled inverters under different conditions were studied by means of simulations. A feeder typically encountered in U.S. distribution systems (MV at 13.2 kV; source impedance: X1=0.5, X1/R1=30, X0/X1=1, R0/R1=1) was considered, with a total DG capacity of 5 MVA connected by means of a MV/LV transformer (13.2/0.48 kV). The focus of the study was on the fuse saving strategy used by many utilities. Main results were the following: - Under three-phase fault occurring at the remote end of the feeder and lasting for 0.2 s, although the voltage drop was not large/long enough to trip the DG inverters under-voltage protection, the DG fault current contribution was only a very small fraction of the total fault current (with inverters supplying constant current with a short transient when the fault occured and cleared). This situation was considered therefore not likely to affect fuse-breaker coordination. However, further simulations revealed larger DG fault current contributions with higher DG penetration and under weaker line conditions than those considered. - Under single-phase fault occurring at the remote end of the feeder and lasting for 0.2 s, similar values of DG current contribution to the fault were obtained as in the three-phase fault case (slightly higher, due to the delta-wye transformers of the inverters providing a path for zero-sequence currents). This further confirms that current controlled DG had little impact on fault contribution and fuse-saving strategy. - For a three-phase to ground fault at the feeder, the closeness caused the DG inverters undervoltage protection trip, leading to a fast disconnection. Again, the fault current contribution was found to be predominantly from the grid; the DG's current contribution, which was already small, was further reduced when the DG trips were off-line. It was also noted that disconnecting the DGs too fast could reduce the benefits to the power system provided by the DG during faults, as described another chapter of the study. - As a comparison, fault currents from induction machine loads (aggregated capacity, 5 MW) at the same power level were also simulated. Results turned to be much larger compared with the inverters case. The authors conclude that there is ample precedent for considering modern current-controlled inverter-based DG as insignificant short circuit current contributors, so that they do not contribute to system fault current beyond the pre-fault operating current level. However, the fault impact of DGs should to be reevaluated in case the DG controls were changed to accomplish other functions such as voltage support.	
In another U.K. study it was also concluded that inverter-connected DG makes no significant contribution to network fault levels.	*4*
EXPERIMENTAL EVIDENCES: Within the framework of the International Energy Agency – Photovoltaic Power Systems Programme (IEA-PVPS Task V), different investigations were done in	*1*

Japan on the effects of short-circuits at distribution level on PV inverters. To that aim, on the one hand four commercial inverters were tested in the laboratory under short-circuit conditions coming from the utility, both individually and in pairs. Results showed that the inverters supplied a fault current of only about twice that before the short circuit at most (values below their over-current protection), and that the time to remove the fault was about 1 to 2 cycles. It was concluded that as long as current controlled inverter were considered, short circuit current from PV inverters was negligible.	
Experimental tests were carried out in a 200 kWp Test field for Photovoltaic systems in Japan. Under certain fault conditions where short-circuits were generated through high resistances, the voltage drop on the distribution line was minimal, and each system continued operation without detecting the fault by itself. This indicated that there were cases where the fault current passing through substations was reduced and the substation over-current relay defaulted.	*5*
NEEDS FOR STANDARDIZATION: In order to prepare the market for a higher penetration of DG, specific standards for inverters should be developed covering, amongst others, limits for short-circuit current contribution. **TIME FRAME:** Short / Medium	
NEEDS FOR RESEARCH AND DEVELOPMENT: Effective means of limiting short-circuit current contribution by voltage-control type inverters. **TIME FRAME:** Short / Medium	

References – Contribution to short-circuit capacity

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[3] IEA PVPS Task V, report IEA-PVPS T5-01: 1998, “Utility aspects of grid connected photovoltaic power systems”.

[4] Halcrow Group, Department of Trade and Industry, “Micro-generation network connection (renewables)” (K/EL/00281/00/00), 2003. <http://www.dti.gov.uk/ publications>

[5] H. Kobayashi et al., “Problems and Countermeasures on Safety of Utility Grid with a Number of Small Scale PV Systems”, 21st IEEE PVSEC (1990), pp.850-855.

1.7 Power value, capacity value	References
DESCRIPTION:	
The Power Value of an electricity generation plant is defined as the economic value of the power produced, given the plant location and its trend of production. This is because the power value is affected by the distance between the power station and the load and by the match/mismatch conditions of the production with the trends of the loads in LV branches. The power value varies therefore instant by instant depending on the present level of power production and surrounding load conditions.	*1*
The power value of PV generation in the grid takes into account the reduction of energy production costs (savings in fuel consumption, operation and management, etc.), the transportation costs and, in some cases, the risk reduction as regards the possible situations of scarcity in given periods (peak hours). The following distributed benefits of PV generation add therefore to its power value:	
- In instantaneous terms: reduction of Joule losses in the distribution system; improvement in quality of service in peak hours (voltage stability); improvement in continuity of service in peak hours (less probability for a LV system to exceed the power limit of a MV/LV substation, e.g. to avoid the switch-off of the over-current protection device); reduction of environmental impacts (pollution and greenhouse effects, risks, etc.).	
- On a long-term period: deferral and/or reduction of investment to upgrade the power distribution network (especially the LV distribution grid); reduction of additional generation capacity.	
Another definition of interest is the “Effective load-carrying capacity” (ELCC), a direct probabilistic measure based on the concept of loss of load probability. It is the ability of a power generator to effectively contribute to a utility's capacity, or system output, to meet its load. Therefore, ELCC for a PV system represents the system ability to provide power to the utility when it is needed. It is the capacity credit of the PV power plant.	*2*
System operators still view effective capacity as a probabilistic measure and usually hesitate to rely on PV as a firm peaking capacity component. A critical test in support of PV capacity claims, and its potential to offer reliability benefits, is to look at PV availability during instances of major grid stress and supply shortfall events caused by high, localized demand and inability for the grid operators to deliver local power through burdened power lines and substations. Particularly important in this sense are the summer-peak, heat wave-driven events often characterized by rolling blackouts resulting from an inability to match supply and demand either locally or regionally. These outages represent the highest possible stress on the grid when electrical demand approaches available generating supply at a time when all supply sources are on line, but are either unable to supply regional demand or make power available locally through overburdened transmission and distribution systems. These situations are often exacerbated by the fact that most power plant efficiencies drop with	

high temperature and extreme conditions increases the wear and tear, hence the probability of failure of plants and transmission and distribution systems components.	
Finally, the capacity value of PV generation can be greatly improved when it is complemented by the following measures:	
- Availability of backup energy to make up for any deficit of PV to meet all loads above a given threshold, quantified as “minimum buffer energy storage” (MBES).	
- Demand Side Management: mitigation of air conditioning use by means of Solar Load Controllers (SLC). These devices are "PV-smart thermostats" that logically modify user-set temperatures as a function of load and insolation conditions. SLC devices could be designed first to maximize user-sited demand reduction; in that case the SLC would control a local [building] load and react to the output of a local PV installation. In the future, pending proper financial arrangements with independent system operators, SLCs could be deployed to control local building loads in response to a wider effective capacity context (e.g., a substation or a regional load and a dispersed set of PV). Evidence has been found that load control through end-use setting adjustments can enhance the natural correlation between a commercial building’s load and the output of a customer-sited PV system, to the point of achieving the equivalent of firm peaking PV capacity.The load control is furthermore accomplished with a very small end-user impact.	*3*
Current scheduling of Distributed Generation for distribution networks is still limited. In the U.K., for example, some Distribution Networks Operators actively schedule while others do none. The literature on the subject is mainly about accommodating volatile wind output and optimising island systems, for both cost of supply and network stability. It is expected that with the New Electricity Trading Arrangements prices of unpredictable Distributed Generation will decrease, which could create a dynamic market for power services from DG.	*4*
THEORETICAL EVIDENCES: Several theoretical studies have been undertaken in the U.S. to identify PV availability during major outage, or near outage, events since the 1990’s. Some of the most relevant results are summarized here. * PV EFFECTIVE CAPACITY	
An extensive study was done on the analysis of over 200 load-years (late 80s’ and early 90’s) from 45 utilities and substations all over the U.S. For a level of 2% PV grid penetration (2 axis tracking PV systems), three regions of high PV capacity were identified, the best of which (the Mid-Atlantic region, showing the best match between generation and load demand) had ELCC peaks at 70% (60-65% if south-oriented fixed PV arrays are considered).	*5*
Analysis of more recent load data (1997-99) from the New York City metropolitan and Long Island areas provided similar results. PV penetration levels between 1 and 15% were simulated on hourly basis using high-resolution	

satellite cloud cover data. ELCC ranges for PV generation were 40-70% for tracking systems, and 40-60% for fixed arrays. Furthermore in the last case, the “minimum buffer energy storage” parameter was found to be only a fraction of an hour’s worth of PV output. This means that, should that backup be available (for example, with storage systems charged by PV generators), PV would deliver 100% effective capacity. For instance, at 5% PV penetration in New York City it would take 0.7 system-hours worth of storage for fixed PV systems to guarantee that all loads above 95% of the peak were met. It would take six times this amount of stored or backup energy to meet the same loads in the absence of PV. Concerning the use of Demand Side Management (Solar Load Controllers mitigation of air-conditioning requirements to cover critical deficits) combined with PV generation, calculations were done for New York City and 10% of PV penetration (i.e., ~ 1000 MW installed PV capacity). Results showed that it would have taken only 4.5 degree-hours of user discomfort on the worse day, with a maximum one-hour offset of 1.5 ºC, to have met all loads above 90% of the City’s peak with non-tracking PV systems. Without PV the figures would have been respectively 19 degree-hours and 4 ºC, respectively (still remarkably small given the achieved peak load reduction but representing a considerably stronger end-use discomfort). For the entire season, the total degree-hour end-use offset would have only been 8 degree-hours to guarantee a 100% PV capacity at 10% penetration; without PV the seasonal impact would have been 65 degree-hours.	
* POWER OUTAGES There were several major summer outages or near outage events in the eastern part of the U.S. during the summer 1999. In 2000, major heat waves spared the eastern US but affected the western US and led to power shortage conditions, resulting in rolling blackouts and/or major price spikes passed onto consumers. Analysis of the availability of PV output during such events shows that in all cases, PV output on the day of the outage would have been within 80% of its maximum (crystalline PV technology assumed) given ideally clear sky conditions and similar temperatures. In all but one case, PV output would have been within 90% of ideal. When analysing in detail the date July 6 1999 in New York City (peak day that was characterized by the failure of overstressed distribution systems in Manhattan), the City’s load reached 10473 MW that day. PV output in Manhattan would have been on that day within 90% of ideal (given the extreme temperature conditions, 38ºC ambient). With 5% installed PV capacity (i.e., 523 MW) all 5% top loads would have been met, either by PV+storage or by PV+solar-load-control. Both the amount of backup energy and end-user temperature impact appear small in light of the fact that the City’s peak would have been shaved down to 9950 MW by a clean, dispersed, and localized resource.	*6*
Studies done within the DISPOWER project have demonstrated the advantages of combining modern Distributed Intelligent Load Controllers and DG-technologies in terms of increase energy availability of power systems. Such controllers are also identified as having the potential to contribute significantly to	*7*

the integration and control of high levels of DG in the networks.	
EXPERIMENTAL EVIDENCES: A prototype of Solar Load Controller (SLC) for mitigation of air-conditioning requirements to cover critical deficits has been developed in the U.S. and tested experimentally in a real building with a 13 kW building-integrated PV generator and a Energy Management System with a 700 kW peaking facility HVAC installation. - Based on experiments done in half of the building, the total impact of the SLC (with PV and load input signals used being actual values) on the reduction of HVAC load was estimated to be 4% of peak capacity per ºC offset modified by the SLC device. When analyzing a full month billing cycle (July 1999, with 3 heat waves), a total SLC action of 2.4 ºC-hours would have been sufficient to make up for all the critical deficit of the PV generator. This level of end-use impact was found too small to be noticed by the occupants of the building. - The SLC was also tested to control a small Air Conditioning unit of 1500 W cooling a west-southwest room. With the local load signal driving the SLC being directly proportional to the monitored outdoor temperature and the real time PV output simulated from a south-west PV array set at 10% of peak load, peak load reductions of 5% (80 W) were obtained per ºC of maximum SLC action. For the entire month (with 3 heat waves), a maximum SLC offset of 4.5ºC guaranteed a peak load reduction of 21% (320 W). To illustrate the potential of the SLC developed, the case of the New York City load was analysed, where each ºC of cooling requirement adds 350 MW to the load. An end-use load control based on a maximum SLC action of 3ºC could “buy” firm capacity for 1,000 MW of PV with minimal end-use discomfort. As reported by the authors, many existing low-to-medium range HVAC controllers could incorporate the SLC action at little extra cost.	*3*
An experimental investigation done in the U.K. with PV-DG installed in residential houses all over the country (8 systems, power sizes below 5 kW, technologies representative of the market) revealed average solar fractions –PV contributions to the building annual loads– of 28%. All the systems used over 50% of the PV system output directly; the average percentage of the load met directly from the PV systems was generally in the 10-30% range.	*8*
The commercial market of PV grid-connected inverters offers nowadays a wide range of concepts, designs and functionalities. An in-depth study done within the DISPOWER project identifies as trends in future developments of PV-DG those providing additional benefits to the grid, such as uninterruptible power supply, backup power and grid improvement features. Concerning consumers responses to Demand Side Management possibilities, a pilot project carried out in Germany has shown the potential that users provide flexibility in the consumption behaviour, and therefore permit innovative concepts. The use of certain appliances (washing machines) was experimentally	*7*

coupled with periods of solar availability by users with domestic PV systems, thus demonstrating the possibility of automatic local power management, thanks to modern Information and Communication Technologies.	
NEEDS FOR STANDARDIZATION: For PV systems to contribute with effective capacity to distribution networks, standards should be developed which establish the associated minimum technical requirements and constraints. **TIME FRAME:** Medium / Long	
NEEDS FOR RESEARCH AND DEVELOPMENT: Further research and development is needed on the capacity of PV systems to contribute to the grid capacity through added-value benefits (uninterruptible power supply, backup power, grid improvement). Although commercial technologies exist that provide complementary storage for PV grid-connected systems, there are still few experimental evidences of their power and capacity values with a minimum (cost-effective) storage capacity. On the other hand, Demand Side Management functionalities such as those provided by Distributed Intelligent Load Controllers and DG technologies (for example, PV in urban areas) remain also an interesting field of R&D. Examples are the development of relatively simple (affordable) controllers with plug-and-play capabilities, and their integration into central network operation strategies. **TIME FRAME:** Short / Medium / Long	

References - Power value, capacity value

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[6] R. Perez *et. al.* , “Availability of dispersed Photovoltaic resource during the August 14th 2003 northeast power outage”, Proceedings of the American Solar Energy Society Conference, 2004.

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7 DISPOWER project (Contract No. ENK5-CT-2001-00522), “Further R&D needs in DG Technology based on the DISPOWER project and statements of international organisations”, 2005. <http://www.dispower.org>

8 University of Northumbria, Photovoltaics Applications Centre, Department of Trade and Industry, “Monitoring of domestic installations” (ETSU S/P2/00319/REP), 2003. <http://www.dti.gov.uk/publications>

1.8 Islanding

References

DESCRIPTION:

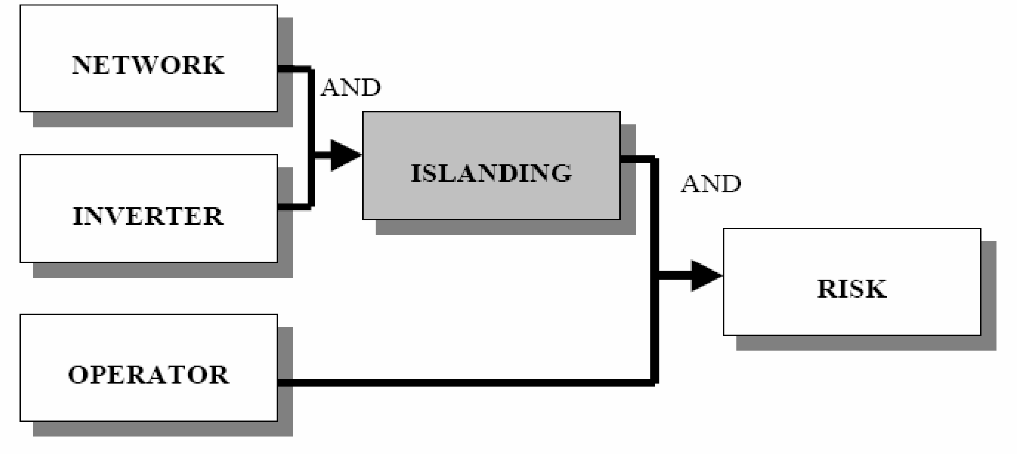
Islanding phenomena can be defined as “any situation where a section of electricity Network containing generation becomes physically disconnected from the DNOs distribution network or user’s distribution network, and one or more generators maintains a supply of electrical energy to that isolated network.” 1

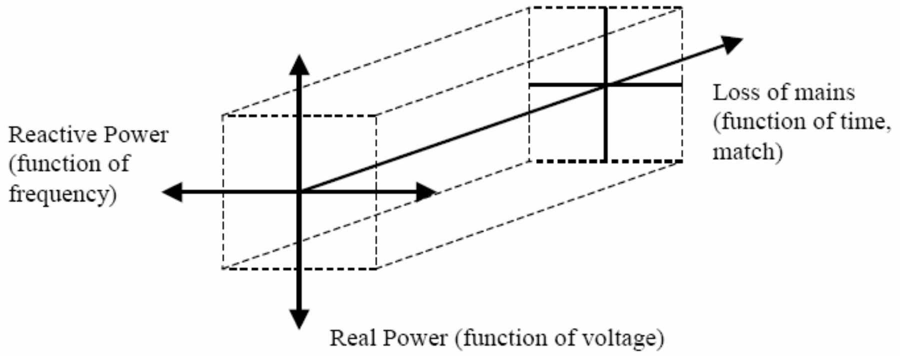
There are two different types of islanding:

- An “operational” island or self-supporting power system capable of reliably delivering power from supplier to consumer within acceptable limits of voltage and frequency. These types of islands form part of the normal operation of the networks. 2
- An “unintentional” island where the generation should have ceased on disconnection from the network. In many countries unintentional islanding is limited in connection guidelines to a certain “disconnection time” after which the generation is required to automatically cease. This is for reasons of safety, mainly to protect electricity personnel maintaining the network, and of protecting equipment from damage.

The key criterion for an islanded AC power system to remain stable is that both active and reactive power must be balanced in terms of load-generation. Any imbalance will immediately result in changes of voltage and/or frequency in the islanded zone, depending on the characteristics of the load, generator control strategy and active protection schemes present at the generator site. Usually, as a consequence of imbalances in terms of active and reactive power, frequency and voltage in the islanded section of the network will move to values outside the permissible windows. Accordingly such a situation can easily be detected by simple monitoring of voltage and frequency. However, if load and generation in the islanded section are closely matched, it is possible that both, voltage and frequency do not exceed the margins of the protection. In such a case, the island would remain stable until fluctuations, either of generation or load drive voltage or frequency outside the above mentioned margins. This range of operating conditions, which would lead to stable islanding are commonly referred to as the “Non-detection Zone” (NDZ).

The possible occurrence of unintentional islanding in distribution networks with distributed resources has been one of the major issues in connection with the ongoing growth of DG in Europe. Furthermore, it is anticipated that the rapid deployment of DG in recent years has substantially increased the likelihood and concerns associated with this phenomenon –especially among network operators. However, there is still widespread discrepancy not only concerning interconnection practices and protection systems required in the various national grid codes or standards, but also regarding the probability of occurrence and persistence of distributed resource islands. It also has been recognised that today existing standards often do not deliver consistent policy among network operators, or consensus with their customers, developers and operators of DG.

In general, a balanced condition of only a few seconds is not categorised as a sustainable power balance. In fact, within the experts from utilities participating in the IEA-PVPS task V working group, unintentional islanding was considered “when a disconnected part of the power network is sustainably powered by the connected PV-systems or other embedded generators for a period of 5 or more seconds”. This disconnection is normally carried out in PV systems by a protection function built in to PV inverters and “type tested” to local countries requirements. Normally this protection is limited to defining voltage and frequency windows, with additional techniques such as Rate of Change of Frequency added. Some countries also use methods that test for network presence by measuring the response to disturbances introduced by the inverter (e.g. some impedance measuring techniques). The “type test” is designed to represent a “worst case” situation of balanced conditions on disconnection, and a resonant load. At present these differ between countries, but agreement is being sought through the Technical Standards committees to harmonise the requirements. IEC 62116 Draft and CENELEC prEN 50438 Final Draft are standards being worked on at the moment to address this topic (see below).	*3* 2,4,5 6
ISLANDING ANALYSIS Islanding to date has been analysed using the ‘fault tree’ methodology of Risk Standard (IEC 61508). This can be summarised in the following formula, and the corresponding fault tree: Risk(islanding) = (P(match) * P(LOM)) * P(protection failure)  Where: - Network issues = (P(match) * P(LOM)), the load/generation match simultaneous with a loss of mains supply (“power cut”) - Inverter issues = P(protection failure), where the inverter protection fails to detect loss of mains (the Safety Integrity Level ‘SIL’ is relevant here) - Operator issues = operator touches conductor & consequences. As it can be inferred from the figure, for an island to occur there has to be a	7,8,2

match between load and generation at the same time as a loss of mains supply occurs. Furthermore, the inverter protection must fail to detect the loss of mains condition. Finally, for an operator to be at risk, he must touch the energised live conductor.	
Probability of conditions for Islanding (Network issues):	
P(match) – This is the key to the studies and has been investigated in two reports to date. The results depend on what assumptions are made about the island and what parameters are applied, e.g.: • How close a match between load & generation is needed to produce an island? • How long does islanding have to occur to be a problem? • What is the boundary for a power island?	*2,3*
P(LOM) - The probability of the loss of mains supply can be estimated reasonably accurately from existing operational data on a network (i.e. “power cut” statistics).	
Inverter Islanding protection:	
P(protection failure) - The third component in the risk analysis is the failure of the protection to detect an island: This is a function of several factors: • The islanding detection method (e.g. non-detection zone), • The inverter designed safety integrity level (SIL), as well as • The quality of the installation.	*7,2*
The “non-detection zone” (NDZ), as shown below, can be used as a way to visualise the normal operating “envelope” for the inverter. The NDZ boundaries reflect the match of both real and reactive power (function of voltage/phase/frequency) sustained for a long enough period to qualify as an “island”.	
	
The “size” of the NDZ can be varied depending on the “passive”’ and “active” protection methods used by the inverter. It can be tailored to reduce the risk of islanding occurring to an appropriate level as below, but should not be so small as to cause nuisance tripping. The values taken for these parameters currently differ in different countries.	*4* *9*
Risk to operator:	
To assess the risk to an operator, on top of the risk of islanding, the probability	

that an operator touches a conductor has to be evaluated along with the seriousness of the consequences if this occurs.

THEORETICAL EVIDENCES:

A theoretical study based on the above method was carried out under IEA Task 7
V in 2002, based on realistic data of P(LOM) in European networks, and
P(match) extrapolated from measured dynamic voltages and currents in a small 3
residential network area of The Netherlands. It was found that the probability of "balanced" conditions for islanding occurring was very low when considering the current situation.

The main conclusions of the study were:

- The "benchmark" risk that already exists for network operators and customers is of the order of 10^{-6} per year for an individual person.
- The risk of electric shock associated with islanding of PV systems under worst-case PV penetration scenarios to both network operators and customers is typically $<10^{-9}$ per year. [Note: worst-case scenario was considered when the PV rating reached approximately six times the minimum (night-time) load or 2/3 of the After-Diversity-Maximum-Demand].
- Thus, the additional risk presented by islanding does not materially increase the risk that already exists as long as the risk is managed properly.
- Loss of mains (LOM) protection functionality provides additional safety, up to a point:
  - An inverter's designed safety integrity level (SIL) affects the level of risk. [Note: Safety Integrity Levels between 2 and 3 are considered reasonable, defined for "low demand operation"; the probability of failure to perform the LOM protection on demand was considered as 10^{-3} (equivalent to 10 consecutive successful operations when asked to perform on demand)].
  - In this sense, since LOM functionality is included in many PV inverters already, it is appropriate to maintain this requirement but emphasis should be put on simple, robust, verifiable and cost-effective solutions (e.g: software-based).
  - The quality of the installation and any subsequent maintenance will also affect the risk.
- There is a need to inform and educate both network operators and customers about the implications of the use of PV as an embedded micro-generator, as PV systems become more widespread.

As a general conclusion, it was stated that as long as an appropriate anti-islanding scheme was included in the inverter, the additional risk presented by islanding did not materially increase the "benchmark" risk that already exists for

operators maintaining the network.	
EXPERIMENTAL EVIDENCES: An experimental study carried out in the Netherlands in 2002 collected data from ~250 houses and 1 small reference PV-generator over a period of 2 years (active and reactive power measurements taken every 1 second). Electricity supply to the houses was obtained from a typical MV/LV transformer feeding 7 lines, with the number of houses connected to each LV line varying between 2 and 80. Theoretical analysis of islanding probabilities for different PV penetration levels were carried out. The main conclusions of the study were: - The maximum PV-power in a power network for which balanced conditions never occur is approximately two to three times the minimum night load of the relevant power network. - Balanced conditions and subsequently probability of islanding cannot occur if PV systems are installed on every house with a power rating of about 400 Wp or less. Given the number of houses, this limit is equivalent to a distributed PV-system of 100 kWp, considered a significantly high value for a residential area. - The penetration level of PV-systems does not significantly influence how often and for how long balanced conditions between the load and the PV-systems occurs. - The size of the margins for active and reactive power had a decisive influence on the probability of balanced conditions in the order of up to 3 orders of magnitude. The studied margins for active and reactive power ranged from 2% to 15%; however, it was assumed that margins for the possible mismatch of 5% for active and 2% for reactive power are realistic. - Balanced conditions between active and reactive load and the power generated by the PV-systems do occur very rarely for low, medium and even high penetration levels of PV-systems. - The probability of a balanced condition does not depend on the number of houses connected to a feeder. - The probability of occurrence of a balanced condition in a low voltage power network is well below 10^{-6} to 10^{-5}. - The probability of encountering an island is virtually zero. Furthermore, the maximum duration of a balance was less than 60 s. - Islanding is therefore not a technical barrier for the large-scale deployment of PV system in residential areas.	3
A thorough, network-based, system approach to islanding protection of DG connected to distribution networks has been carried out within the DISPOWER project. The approach included theoretical analyses of the behaviour of the	2

power system during islanding, an assessment of the probability and risk of islanding in distribution networks as well as a detailed investigation of the performance of currently used schemes. With respect to protection, available principles and detection methods as well future solutions are presented and guidelines for designing appropriate protection schemes are given together with recommendations for future DG standards and interconnection guidelines.

Within this project, a experimental study was done in an Austria urban community with a large Distributed PV generator (100 kWp, installed as a noise barrier along a highway), representative for suburbs in central Europe, with single-family residential homes as dominant loads, some public buildings and a few multi-dwelling houses. The PV electricity was fed into the local LV grid through 55 string inverters (single-phase type) designed to operate at unity power factor, in order to achieve the optimal performance with reduced impact on voltage increase in the network. Data were collected from the LV lines (loads and PV system) every second during 8 months (covering the summer, autumn and winter seasons).

Main conclusions were the following:

- DG penetration level: The ratio between the actual load and the generation has a fundamental influence with the maximum probability for balanced conditions occurring at penetration levels between 1 and 2. At levels below 0.5 the probability tends to approach zero.
- Reactive power supply:
    - With a DG operating at unity (as it was the case with the PV inverters) or lagging power factor and no other reactive power supply present, balanced conditions never occur.
    - Operating a theoretical DG at a power factor in the range of that of the network load increases the probability of balanced conditions by 3 to 4 orders of magnitude.
- Protection settings: The frequency window defines the width of the NDZ in terms of reactive power and thus has a decisive influence on frequency and persistence of the balanced conditions.
- With a worst-case – but realistic – set of parameters, under the current scenario with PV generation, a probability in the range of 10-5 to 10-3 could be expected.
- The maximum persistence for a single phase balance was less than 1 minute. For 2 or 3 phases, no simultaneous quasi-stable (≥ 5 s) conditions were observed.

2

Also within the DISPOWER project, experimental tests were done in state-of-the art inverters designed for the German market (10 single-phase units with different design concepts, low-frequency transformer, high-frequency transformer and transformerless), mostly equipped with a grid impedance measurement facility (ENS/MSD) as a third criterion for the detection of islanding (besides grid voltage and frequency monitoring). The tests revealed the following results:

- All inverters worked well under normal conditions for the grid impedance. However, at higher grid impedances, frequent inadvertent tripping was observed, even when there was no change in grid impedance. It could be shown, that under these conditions, the measurement accuracy and stability was considerably reduced.

- Additional tests of the inverters with a balanced resonance circuit (simulating a certain, rather high step of the impedance) showed that some devices had considerable difficulties in detecting the islanded situation.

- The test clearly indicated that while the protection systems worked well under normal grid conditions with rather low impedance, less ideal conditions lead to problems for the devices. This issue is currently not satisfactorily addressed in the according standards which define the requirements for protection systems.

From the conclusions and results of the DISPOWER study, a set of recommendations was derived which should be considered in order to ensure a high level of safety for customers as well as maintenance personnel. These recommendations relate to future scenarios with a level of DG in the same order of magnitude or exceeding the average loading of the network, and with DG enabled to provide reactive power. Under these circumstances it is recommended that:

- In addition to standard voltage and frequency monitoring, further Loss-Of-Mains (LOM) detection should be part of the interface protection of DG. The LOM detection methods should be appropriate to work properly even in situations where load and generation are closely matched and should not have a NDZ under realistic conditions. Furthermore, it is important that the schemes also work in case of multiple generators connected to the network and in weak grid sections.

- Protective function at the generator should be implemented based on a certain safety integrity level in order to guarantee their “function-on-demand” during the whole technical life time of the system and reduce the risk of malfunctions. Interconnection standards should encourage this by omitting the requirements for external accessible disconnection switches or repeated inspections if the grid interface has a minimum SIL of 3 or higher. Furthermore:
    - For small-scale DG standardised, integrated protection systems help to keep the system and interconnection costs on a reasonable level. These protections should be type tested based on realistic situations in the network, such as matched load conditions (e.g. with a tuned RLC circuit). Additionally, in order to prevent inadvertent, spurious tripping and avoid negative impacts of protection devices on the quality of supply, clear requirements and limits for immunity as well as emission levels to be fulfilled by the methods need to be included into the qualification procedures and interconnection standards. When applying destabilising protection

schemes, the potential impact on system stability during network disturbances should be taken into account.

  - For larger DG units, protection shall be designed on basis of a rigorous assessment of discrimination and risk. Since islanded operation does not necessarily carry high short term risk, delayed protection allows a better discrimination of the system and thus increases system security. Potential to derive appropriate solutions was identified in the areas of frequency/speed governing systems which assist the detection of islands, source impedance as a means of islanding protection, earth impedance as criterion where the undesirable island is associated with the loss of earth reference and the influence of voltage phase shift on the measurement of rate of change of frequency and filtering methods that allow good discrimination.

- The recommended practises for performing maintenance on the network should take into account the reverse power flow that may be caused by the presence of DG and the potential risks associated with the fact that conductors may still be live after opening of a circuit breaker.

- At key locations in the network, the presence of distributed generators should be indicated by appropriate warning signs.

Taking into account these safety recommendations, the risks associated with unintentional islanding –even under a future scenario with a high penetration level and network support by DG– can be kept at a level, which does not substantially increase the already existing risk. Accordingly unintentional islanding and its risks should not be seen as a barrier or limiting factor for the further development of Distributed Generation.

NEEDS FOR STANDARDIZATION:

In all standardization efforts regarding grid connection of distributed generation the issue of unintended islanding must be taken seriously as the probability of spontaneous islanding events in future grids with very strong penetration of DG might be higher than anticipated before.

Two standards are currently nearing the end of their development to help in this area:

- IEC 62116 CDV2007: Test procedure of islanding prevention measures for utility-interconnected photovoltaic inverters (Committee Draft for Vote).

  This standard, if adopted, specifies the test circuit and test requirements for anti-islanding measures in PV inverters. It attempts to harmonise the different test circuits adopted by individual countries to date. The ‘pass’ parameters will be included in the European EN standard below, which is currently also at final draft stage. It is a ‘functional’ test and helps specify what the anti-islanding measures have to achieve, rather than being prescriptive on exactly which techniques must be used.

- prEN 50438 FinalDraft2007: ‘Requirements for the connection of micro-generators in parallel with public low-voltage distribution networks' (CENELEC Final Draft)

This European EN standard, which is currently at final draft stage, includes the 'pass' figures for the anti-islanding inverter tests specified above. It includes a generic section and then annexes for individual countries where national regulations have to be met to suit the local electricity network implemented.

TIME FRAME: Short

NEEDS FOR RESEARCH AND DEVELOPMENT:

Further research has to be done to evaluate different methods for islanding detection used in European countries regarding safety of detection, grid disturbances, cost and usability at very strong penetration.

TIME FRAME:

Short term - R&D support to standardisation committees IEC 62116 & CENECEC prEN 50438

Medium term - monitoring of 'islanding' conditions logged on real networks

Long term – review of methods as networks become more 'actively' managed, and as maintenance practices change, to check that they are still appropriate.

References - Islanding

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1 UK Engineering Recommendation G83/1September 2003; "Recommendations for the connection of Small-Scale Embedded Generators (up To 16 Amps per Phase) in Parallel with Public low-Voltage Distribution Networks".

2 DISPOWER project (Contract No. ENK5-CT-2001-00522), "State-of-the-Art Solutions and New Concepts for Islanding Protection", 2006. <http://www.dispower.org>

3 IEA PVPS Task V, report IEA-PVPVS T5-07: 2002: "Probability of islanding in utility networks due to grid connected photovoltaic systems".

4 IEA PVPS Task V, report IEA-PVPS T5-09: 2002, "Evaluation of Islanding Detection Methods for Photovoltaic Utility-interactive Power Systems".

5 Woyte A., De Brabandere K., Van Dommelen D.I, Belmans R., Nijs J., "International Harmonization of Grid Connection Guidelines: Adequate Requirements for the Prevention of Unintentional Islanding", Progress in Photovoltaics: Research and Applications 11 (2003), pp. 407-424.

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9 prEN 50438: “Requirements for the connection of micro-generators in parallel with public low-voltage distribution networks”’ (CENELEC Final Draft), 2007.

2 IMPACTS OF DISTRIBUTION NETWORKS ON PV-DISTRIBUTED GENERATION

2.1 Voltage dips	***References***
DESCRIPTION:	
IEC definition (IEC 60050): "A sudden reduction of the voltage at a point in an electrical system followed by a voltage recovery after a short period of time from a few cycles to a few seconds."	*1*
European definition (EN 50160): "A sudden reduction of the supply voltage to a value between 90% and 1% of the declared voltage Uc, followed by a voltage recovery after a short period of time. Conventionally the duration of a voltage dip is between 10 ms and 1 minute. The depth of a voltage dip is defined as the difference between the minimum RMS voltage during the voltage dip and the declared voltage. Voltage changes which do not reduce the supply voltage to less than 90% of the declared voltage Uc are not considered to be dips."	*2*
IEEE definition (IEEE P1433): "A decrease to between 0,1 and 0,9 pu in RMS voltage or current at the power frequency for durations of 0,5 cycle to 1 min. Typical values are 0,1 to 0,9 p.u."	*3*
Basic causes of voltage dips are sudden and large increases of current flow through the system impedances which result in large voltage drops. This sudden change can have mainly two origins: short circuits and switching of large loads (e.g. induction motor starting), the first one causing more severe events.	*4*
Voltage dips and short interruptions are widely considered to be the most serious power quality disturbances due to their effect on sensitive processes (equipment failure). They are to be accepted as an intrinsic feature of public electricity supply systems.	*5*
Generally, voltage dips are characterized by their magnitude (expressed in percent of the voltage, for example) and duration (in cycles or milliseconds).The majority of voltage dips have a magnitude of about 80 % and duration of 4 to 10 cycles. However, voltage dips are rather complex phenomena: the point on wave of dip initiation/voltage recovery and the phase angle jump are also influencing parameters.	*6*
Sensitivity of general electric equipment to voltage dips is defined by the "voltage tolerance characteristic", which defines the domain (magnitude-duration range) in which the equipment can operate.	
For Distributed Generators (DG), in addition to the possible internal effects that voltage dips might have (e.g. over-current, unbalance), voltage dips may also cause network disturbances through their effect on DG (external effects). A special concern in this sense is the loss of generation resulting from the disconnection of a significant amount of DG after a voltage dip, particularly in scenarios with large DG penetration. For example, at transmission levels, large wind parks might adversely affect the stability of the network in case of sudden	*7*

disconnection due to a network disturbance. At distribution levels DG installations are much smaller but widespread; therefore, a disturbance at the transmission level might propagate over a wide part of the territory and result in a loss of a substantial fraction of DG production. This leads to the idea that as the penetration of distributed generation increases, the philosophy of disconnecting “at first sign of trouble” is not acceptable anymore. These concerns have recently resulted in “ride-through” requirements for Renewable DG generators connected to the transmission network in some countries (e.g. Germany and Spain, for wind turbines).	*8*
THEORETICAL EVIDENCES: Simulations have been done within the DISPOWER project in a weak network scenario (Kythnos island, Greece), where the grid behaviour when several renewable resources, such as PV and wind, were integrated at various points. Annual average of load served from the network was about 600 kW, with strong seasonal fluctuations. Network configuration was radial and includes, besides renewable Distribution Generators, five diesel generators (total, 4 MW) and a battery plant. Frequency and voltage control were also performed (in the diesel-off mode) by using a dump load and a phase shifter equipment, respectively. One of the scenarios considered involved the installation of 10 PV systems, distributed across the island grid. The maximum power that can be injected from each photovoltaic system is 130 kWp (total, 1.3 MWp). A load-flow analysis was conducted for different levels of power injected from the PV systems. Simulations on steady-state issues gave the following results: - For a lightly loaded grid, the observed voltage rise was well within the limits prescribed by the EN-50160 standard (±10%); - Considering the heavy load condition for the grid, it was observed that the voltage was below the nominal value (the high load currents resulting in large voltage drops). Incremental increases in power injected from the PV systems resulted in an improvement of the voltage profile, and the size of the voltage drops was reduced. Stability of the network was analyzed, by investigating the effects of a considerable penetration of PV systems on the grid transient behaviour. In particular, the disconnection of distributed PV units due to under-voltage protection trip during a three-phase fault was simulated for different penetration scenarios (up to 33%). Results showed that the network exhibited stable behavior provided that sufficient spinning reserve existed. However, due to the high cost of the energy produced by the diesel generators it was found highly desirable to achieve a reduction of this reserve without sacrificing the safety of the power system operation. A solution to the previous problem was proposed, by means of using PV power electronic inverters with disturbance ride-through capability. Disturbance ride-through capability means, among other things, that the grid interface should stay connected during the disturbance or it should be reconnected quickly after the disturbance. This option was also simulated and the results indicated that, in this way, it should be possible to operate the power system with a lower spinning	*9* *10, 11*

reserve without any safety risk.	
EXPERIMENTAL EVIDENCES: * SENSITIVITY OF PV INVERTERS Experimental tests carried out within the DISPOWER project on state-of-the art inverters (representative of the European domestic market: 12 single-phase units with different design concepts, low-frequency transformer, high-frequency transformer and transformerless) revealed the following results: - Most inverters appeared to be very sensitive to voltage dips (did not withstand events severer than 50% magnitude – 40 ms duration, or 70% - 100 ms). - In general, inverters appeared to be very sensitive to phase angle jumps: in most cases, they tripped for a jump of 5° (angle jump interpreted as a frequency deviation by the inverter). - In some cases, voltage dips with severer effects on the inverters operation (not just disconnection) were observed. A rather large part of the inverters showed current peaks at voltage recovery. - Stability of the current control loop was also affected in some cases (current control problems: high frequency or low frequency current oscilations). - Ride-through capability against voltage dips was shown only by 25% of inverters having a quick current control loop. In one case an inverter increased its output current to keep output power constant, showing the capability to mitigate voltage dips. - High sensitivity of inverters to voltage dips can have a negative effect on the inverter (and PV plant) yield performance, components lifetime (induced stress) and, ultimately, the network. Implementation of the mains monitoring is determinant in the inverters sensitivity to voltage dips.	*6*
Experimental tests were also carried out in a 200 kWp Test field for Photovoltaic systems in Japan. A maximum 40% drop with a 0.2 second duration was created on a distribution line and the operating performance of each PV power generation system in the grid interconnection operation was observed: - PV systems provided with an instantaneous current control on the inverter continued stable operation without generating over-current. - PV systems not provided with this function (voltage control type) generated over-current and operation was interrupted by the over-current relay.	*12*
Experimental measurements carried out in a 100 kW PV in Austria plant revealed the importance of a proper design of the PV system decoupling protection. Too sensitive settings or an inappropriate design can not only lead to	*13*

problems regarding the reliable operation of the plant but furthermore also be a source of power quality disturbances in the network.	
NEEDS FOR STANDARDIZATION: Future technical requirements for the interconnection of DG should consider immunity issues. By addressing the grey zone between immunity and disconnection, requirements, this would positively contribute to safety and quality goals without imposing significant additional constraints on DG equipment. In this sense, current standards of inverters lack detailed requirements of decoupling protection against voltage dips. The way this requirement is understood conditions the performance of the voltage monitoring (and therefore of related trips), which can vary between the following extremes: - Instantaneous measurement of RMS voltage → leads to instantaneously trip signal after a voltage dip occurs and therefore, inverter disconnection; - Measurement of RMS voltage over a moving window → a trip signal is only sent when the RMS voltage remains below the prescribed threshold in the whole window, which means that the inverter can tolerate voltage dips up to the limit. This shows how different implementations of the mains monitoring by inverters can have a large influence on their sensitivity to network disturbances. **TIME FRAME:** Short / Medium	*6*
NEEDS FOR RESEARCH AND DEVELOPMENT: Adequate and realistic immunity requirements for inverters against voltage dips. **TIME FRAME:** Short / Medium	*6*

References – Voltage dips

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1 IEC 60050, “International Electrotechnical Vocabulary”.

2 EN 50160:1999, “Voltage characteristics of electricity supplied by public distribution systems”.

3 IEEE P1433, “A standard Glossary of Power Quality Terminology”.

4 IEC 61000-2-8: 2000, “Voltage dips and short interruptions on public electric power supply systems with statistical measurement results”.

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6 DISPOWER project (Contract No. ENK5-CT-2001-00522), “Identification of general safety problems, definition of test procedures and design-measures for protection”, 2004. <http://www.dispower.org>

7 Math H.J Bollen et al, “Voltage Dips at the Terminals of Wind Power Installations”, Nordic Wind Power Conference, March 2004.

8 EEG generators (under the Renewable Energy Law Regime) connected to the High Voltage. Guide for the connection and operation of renewable energy generators connected to the high voltage network – enlargement of the grid code, VDN, August 2004.

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12 IEA-PVPS Task V, report IEA-PVPS T5-02: 1999, “Demonstration test results for grid interconnected photovoltaic power systems”.

13 Bletterie B., Heidenreich M., “Impact of large photovoltaic penetration on the quality of supply – a case study at PV noise barrier in Austria”. 19th European Photovoltaic Solar Energy Conference, Paris, 2004.

2.2 Voltage swells	***References***
DESCRIPTION: Voltage swell is a temporary increase of the voltage at a point in the electrical system above a threshold, typically 1.1 p.u. As voltage dips, they are usually characterized by their magnitude and duration. Voltage swells are usually related to electrical systems fault conditions (e.g. temporary voltage rise on the unfaulted phases during a single-to-ground fault). They can be also caused by switching off large loads or energizing large capacitor banks. The severity of a voltage swell during a fault condition is a function of the fault location, system impedance, and grounding. Voltage swells are less common than voltage dips, especially for grounded systems.	*1*
THEORETICAL EVIDENCES:	
EXPERIMENTAL EVIDENCES: * SENSITIVITY OF PV INVERTERS Experimental tests carried out within the DISPOWER project on state-of-the art inverters (representative of the European domestic market: 12 single-phase units with different design concepts, low-frequency transformer, high-frequency transformer and transformerless) revealed the following results when voltage swells up to 120% occurred at the grid voltage: - Tested inverters proved to be very sensitive to voltage swells. Their decoupling protection method (e.g. overvoltage protection) played a decisive role in the devices behaviour. - In some cases, the current control of the inverters was strongly influenced by small voltage swells (whereas it was not the case with voltage dips).	*2*
NEEDS FOR STANDARDIZATION: Future technical requirements for the interconnection of DG should consider immunity issues. By addressing the grey zone between immunity and disconnection requirements, this would positively contribute to safety and quality goals without imposing significant additional constraints on DG equipment. Current standards for inverters lack detailed requirements of decoupling protection against voltage swells. **TIME FRAME:** Short / Medium	*6*
NEEDS FOR RESEARCH AND DEVELOPMENT: Adequate and realistic immunity requirements for inverters against voltage swells.	*6*

TIME FRAME: Short / Medium	

References – Voltage swells

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[1] DISPOWER project (Contract No. ENK5-CT-2001-00522), “Report describing and comparing opportunities and effectiveness of generator control, load management, and additional storage and power electronic controller options for managing LV networks with distributed generation”, 2003. <http://www.dispower.org>

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2.3 Short circuits in electrical installations

References

DESCRIPTION:

Short-circuits in electrical installations represent a severe stress situation for equipment connected to the same branch where the short-circuit has happened. A particular threat exists if the short circuit is interrupted by a branch fuse or circuit breaker. In this case, equipment connected to the same branch experience first a deep voltage dip (due to the short circuit), followed immediately by a transient over-voltage (resulting from the interruption of the short circuit by the protective element). 1

Transient overvoltage characteristics depend on the network impedance, the peak short-circuit current, the switch-off characteristics of the protective element, and capacities present in the network. The most decisive factor with respect to these transients is their energy content, which is determined by the energy stored in the inductive components of the network. Regarding the protective elements, thermal magnetic circuit breakers have shown to produce no considerable over-voltage effects (although the maximum current through them can reach very high values), whereas typical over-voltages induced by glass tube fuses are in the range of 1-1.5 kV. 2

THEORETICAL EVIDENCES:

The consequences of short-circuits for active elements of DG systems such as inverters are: 1

- The voltage dip following the short-circuit results in high du/dt and associated large over-currents, in case no current limitation exists in the inverter. Actual impact of these over-currents depends mainly on its hardware design and current control strategy.

- Interruption of the short-circuit current by means of the protective element (high di/dt) will make the energy stored in the inductive part of the network impedance to be released and dissipated in capacitances. This results in a voltage transient that will be also seen by the inverter and therefore cause stress on the electronic components in its output circuit.

Extensive tests made with fuses and circuit breakers under different grid conditions have shown that transients following short-circuits can have energy contents of 0.1-1 kJ, depending on the inductive impedance and the protective elements characteristics. Usually, inverters are not tested with such transients.

EXPERIMENTAL EVIDENCES:

* SENSITIVITY OF PV INVERTERS 1

Experimental tests were carried out within the DISPOWER project on state-of-the art inverters, representative of the European domestic market (8 single-phase units with different design concepts: high-frequency transformer and transformerless). The tested units were operated under different inductive grid

impedances and exposed to output voltage transients equivalent to those of quick fuses. Most relevant results were the following: - Regarding over-currents, values up to 20 times the nominal output were measured, which in some cases created severe stress for the components carrying those currents and lead to device defects. - Concerning the internal over-voltage protection of the inverters, the commonly used design was simple varistors (in some devices also complemented with additional components such as arrestors or spark gaps to achieve further protection). With usual protections, the peak over-voltages were limited to approximately 2 to 2.5 times the peak amplitude of the nominal grid voltage. However, at low limitation-voltages of the arrestors, high energies had to be absorbed and high over-currents resulted. Analysis of the inverter defects highlight some key factors for a proper implementation of protection against short-circuits: - The current control of the inverter output bridge has a key influence on its behaviour during short-circuit situations. A proper control strategy should not create additional over-currents during fast drops of the grid voltage or at the recovery of the voltage after a short circuit. - The withstand voltage of all inverter elements which are directly connected to the grid has to be properly coordinated with the voltage limitation of the protective elements used (e.g. varistors). This is particularly important for the internal power supply (if this is done from the AC side), control and measurement parts of the device and the power conversion stage. - Special care has to be taken to ensure that the over-voltage protection is working during all operating conditions. If the protective elements are dedicated e.g. to the power conversion stage, critical defects might happen if the power stage is not connected to the grid (for example, at night time). - Highly sophisticated protective designs do not seem to be necessary for DG components used in residential applications. However, in special cases and under rough operation environments, additional external protections could become necessary.	
NEEDS FOR STANDARDIZATION: Specific standards for PV inverters should include testing under realistic short-circuit conditions at the AC side. **TIME FRAME:** Short / Medium	
NEEDS FOR RESEARCH AND DEVELOPMENT: Experimental tests done with inverters under short-circuit events on the AC side have revealed that there are still problems regarding the proper implementation	

of the protection. Inverter manufacturers should improve this, in order to increase the inverters reliability against such phenomena, which cannot be excluded in electrical installations. This is especially important if inverters are to be operated under rough operation environments, where additional external protections might become necessary. **TIME FRAME:** Short / Medium	

References – Short circuits in electrical installations

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1 DISPOWER project (Contract No. ENK5-CT-2001-00522), “Identification of general safety problems, definition of test procedures and design-measures for protection”, 2004. <http://www.dispower.org>

2 European project ESDEPS (Contract No. JOR3-CT98-0246), “EMC and Safety Design for Photovoltaic Systems (ESDEPS)”, , 2001.

2.4 Superimposed harmonics and interharmonics on the grid voltage

References

DESCRIPTION:

The grid voltage in public supply systems is never a pure sinewave. Disturbances in form of harmonic and interharmonic voltages superposed on the grid voltage are indeed some of the main steady state power quality phenomena. Voltage and current harmonics and interharmonics are defined in terms of the spectral components over a defined range of frequencies:

- Harmonics (IEEE P1-433-A) are sinusoidal voltages or currents having frequencies that are integer multiples of the frequency at which the supply system is designed to operated (termed the fundamental component, usually 50 Hz or 60 Hz); 1
- Interharmonics (IEC 61000-2-1) are voltages or currents whose frequencies are not an integer of the fundamental; they can appear as discrete frequencies or as a wide band spectrum. 2

The main sources of harmonics existing in the networks are nonlinear loads, 3
mainly present in the MV and LV levels of the power system. Harmonic voltages superimposed on the fundamental grid voltage have their origin in the harmonic currents drawn by these loads. The harmonic voltages then propagate around distribution systems and branch circuits not concerned with carrying the harmonic currents. Examples of sources of harmonic currents in the networks are: switch mode power supplies, gas-discharge and fluorescent lamps, variable speed drives, uninterruptible power supplies, cyclo-converters, phase angle controlled loads, arc furnaces, static VAR compensators and transformers. Also,
linear loads (consisting of resistors, capacitors and/or inductors) may become 4
source of harmonic currents when they operate under distorted voltage conditions. The distortion in the current can be much higher than the distortion in the voltage: harmonic current distortion levels above 100% occur often for single phase loads, but harmonic voltage distortion above 8% is very unlikely.

Concerning interharmonics in the networks, they can be created whenever there is an amplitude modulation of load current (e.g. transient changes in operating conditions of loads), when in static converters switching of the semiconductor devices is not synchronized with the grid frequency, or where transformers are subject to saturation. Typical sources of interharmonics include: cyclo-converters, static frequency converters, arc furnaces and arc welders, induction motors, wind turbine generators, loads controlled by integral cycle control and low frequency power line carriers. 2

Harmonics and interharmonics have a wide range of impacts on the network components and customers side of the system (including loads and generators). Typically associated problems are variations in RMS voltage and flicker, thermal effects on transformers, rotating generators and motors (increased losses), disturbances of electronic equipment, acoustic disturbances, overloading of passive filters, disturbance of protection systems and protective relays, interference with communication systems (telephone, control and data transmission signals), stress on insulation materials, transformer saturation and

system resonances.	
THEORETICAL EVIDENCES:	
DG inverter components that are potentially sensitive to voltage disturbances (harmonics and interharmonics) are the following:	2
- Current control unit and power conversion stage. Depending on the inverter control strategy, the shape of the grid voltage might have a fundamental influence on the current control and thus the shape (distortion) of the output current. Therefore, high distortion levels of the voltage might cause problems for the control of the clean, sinusoidal output current.	
- Grid interface and protection. Interharmonics present on the grid voltage result in fluctuations of the grid voltage and frequency: if any of these parameters is out of range, the integrated protection disconnects the inverter from the grid. Particularly methods which rely on a high accuracy of the zero-crossings of the voltage signal (frequency and impedance monitoring) will be affected.	
EXPERIMENTAL EVIDENCES:	
* SENSITIVITY OF PV INVERTERS	2
Experimental tests were carried out within the DISPOWER project on state-of-the art inverters, representative of the European domestic market (12 single-phase units with different design concepts, low-frequency transformer, high-frequency transformer and transformerless).	
Tests were based on European standards dealing with harmonics and interharmonics (EN 61000-4-13), for electromagnetic environments applicable for Points of Common Coupling (Class 2). Combined harmonic voltage waveforms containing large amounts of the most critical harmonics (3rd, 5th and 7th; "flat curve" with a total harmonic distortion of roughly 4%, and "overshoot curve" with a total harmonic distortion of roughly 7%), and individual harmonics (odd and even order) were applied. Also, "Meister curve" tests were conducted to evaluate the impact of audio frequency ripple control signals and other types of mains signalling used in many European countries.	5 6
Inverters (most of them with an interface complying with the German draft standard VDE 0126) were operated at their nominal power output and voltage input. Most relevant results were the following:	7
- Inverters are in general relatively insensitive towards harmonics present on the grid voltage. However, harmonics resulting in a notable increase of the peak amplitude of the voltage ("overshoot curve") might induce over-currents which could cause an unintended tripping of the internal over-current protection. The implementation of the AC current control and control strategies has a decisive influence on the behaviour of the inverter in terms of resulting total harmonic current distortion and the potential of critical over currents.	

- Some inverters were able to control the output current independent of the voltage shape. In other cases voltage distortion led to a considerable increase of total harmonic current distortion (THDI up to 40-50%), with the output current either tending to compensate for the existing voltage distortion ("active filter behaviour"), or no compensating at all.

  A comparative analysis of the inverters behaviour and their output control under normal conditions (THDI) results reveals the following pattern:

  - Low current distortion – low impact: the inverters with a very low THDI under normal conditions were only slightly influenced by high levels of distortion. Across a wide frequency range, the THDI was even lower than the THDU.

  - Constant current distortion – low impact: a number of inverters with average THDI showed a relatively constant THDI independent of the disturbed voltage waveform. No significant impact of the THDU on the current shape was observed.

  - High impact: two devices with average THDI were highly impacted by superposed frequencies, particularly in the range of 100 Hz to 1000 Hz. At these frequencies, the THDI reached levels up to 48%.

- Superposed interharmonics at levels of the "Meister Curve" created severe troubles for the large majority of the tested inverters. The most critical component influenced by these disturbances was the frequency and/or impedance measurement of the grid monitoring unit.

- Adequate implementation of the frequency monitoring is critical in order to achieve a high level of immunity against interharmonics. Frequency measurement schemes working on a period-by-period base showed to be very sensitive to short-term fluctuations of the period duration caused by interharmonic components on the grid voltage. Also, too narrow frequency limits leading to disconnection were counterproductive to achieve high immunity level.

NEEDS FOR STANDARDIZATION:

Existing immunity standards related to harmonics and interharmonics on the grid voltage, such as EN 61000-4-13, seem to be adequate for grid-connected inverters. However for DG to play a fundamental role in future distribution networks (which would fundamentally rely on the contribution of DG), additional requirements should be standardized regarding the desired behaviour of inverters during the network disturbances.

On another hand, the operation of DG inverters as "active filters" to locally compensate existing harmonics produced by loads is highly recommended in future DG networks. Specific standards for inverters with such capabilities should be developed to guarantee quality of performance and proper integration in the networks, to avoid negative effects due to unpredictable interaction between these devices and the network.

TIME FRAME: Short / Medium	
NEEDS FOR RESEARCH AND DEVELOPMENT: Test results done with state-of-the-art inverters show that the potential impact and troubles caused by superimposed harmonic and interharmonic voltages are usually not adequately considered during the design process of the devices. Inverters manufacturers should put efforts in designing inverters with a high level of robustness against these phenomena, given their increasing importance in electricity networks. **TIME FRAME:** Short	

References – Superimposed harmonics and interharmonics on the grid voltage

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1 IEEE P1433, “A standard Glossary of Power Quality Terminology”.

2 IEC 61000-2-1:1990, “Guide to electromagnetic environment for low-frequency conducted disturbances and signalling in public power supply systems”.

3 DISPOWER project (Contract No. ENK5-CT-2001-00522), “Identification of general safety problems, definition of test procedures and design-measures for protection”, 2004. <http://www.dispower.org>

4 DISPOWER project (Contract No. ENK5-CT-2001-00522), “Summary report on impact of power generators distributed in low voltage grid segments”, Deliverable del_2005_0077. <http://www.dispower.org>

5 EN 61000-4-13:2003, “Testing and measurement techniques – Harmonics and interharmonics including mains signalling at AC power port, low frequency immunity tests”.

6 IEC 61000-2-1:1990, “Guide to electromagnetic environment for low-frequency conducted disturbances and signalling in public power supply systems”.

7 DIN VDE 0126:1999, “Automatic disconnecting facility for photovoltaic installations with a rated output smaller than 4.6 kVA and a single-phase parallel feed by means of an inverter into the public low-voltage mains”.