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

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THE PV-UP-SCALE PROJECT

PV-UP-SCALE (PV in Urban Policies – Strategic and Comprehensive Approach for Long-term Expansion) is a European funded project under the Intelligent Energy for Europe programme related to the large-scale implementation of photovoltaics (PV) in European cities. Its’ objective is to bring to the attention of the stakeholders in the urban planning process the economic drivers, bottlenecks like grid issues and the does and don’ts within the PV-urban planning process. To reach the urban decision makers workshops will be organised and a quality handbook will be written using experience gained with PV-Urban projects in the Netherlands, Germany, France, Spain and the United Kingdom. The project complements the activities that are being executed in the International Energy Agency – Photovoltaic Power Systems Programme (IEA PVPS) Implementing Agreement, in particular IEA PVPS Task 10. It takes information from Task 7 (building integrated PV), which ended in 2001 and Task 5 (grid issues), ended in 2003.

The structure of the project is summarised in the following figure.
PV-UP-SCALE consortium brings together complementary expertise from Educational, Research and Development, Engineering, Architecture and Utility sectors:

<table>
<thead>
<tr>
<th>Sectors</th>
<th>Institutions</th>
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</thead>
<tbody>
<tr>
<td>Educational</td>
<td>ECN- Energy research Center of the Netherlands, Research Institute, The Netherlands (Project Coordinator)</td>
</tr>
<tr>
<td>Research</td>
<td>Vienna University of Technology - EEG, Energy Economics Group, Austria</td>
</tr>
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<td></td>
<td>Fraunhofer Institute für Solare Energiesysteme, Research Institute, Germany</td>
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<td>Universidad Politecnica de Madrid – Instituto de Energia Solar, Spain</td>
</tr>
<tr>
<td>Consultancy</td>
<td>HORISUN- Consulting, The Netherlands</td>
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<td>HESPUL- Consulting, France</td>
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<td></td>
<td>Halcrow- Halcrow Group Ltd, Consulting, United Kingdom</td>
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<tr>
<td></td>
<td>Ecofys- Ecofys Energieberatung und Handelsgesellschaft GmbH, Consulting, Germany</td>
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<tr>
<td>Electricity</td>
<td>Continuon- Netbeheer NV, Utility, The Netherlands</td>
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<td>MVV- MVV Energie AG, Utility, Germany</td>
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</table>

Of the project Work Packages, Work Package 4 (WP4) is the one dealing with technical issues of grid interconnection such as mutual impacts of PV systems and Distribution networks, interconnection guidelines, network risks, and required inputs to network planning. Fortunately, some thorough collective work on PV-grid issues has been done under the framework of IEA PVPS-Task 5, R&D projects previously supported by the European Commission, national and international Standardization bodies (IEC-TC82, CENELEC-SC82). WP4 draws upon this work to contribute to identify still existing barriers and solutions for a successful dissemination of PV systems in electricity networks of urban areas.

For more information, please visit the project web-site:  www.pvupscale.org
EXECUTIVE SUMMARY

This report has been produced by the consortium of the project PV-UPSCALE under the European EIE programme. It addresses the mutual impact of grid interconnected PV systems and distribution networks. It presents the result of a review of some 100 papers and reports from European countries Austria, France, Germany, Netherlands, Spain, United Kingdom and Japan.

PV is currently the most important DG technology at a domestic level using inverters. This fact makes PV an exemplary subject also for other DG technologies employing static inverters. In order to allow detailed insight on the different impacts specific “Impact records” have been created and added as appendix.

The report covers following issues:

**Impacts of PV generation on distribution networks:**
- Voltage rise and voltage fluctuations
- Current harmonics
- DC from inverters
- Ground faults
- Contribution to short-circuit capacity
- Power value, capacity value
- Unintentional islanding
- Network design and operation
- Added value capabilities of modern inverters

**Impacts of distribution networks on PV systems:**
- Voltage dips and swells
- Short-circuits in the distribution system
- Harmonics and interharmonics on the grid voltage

It discusses the current state of knowledge concerning these topics from a European perspective with regard to different grid structures in various regions of Europe. Focus is laid on urban grids. It also discusses existing standards and new opportunities to provide grid services, which are currently left only to central powers stations. Several options from Japan for developing the distribution grid towards increased inherent stability and operation in island mode for emergency situations are included; Japans network structure is different from urban European grids since it employs overhead lines.

RESULTS

Relevance of many findings depends strongly on the network characteristics under consideration. For urban environment, typically low impedance, underground cable networks are used. Less densely populated areas and more rural areas mostly employ overhead lines with higher, inductive impedance.

The technology for grid interconnection of PV systems has matured over the past years. Inverters with very good efficiencies and good reliability are available. However, standards and control settings governing the operational control of PV systems are not uniform over Europe. They need to be harmonised and adapted to the large power capacity already employed.

For specific technical issues the most important findings are:
- **Voltage rise, voltage dips and voltage fluctuations**
  Decentralised generation causes a voltage rise at the point of interconnection. This voltage rise limits the admissible power for DG. Modern network sections in Germany have shown to accept about 6 kWp per household without violating the relevant standard EN 50 160. Voltage fluctuations from passing clouds have essentially no impact on voltage dips and swells, because of slow ramps and an averaging effect over large areas.

  Voltage dips have shown to cause nuisance tripping of protective functions in inverters. Considering the installed PV capacity of more than 2 GWp there is a concern that this sensitivity can amplify grid instability under overload conditions. Therefore, in Germany inverter requirements have been changed and include now some “fault-ride-through” thresholds similar as for wind turbines.

- **Current harmonics and DC injection**
  Current harmonics from inverters are no problem, if inverters comply with generic standards of the IEC 61000 series. Inverters perform better than conventional non-linear loads. For larger inverters above 16 A current per phase dedicated standards are missing.

  DC-injection from PV systems has not been found to have caused trouble for network operation.

- **Unintentional islanding**
  The possible occurrence of unintentional islanding in distribution networks with distributed generation has been one of the major issues in connection with DG. However, investigations have shown that likelihood and risk of personal injury or death from such an event are below other risks accepted by society.

  There is still widespread discrepancy concerning protection systems required in the various European national grid codes and standards, so harmonisation is needed.

  For small-scale PV-DG, standardised, integrated protection systems should be employed. These systems should be implemented based on a risk analysis given in standards for safety relevant machine design to ensure a “one failure” tolerance. Redundant and independent acting main components as well as a “fail-safe” control is required. They should be type tested to a common standard.

  A high level of immunity against dips, swells and transients from the grid is required to prevent nuisance tripping.

- **Contribution to short-circuit capacity**
  In urban areas employing underground cable networks the currents from PV systems are small compared to the high short circuit current of the network. Therefore no adverse effect on fault clearance is expected.

  Only under high penetration of PV-DG, in case of faults occurring at the end of lines with high impedance, currents from PV systems might hamper fault detection and clearance. In future, inverters may be required to contribute to fault clearance by delivering a short-term overload current, for example 300 % of rated current for 100 ms.

- **Added value capabilities of modern inverters**
  Modern inverters can perform additional functions such as: active filtering by injecting compensating current harmonics, reactive power control, voltage level control, phase
symmetry control. In combination with energy storage more options are possible: intended islanding, extended voltage control, peak shaving. To employ these options a regulatory framework including financial compensations needs to be developed.

- **Network design and operation control**
  New approaches are required for true grid integration of decentralised power systems. Network control and safety approaches need to be adapted for downstream as well as upstream energy flows. Stochastic and controllable generation units can be organised into “virtual power plants”, which in turn can be integrated into the existing structures for control of generation and transmission.

  Grid costs distribution models need review and adaptation to additional network usage. Tariff models should be developed for optimised control of generation and consumption. It has been demonstrated that fluctuations of the grid frequency within a narrow band could be allowed to represent a cost function.

- **Standardisation needs**
  Product standards for inverters should be improve to include limits for current harmonics emissions also for devices with phase currents higher than 16 A, DC current level in AC output and short circuit/overload behaviour. For inverter shut-down under system faults and grid disturbances the same thresholds as for central power stations should be chosen. This insures system stability by not taking out several Gigawatts of power due to oversensitive settings required in former standards.

  European harmonisation is also needed concerning islanding protection methods and settings.

- **Research and development needs**
  Several developments for inverters are suggested:
  - New voltage control techniques to maintain network voltage control with Distributed Generation technologies
  - Controlling short-circuit current contribution from inverters.
  - Robust control algorithms for current control; positive feed back loops by taking grid voltage as reference for current control are to be avoided.
  - Robust islanding detection circuitry, insensitive against common voltage disturbances
  - Robust protection against overvoltages from the grid

  Evaluate methods for islanding detection used in European countries regarding safety of detection, robustness against grid disturbances, compatibility with various network characteristics, cost and usability at high PV penetration level.

  Develop new approaches for economic assessment of DG and optimisation of control schemes.

  Incorporate PV-DG added value capabilities in networks operation and accounting.

**CONCLUSION**

PV systems generally have been considered as individual systems and their respective components. It is important to broaden this view and also regard the total capacity of DG on the European network.
PV systems offer good options to improve grid supply quality and provide grid services. In order to realise these opportunities future work has to address technical developments closely with standards’ development.

Most of the above considerations are valid also for other distributed power sources expected to be installed in large numbers, e.g. µ-CHP systems for domestic use.
Glossary of selected terms

**Blackout, Brownout:** A blackout is a complete loss of grid voltage, an interruption of power supply. A brownout is an under-voltage situation, where the grid is not altogether down, but exhibits a voltage severely below acceptable tolerance. Some equipment will not work in a brownout, whereas others will, depending on the severity.

**Energy buffering:** By means of an additional energy storage device, energy production or demand can be decoupled to a certain extend from power delivery to, or consumption from, the electricity grid.

**ENS:** Mains monitoring unit with circuit breaker, for use between grid-connected PV inverter and public LV (low voltage) distribution grid. Automatic shut-off device, consisting of two independent grid monitoring devices with one circuit breaker assigned to each. Involved detection methods include measurement of voltage, frequency and grid impedance. Whenever one or more of these grid parameters leave the tolerance band, the PV inverter is disconnected from the electricity grid, until regular grid conditions return.

**Grid-forming, grid-supporting, grid-parallel:** An energy generator in grid-forming mode is responsible to establish and maintain voltage and frequency of the concerned grid. A grid-supporting device accepts control signals for varying its power output according to the needs of the grid, but it does not bear direct responsibility for voltage and frequency. In grid-parallel operation, the generator is not remotely controlled, but simply delivers energy according to its own circumstances.

**Islanding:** Islanding is a condition in which a portion of the utility system, e.g. a branch of the low voltage electricity grid, which contains both load and generation, is isolated from the remainder of the utility system and continues to operate. Islanding is mostly viewed as a safety threat to be avoided at all cost, but can also be viewed as a regular operating mode for an uninterruptible power supply system (UPS) for selected loads, such as essential computer systems.

**Load shifting:** For some appliances (such as refrigerators or washing machines), electric energy consumption can be shifted in time, in order to improve correlation between energy generation (possibly renewable / stochastic) and demand.

**Peak shaving:** By means of consumer energy management, e.g. through load shifting, energy consumption can be distributed more evenly over time, in order to reduce the peak power drawn from the electric grid.

**Ride-through capability:** Robust and fast AC current control and appropriately optimized control strategies enable an inverter to provide continuous operation and sustained energy delivery during grid disturbances (such as voltage sags and surges or superimposed sinusoidal signals of other frequency, e.g. remote control signals) of limited time. Lack of ride-through capability causes unnecessary occasions and lengths of interrupted operation, and hence - in case of a grid connected PV inverter - lost solar energy.

**THD, THD filter:** THD (= Total Harmonic Distortions) is a measure for the amount of harmonics present in a periodic signal, such as the grid voltage, which is supposed to be sinusoidal. A THD filter is a device, or a function of an inverter’s AC current control, which is capable of injecting/compensating harmonics, thus reducing the THD value of the concerned voltage signal.
1 Introduction

Over the last decade, a growing number of technical information has been produced regarding the impact of Distributed Generation (DG) on electricity networks and vice versa. Contents vary from theoretical analysis (e.g. simulations) to experimental results (laboratory tests, field experiences) as well as prospects for DG in the near (or far) future, standardization needs, R&D needs, etc. Concerning PV-DG, although its impact on electricity networks is still much more reduced than that of other DG technologies (namely wind technology), its specific technological characteristics (currently is the most important DG technology using inverters to convert the primary current into AC)\(^1\) make PV an interesting subject of research and development.

Deliverable 4.1 (D4.1) focuses on the state-of-the art of PV-DG and is a key opportunity to learn from past experiences, particularly:

- To provide insight on the evolution of PV technology in the last decade (always regarding interaction with electricity networks);
- To identify still existing technical barriers (e.g. unappropriate standards and/or requirements);
- To identify new opportunities and values (new product developments) that can contribute to a higher penetration of PV electricity in distribution networks;
- To provide inputs for later work to be done within PV-UP-SCALE project, WP4 (effects of urban scale PV on Low Voltage networks, recommendations for utilities on PV interconnection issues, discussion papers for the standardisation bodies, etc.).

To that aim, an extensive review of literature has been carried out (national and international R&D projects, reports, articles, workshops, etc.) to identify the mutual impacts between PV-DG and electricity networks relevant to PV-UP-SCALE stakeholders group involved with grid interconnection issues (utilities and their associations, PV system planners, PV components manufacturers, installers, standardisation bodies, etc.), with Power Quality and Safety being central topics.

The mutual impacts identified are summarized in Table I, divided in two main categories:

- Impacts of PV-DG on Distribution networks: they cover voltage, current and power impacts arising from the individual or multiple operation of PV systems in separate and relatively concentrated areas.
- Impacts of Distribution networks on PV-DG: these are relatively frequent events that can affect negatively the operation of PV-DG in quantitative terms —final yield, useful output— as well as qualitatively (power quality).

In order to structure the information found in the literature survey in such a way that readers can gain a general insight on the different impacts, details on reported evidences, needs for new standards, R&D activities, etc., “Impact records” have been created with a common format, shown in Table II. Also, whenever relevant, information has been also included of other DG technologies.

Section 2 of this report presents some important issues concerning the connection of PV systems to Distribution grids. Sections 2 and 3 summarise the main findings of the impacts analysed, with the individual Impact records included in the Annex section of this report. Section 4 summarises the standardization, research and development needs identified to overcome the still existing technical barriers, as well as to increase the values of PV Distributed Generation (new technical functionalities) leading to a higher penetration of PV electricity in distribution networks. Section 5 summarises the main findings of the literature survey.

### Impacts of PV-DG on Distribution networks:
- Voltage rise and voltage fluctuations
- Current harmonics
- DC from inverters
- Ground faults
- Capacitive leakage of transformerless inverters
- Short-circuit capacity
- Power value, capacity value
- Unintended islanding
- Added value capabilities of modern inverters
- Impact on grid design and operation

### Impacts of Distribution networks on PV-DG:
- Voltage dips
- Voltage swells
- Short-circuits in installations
- Superimposed harmonics and interharmonics on the grid voltage

Table I. Impacts covered in this report

<table>
<thead>
<tr>
<th>Impact</th>
<th>Reference</th>
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<tr>
<td>Description:</td>
<td>(Definition of impact, main causes,... and whatever information is considered useful to better understand the impact. References to impacts of networks in DG other than PV could be also included)</td>
</tr>
<tr>
<td>Theoretical evidences:</td>
<td>(Summary of theoretical analysis, simulations,...)</td>
</tr>
<tr>
<td>Experimental evidences:</td>
<td>(Summary of laboratory tests, field experiences,...)</td>
</tr>
<tr>
<td>Needs for standardization:</td>
<td>(International standards needing specific requirements that at present are not considered; New standards needed)</td>
</tr>
<tr>
<td>Time frame:</td>
<td>Short / Medium / Long</td>
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<tr>
<td>Needs for Research &amp; Development:</td>
<td>(R&amp;D needs on impacts of electricity networks on PV-DG)</td>
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<tr>
<td>Time frame:</td>
<td>Short / Medium / Long</td>
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Table II. Format used for the different impacts covered in this report (see Annexes document)
2 Connection between PV Systems and Distribution Grids

2.1 Three-phase grid-coupling

The use of three-phase grid-coupling and three-phase inverters is increasing. This coincides with inverters having higher rated power and longer lifetime expectations. Increasing use of three-phase grid-coupling PV module integrated inverters for free and easy building integration will come up when pricing hurdles have been broken. (Zacharias, 2006)

2.2 Grid interface safety devices (e.g. ENS)

Mainly in Germany, Switzerland and Austria a special safety device for protection by automatic disconnect (ENS) had been developed in the late 90s. Many devices built according to the former German ENS standard exhibit a high level of malfunctioning which justifies not only the relative optimization of trip parameters (e.g. threshold settings for amplitude and duration of tolerated voltage sags), but also the fundamental reconsideration of the basic approach (active impedance measurement), and the application of alternative approaches. Frequent faulty behaviour, which is reported by many authors independently, leads to wide-spread and unnecessary disruptions of PV power delivery into the grid. In addition, the active impedance measurement method of ENS introduces disturbances into the grid, degrades power quality, and leads to significantly increased malfunctioning in case of many inverters being operated close to each other.

It is furthermore a fact that the German ENS approach is not accepted in other European countries, where different approaches are implemented which demonstrate satisfactory functioning. Stability studies have shown that, if there is no capability for frequency maintenance, no islanding problems occur. Recently, an additional approach (resonant circuit type test) has been allowed in Austria, where the ENS devices already produce less irregular disconnects than in Germany, because the Austrian ENS trip values are set more tolerantly.

In 2006 the governing standard had been revised (DIN VDE 0126 -1) to allow for various operation principles, less sensitive settings and an enhanced grid stability in case of undervoltage disturbances. European standards definitely need improvement and harmonization in this issue. Tele-control for external disconnect keeps being discussed, and is considered convenient especially for the MV grid level. (Bergmann 2006, Panhuber 2004, Bletterie 2004, Schulz 2001)

It has been observed that the (ENS) have been irritated by utility remote control signals. There are however no reports that the proper functioning of the utilities’ remote control signals have been affected by the presence of PV inverters. (Bründlinger 2006)

2.3 Interactions of large numbers of inverters

If many inverters, possibly of the identical type, are connected in vicinity to the same grid, they may interact or interfere with each other. This can lead to increased emission of harmonics, mutual disturbances (especially caused by ENS active impedance measurement method), and increased number of unjustified grid disconnects and shutdowns with subsequent loss of energy yield. This issue needs to be addressed in further research and development, combined with improvement of grid interfacing safety devices. (Bosman 2006)
2.4 Phase symmetry with multiple single-phase inverters

Whenever a larger number of single-phase inverters is connected to the three-phase grid, care should be taken to distribute these inverters evenly across the three-phases, in order not to increase phase imbalances. In some installations this recommendation has been neglected to the detriment of power quality, concerning symmetry of phase voltages. (Laukamp 2004)
3 Impacts of PV-Distributed Generation on Distribution networks

This section describes the potential impacts of Photovoltaic Distributed Generation (and/or other DG technologies) on Distribution networks. They cover voltage, current and power phenomena arising from the individual or multiple operations of PV systems in separate and relatively concentrated areas.

3.1 Voltage rise and voltage fluctuations

- 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. The power direction through the system is therefore expected to be from the higher to the lower voltage levels.

Voltage variations are relatively frequent in distribution systems, they are partly caused by load variations, with minimum values occurring when the loads are reduced (e.g. during nights or summer holidays). To avoid the grid voltages surpassing acceptable limits at the MV distribution levels, different regulation techniques are used, depending on the networks characteristics (automatic step-up-transformers and voltage regulators at MV levels, manual tap changers in MV/LV transformers, etc.). This regulation is important, since the electricity supply companies must fulfil certain obligations regarding the power quality of supply to consumers.\(^2\)

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 a 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).

- Voltage fluctuations

The output of PV power generation fluctuates with hourly changes of solar radiation. The hourly fluctuation of the PV power output might, under specific conditions —concentrated arrangement in a limited area— cause power flow or voltage fluctuations in the distribution line. Besides these, the distribution system is also affected by load-induced fluctuations (power and voltage). Situations where the hourly voltage fluctuation due to PV power generation could become larger than the fluctuation induced from the loads might become a technological issue affecting the penetration of PV power generation in electrical distribution systems.

- Theoretical evidences

Theoretical analysis done within the framework of the International Energy Agency – PV

\(^2\) For supply voltages in European LV networks, ±10% of the nominal value is (EN 50160:1999, Voltage characteristics of electricity supplied by public distribution systems). Stricter limits apply however in many countries, both in Europe and elsewhere, with accepted voltages typically lying between 90% and 106% of the nominal values.
Power Systems Programme (IEA-PVPS-Task 5, 1998) have shown that if a large number of PV systems are connected to voltage-regulated distribution lines, the voltage at the customers’ terminals might increase because reverse power flow situations (the increase depending upon the relative sizes of the load and the power generation). If the voltage regulation is done in the transformers, the voltage at the end of a distribution line could exceed the upper limit even with slight reverse power flow created by PV-DG during light-load hours in the daytime. For distribution lines provided with voltage regulators, they might operate frequently because of the voltage changes and therefore reduce their service life-time.

Different solutions have been proposed to deal with this impact (IEA-PVPS-Task 5, 2002a). They could be adopted individually or combined in planning of future distribution systems:

- To limit the effective output of the inverters when overvoltage occurs;
- To turn the inverters to voltage regulators as soon as the upper voltage limit is reached;
- To adapt the MV/LV transformers to the expected periods of load demand (i.e., when maximum load situations are/are not expected);
- To include PV-DG in distribution systems planning, by limiting the amount of generation allowed by each customer, in a similar way as it is done for sizing the distribution transformers.

Theoretical studies done in the U.K. based on DG modelling (EA Technology, 2001a) have revealed potential problems due to the interaction of DG with Automatic Voltage Control schemes commonly used in distribution networks. It was concluded that the correct strategy for managing voltage regulation in the presence of DG depends on the operating mode of the DG generators (power factor or voltage control) combined with a complementary operating mode for the Automatic Voltage Control schemes used, and the selection of the correct relay characteristic/algorithm.

In another study done also in the U.K. (EA Technology, 2001b) to investigate the effects upon a typical 11 kV network from various DG technologies (small scale hydro, landfill gas and wind power), 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. Similarly, 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 (UMIST, 2002). This type of distribution network, which can be found in rural and semi-urban areas, has been also identified in another French study as a possible limiting factor for PV-DG penetration in relation to voltage rise effects (Andrieu, 2003).

Also to be mentioned is the situation of unbalanced load flows that can result from single phase DG connections. Simulations done in the U.K. with PV-DG 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 (Halcrow, 1999).

Several studies (IEA-PVPS-Task 5, 2002a; DISPOWER, 2005; Paatero, 2007) have shown the implicit advantages of load management as an effective strategy for mitigating voltage rise and facilitating the penetration of DG technologies powered by renewable energies in distribution grids, and therefore PV. Not only do small increases in the loads open up for a considerable amount of PV. PV technology is considered likely to offer benefits such as a reduction of the

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3 Especially in weak network scenarios (rural areas).
peak power demand from the network if high generation coincides with peak demand situations (such as in areas with significant use of air conditioning) that far exceed the costs of PV penetration.

Concerning voltage fluctuations by PV-DG, theoretical simulations of typical distribution lines of residential areas with PV-DG connected uniformly revealed slow output fluctuations, with total fluctuation largely decreased and levelled-off, compared with individual fluctuations (IEA-PVPS-Task 5, 2002a). New evaluations based on satellite-radiation data and frequency analysis are presently being done to gain more knowledge about this smoothing effect (Kawasaki, 2006).

### Experimental evidences

Due to the still reduced penetration of PV technology in distribution systems, very little experimental evidence exists of overvoltages and voltage fluctuations induced. In one country, however —Japan—, commercial inverters are provided with voltage regulation systems that prevent overvoltages at the point of interconnection by reducing the PV generator output (Ueda, 2005).

Concerning the importance of load control for enabling a higher penetration of DG-technologies, one Danish experiment has shown the potential of customers as active stakeholders that change their consumption behaviour when at the same time they become power producers. In particular, many PV system residential owners endeavour to move their electricity consumption to moments with high PV power production when some kind, especially if they experience different buying and selling prices of electricity (IEA-PVPS-Task 5, 2002a).

Regarding voltage fluctuations, experimental tests done in Japan have confirmed the relatively slow speed of output changes (Takeda, 1998). However, with the voltage change magnitudes increasing in proportion to the number of PV systems involved it was found, particularly with low voltage distribution lines, that the proper voltage range could be exceeded if no countermeasures were provided.

Experimental test done in The Netherlands also confirmed the relatively slow speed of output changes. Due to the increase of the acceptable upper limit of the voltage level in the Netherlands (from 242 V to 253 V) implementation of DG is possible to 70% of the nominal power of the power of the MV/LV transformer without additional control (Cobben, University of Technology Eindhoven, 2007a).

### 3.2 Current harmonics

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.

The main sources of existing harmonics in the networks are nonlinear loads, mainly present in the MV and LV levels.\(^4\) Harmonic voltages superimposed on the fundamental grid voltage have their origin in the harmonic currents drawn by these loads: they propagate then around distribution systems and branch circuits not concerned with carrying the harmonic current. Also, linear loads (consisting of resistors, capacitors and/or inductors) may become source of

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\(^4\) Examples of nonlinear loads 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.
harmonic currents when they operate under distorted voltage conditions. The distortion in the current can be much higher than the distortion in the voltage.\(^5\)

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.

Inverters to be used in grid-connected PV systems (or by any other Distributed Generation technology) are not covered in this aspect by specific standards, with generic standards for electrical equipment being generally applied, which are complied with by most commercial devices. At present, an international standard exists only for equipment operating in LV networks with rated currents up to 16 A per phase; different requirements exist, however, in some countries. For electrical equipment with higher currents operating in LV networks, still no international standard has been agreed; the same applies for MV and HV loads.

When many PV inverters operate in the same low voltage distribution grid segment, their combined harmonic current emissions may lead to voltage harmonics (especially the 11th harmonic frequency) exceeding tolerated limits. This is because the impedance and resonance frequencies of the grid may be altered, and a non-sinusoidal shape of the grid voltage may increase the harmonic currents produced by an inverter where the current control electronics is not able to cope adequately. (Bründlinger 2007, Schmitt 2007, Nietsch 2007, Schmitt 2006, Kremer 2006, Seifemann 2005)

\[\text{Figure 4. Example of the effect of an active THD filter (in inverter current control) on current THD (Seifemann 2005)}\]

\(^5\) Total Harmonic Distortion levels above 100% occur often for single phase loads, but harmonic voltage distortion above 8% is very unlikely.
### Experimental evidences

Experimental measurements carried out in a Danish residential area where 80% of the houses had PV systems led to conclude that the most important part of the voltage distortion in the local network was not produced by the PV systems, but came from external sources (IEA-PVPVS-Task 5, 1998). At the same time the most significant part of the current harmonics produced in the neighbourhood was produced by appliances (mainly TV sets) and only to a limited extent by the PV installations. The authors consider the results representative of a highly concentrated PV-DG in a geographically limited residential area, with a distribution line having relatively high short-circuit power. Different results could be obtained if the local grid had a significantly lower short-circuit power.

In Japan (IEA-PVPVS-Task 5, 1999), the harmonic distortion arising from the operation of multiple PV systems connected to the same distribution transformer (pole transformer type, typical in residential areas) was experimentally measured, with inverters of the same and different manufacturers (same and different control schemes). It was found that for a few specific harmonics, the total harmonic current could be superimposed when the same type of inverters were used due to the intrinsic operation of the device.\(^6\) This was not the case with higher harmonics even with different inverters, where the total harmonic current was cancelled.

Similar results were obtained after experimental tests done in the U.K. (Halcrow, 1999) with different inverters operating simultaneously: the higher frequency harmonics tended to be attenuated quickly; for the lower frequencies the situation appeared to be more complex, depending on the nature of the inverter control and the strength of the grid (in a strong grid the 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.

To prevent oscillation of specific harmonics the capacity of the inverters (and in general of all devices) has to be limited.

### 3.3 DC from inverters

Requirement of isolation transformers for PV grid-connected systems varies amongst countries. Whereas they are compulsory required in some countries for safety reasons, in others the requirement depends on technical characteristics of the devices (e.g., DC currents monitoring scheme) or specific utility requirements.

Many commercial inverters employ transformers that suppress intrinsically any DC component. However, transformerless inverters have gained over the last decade an increasing importance due to technical and economical advantages such as higher efficiency, lower weight, volume and costs. Modern PWM-techniques enable nowadays the suppression of undesirable components at the inverters output. However, when a positive-negative imbalance exists on the network voltage waveform (equivalent to even order harmonics in the voltage), the resulting distortion might affect the operation of PWM-controlled inverters.\(^7\) Such voltage distortions arise often from even harmonic currents injected by loads that exhibit asymmetrical i-u characteristics, which propagate through the distribution system impedances.

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\(^6\) The cause being the excitation current the inverters isolation transformers.

\(^7\) Especially in the cases where the synchronization of the inverters with the network voltage is done by taking as reference the zero-crossings of the voltage waveform.
Impact of DC currents on network equipment mainly concerns distribution transformers, Residual Current Devices (RCD), current transformers, energy meters, pipelines and metallic structures. Of these, critical effects are to be expected on RCDs (trips exceeding the nominal value due to the presence of DC currents) and distribution transformers (harmonic distortion, losses, heating and noise increases).

- **Theoretical evidences**

  Simulations done within a large European R&D project (DISPOWER, 2004) to quantify the amount of DC voltage that PWM inverters with different design topologies might generate under distorted voltage conditions (even order harmonics) reveal a direct relation between the level of DC-voltage component and a particular design parameter, the Modulation Frequency. PWM inverters can in principle eliminate DC-components by filtering the network voltage or increasing the Modulation Frequency.

Concerning the impact of DC currents on distribution transformers, there is still no international consensus on the maximum limits allowed. One study in the United Kingdom suggests an equivalent limit of 5% Total Harmonic Distortion for the phase current (Univ. of Strathclyde, 2005), or 40 mA per small-scale DG for a typical 500 kVA distribution transformer. In the United States a limit of 0.5% the nominal phase current has been proposed (NRECA, 2003).

- **Experimental evidences**

  No evidence has been found of DC-related disturbances in the network caused by PV systems, even when relatively concentrated in a geographical area.

Experimental tests carried out within a large R&D project (DISPOWER, 2004) on 12 state-of-the-art single-phase inverters representative of the European market (low-frequency transformer, high-frequency transformer and transformerless types) operating in realistic voltage conditions have shown that they do not produce relevant DC current components.

Concerning the impact of DC currents on network equipment:

- Distribution transformers. Laboratory tests done with 3-10 kW transformers in different Germany and Japan have shown that with DC currents equivalent to about 10% of the rated current, no problems such as overheating or hazard situations occurred (Hotopp, 1995; IEA-PVPVS-Task 5, 1998-99).

  Noise level increase due to DC currents is, however, the most limiting factor, both for relatively old (1970’s) and new (2005) transformers. A translation of this transformer immunity limit into emission limit for DG technologies has been proposed (DISPOWER, 2004):

    - Maximum DC injection: 0.5% of the transformer rated current, with an exception of small/micro distributed generation;
    - Maximum DC injection for small/micro distributed generation: 100 mA per unit.

    Taking into account existing design possibilities of inverter control to meet these levels, it

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8 Harmonic distortion typical of European public networks, as given by EN 61000-4-13 (class 2 for points of common coupling).

9 The three factors analysed being noise increase, the increase of current harmonic distortion and no-load losses.
can be concluded that the injection of DC current by inverter-based generators should not be a decisive limiting issue for the integration of Distributed Generation in distribution networks.

- Residual Current Devices (RCD). A distinction should be done between symmetrical and unsymmetrical DC currents, since only the second have noticeable effect on RCDs of types mostly used in electrical installations (AC and A). For this reason, RCDs of type B (all-current sensitive) should be used in connection with generators which could present DC residual currents, such as PV-DG (DISPOWER, 2004; Univ. of Strathclyde, 2005).
- Current measurement transformers. Same as distribution transformers (10% of rated current).
- Electricity meters. While new meters 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 (Univ. of Strathclyde, 2005).

3.4 Ground faults

Due to the electrical nature of PV systems and their particular location (exposed to outdoor meteorological conditions as well as to eventual faults coming from the distribution network or the electrical installation), insulation failures between current-carrying conductors and ground, known as ground faults, cannot be totally excluded during the systems lifetime.\(^\text{10}\)

System and equipment grounding are two complementary measures widely used in PV systems to provide safety. System grounds 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 safe (at or near ground potential). System and equipment grounding practices and requirements vary widely with applications and among different countries.\(^\text{11}\) In any case, with proper design and maintenance, both grounded and ungrounded PV systems can achieve good personnel, fire and equipment safety.

- Theoretical and experimental evidences

   Installed PV systems rarely perform exactly in the manner indicated by electrical schematics. Accumulative leakage currents associated with large PV arrays, long runs of wiring, surge protection, diodes, junction boxes that collect moisture, and conduits 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 (IEA-PVPVS-Task 5, 1998). Fortunately, the combination of adequate standards, better designs and components has given rise to more reliable PV systems in terms of safety. In this sense, it is worth noting the absence

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\(^\text{10}\) Even if good design practices are adopted, ground faults can develop within a PV array, in connection boxes, switches or inverters, due to components/materials damages or ageing, which are not replaced.

\(^\text{11}\) For example, PV systems over 50 V are system-grounded in the United States (one grounded current-carrying conductor), whereas Japanese and European codes require equipment grounding, but not system grounding (in fact, most PV systems do not have grounded current-carrying conductors).
of experimental references found about this impact, which could be seen as indicative of “no trouble” situations. However, with the increasing penetration of building-integrated PV systems using DC wiring circuits and inverters, ground-fault detection and PV array disable are still issues to look upon, given the particular interaction between the PV system, the building and building users, and the electricity network.

3.5 EMC – Capacity leakage of PV systems with transformerless inverters

Under normal operation of grid-connected PV systems capacities develop both on the DC and AC parts, which are related to the PV generator (PV modules and supporting structure capacitances to earth) and inverter (EMC filters used at the input and output sides which contain capacitors against the ground wire). When AC voltage components lie across these capacities, as it can be the case with transformerless inverters, leakage currents can flow over the ground (protective) wire, which normally should be free of current. If the leakage currents from several PV systems add up in the ground wire, in case of an error (interruption of the ground wire) a dangerous situation can arise if it is touched. Also, if the sum of the ground wire currents is too large Residual Current Devices might trigger.

- **Theoretical evidences**

  Theoretical simulations done under a German R&D project (SIDENA, 2005) on PV modules and generators connected to transformerless inverters have shown that due to their capacitive behaviour, voltage jumps appearing at the DC side (arising from the operation of the inverter) might cause relatively high leakage currents.

- **Experimental evidences**

  Concerning leakage currents on PV generators with transformerless inverters, experimental measurements carried out within two large R&D projects (DISPOWER, 2004; SIDENA, 2004) over several months (different weather conditions) showed the following results:

  - PV modules technology: glass-foil PV modules leakage currents were approximately 1.5 times higher than glass-glass PV modules when the PV generators were touched on the back side. Under front touch conditions no differences appeared. 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.

  - No apparent correlation could be found between the leakage current amount and meteorological variables such as solar irradiation, humidity, rainfall, atmospheric pressure or wind. Contact pressure and, above all, the inverter topology have the greatest influence on the amount and the curve form of the leakage currents.

  - During the tests, there were repeated undesired shut-downs from Residual Current Devices when a specific number of inverters were put in operation. Effective values of the ground wire currents measured on 11 single-phase transformerless inverters of different topologies at loads equivalent to human body resistance varied between 1 and 15 mA.

It was concluded that the problematic of ground wire currents should 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 limit values given by the standards, or they can represent a potential for danger if the ground wire is interrupted.
3.6 Contribution to short-circuit capacity

It is generally considered that PV generators connected to distribution networks do not contribute significantly to short-circuit faults, in case such events occur on the distribution system side. This is so because the short-circuit current of a PV array is 10-20% more than the rated maximum output current at most, inverters are normally equipped with under-voltage relays and current controlled types mainly used in PV-DG have over-current limiting in case of disturbances on the distribution system side.

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, the PV systems might be unable to detect a fault and supply a significant fraction of the fault current, reducing the one flowing through the substation and therefore hampering fault detection:

- If the value of short-circuit current exceeds the rupturing capacity of the over-current circuit breakers installed at the customers end, they may become incapable of clearing faults at the customers premises.
- For the distribution network, the change the short-circuit levels might cause overcurrent protection of the distribution system (fuse-breaker) miscoordination, excessive fault currents and nuisance fuse operation.
- Especially on the urban LV grid employing buried cables increased short circuit currents from inverters are desirable (at least in Germany) to achieve a fast fault clearance by blowing a fuse.

The coordination of the different protections —grid, PV-DG, customers— at different fault current levels is therefore a critical issue to guarantee short-circuit protection.

- Theoretical evidences

Theoretical analysis has been carried out in the U.S. to determine the mutual impact of Distribution Generators and power systems performance, with a primary focus on inverter-based devices (NREL, 2003). To that aim, simulations were done on a feeder typically encountered in MV distribution systems (13.2 kV) with a total DG capacity of 5 MW, the focus of the study being the fuse saving strategy used by many utilities. Single-phase and three-phase faults to ground were simulated both at the remote end and beginning of the feeder. In all cases the DG inverters had little impact on the overall fault contribution, and the main contribution was found to be predominantly from the grid. As a comparison, fault currents from induction machine loads of the same 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. However, the fault impact of DGs should be re-evaluated in case the DG controls were changed to accomplish other functions such as voltage support, or in weak lines. Similar conclusions were obtained in a study carried out in the United Kingdom (Halcrow, 2003).

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12 Faults occurring at the end of long distribution lines with a high resistances or line overload situations.

13 A fuse is to be sized so that its minimum melt time is longer than the total breaker fault clearing time. If the fault current increases due to DG contribution, its minimal melt time may be significantly shorter and it will no longer coordinate appropriately with the circuit breaker.
**Experimental evidences**

Experimental tests done in Japan with 4 current-controlled commercial inverters (different manufacturers) operating under short-circuit conditions occurring at a pole transformer showed that current contribution was less than twice the pre-fault one, with clearance times between 1-2 cycles. It was concluded that as long as current controlled inverter were considered, short-circuit current from PV inverters was negligible (IEA-PVPVS-Task 5, 1999).

In other tests carried out also in Japan in a 200 kW Test field for PV systems, when short-circuits were generated through high resistances and the voltage drop on the distribution line was minimal, that there were cases where the fault current passing through substations was reduced and the substation over-current relay defaulted (Kobayashi, 1990).

### 3.7 Power value, capacity value

The Power Value of an electricity generation plant is defined as the economic value of the power produced, given the plant location (distance to the loads) and its trend of production (match/mismatch conditions of the production with loads trends). The power value of PV-DG 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, quality of service and continuity of service improvements in peak hours, reduction of environmental impacts, 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 concept of interest is the “Effective load-carrying capacity” (ELCC), a direct probabilistic measure reflecting the ability of a power generator to effectively contribute to meet the existing load. The ELCC for a PV system represents therefore its ability to provide power to the utility when it is needed, that is, the capacity credit of the PV plant.

Traditionally, system operators view effective capacity as probabilistic measure and usually hesitate to rely on PV as a firm peaking capacity component. However, a critical test in support of PV 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 are the summer-peak, heat wave-driven events often characterized by rolling blackouts, which represent the highest possible stress on the grid when electrical demand approaches available generating supply at a time. The capacity value of PV generation can be greatly improved when complemented by:

- The availability of backup energy to make up for any deficit of PV to meet loads above a given threshold;

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14 In such situations, many power plants are on line but might be unable to supply regional demand or make power available locally through overburdened transmission and distribution systems. In addition, they are often exacerbated by the fact that most power plant efficiencies drop with high temperatures, and extreme conditions increase the wear and tear, hence the probability of failure of plants, transmission and distribution systems.
Demand Side Management. For example, mitigation of air conditioning use by means of Solar Load Controllers\(^\text{15}\) can be particularly useful 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-DG).

It is expected that with new electricity trading arrangements being implemented in several countries, the prices of unpredictable DG (such as wind and solar) will decrease, which could create a dynamic market for power services from DG technologies.

- **Theoretical evidences**

  Several theoretical studies have been done 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:
  - PV effective capacity. Analysis of over 200 load-years of the late 80’s and early 90’s from 45 utilities and substations all over the U.S. have shown that for a level of 2% PV grid penetration, the ELCC peaks at 60-70% in the Mid-Atlantic region (the one showing the best match between generation and load demand) (Perez, 2001).

    Analysis of more recent load data (1997-99) for the New York City metropolitan and Long Island areas provided similar results. For PV penetration levels between 1–15% simulated on hourly basis using high-resolution satellite cloud cover data, the ELCC for PV generation ranges were 40-70%.

    Also in this case it was found that buffer energy storage (charged for example by the PV generators) of only a fraction of an hour’s worth of PV output would lead to a 100% effective capacity for PV. For instance, at 5% PV penetration in New York City, it would take less than 1 system-hour worth of storage for fixed PV systems to guarantee that all loads above 95% of the peak were met.

    Concerning the use of Demand Side Management combined with PV generation (Solar Load Controllers mitigation of air-conditioning to cover critical deficits), calculations done for New York City and 10% of PV penetration showed that it would have taken only 4.5 °C-hours of user discomfort on the worse day to have met all loads above 90% of the City’s peak with PV systems. Without PV the figure would have been 19 °C-hours, representing a considerably stronger end-use discomfort. For the entire season, the total degree-hour end-use offset would have only been 8 °C-hours to guarantee a 100% PV capacity (8 times more without PV).

  - Power value. In 2000, major heat waves affected the western part of the U.S. 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 show that in all cases, PV output on the day of the outage would have been within 80% of its maximum (Perez, 2004).

    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), it was found that with 5% installed PV capacity, all 5% top loads would have been met, either by PV+storage or by PV+solar-load-control.

- **Experimental evidences**

\(^{15}\) PV-smart thermostats that logically modify user-set temperatures as a function of load and insolation conditions; they are designed primarily to maximize user-sited PV demand reduction.
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 an Energy Management System with a 700 kW peaking facility HVAC installation (Perez, 2000).

- Based on experiments done in half of the building, the total impact of the SLC on the reduction of HVAC load was estimated to be 4% of peak capacity per °C offset modified by the SLC device. The analysis of a full month billing cycle (July, with 3 heat waves) showed that a total SLC action of 2.4 °C-hours would have been sufficient to make up for all the critical deficit of the PV array; 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 window unit (1500 W). With a simulated PV generator of installed capacity being 10% of peak load, analysis of a full month (with 3 heat waves) showed that a maximum SLC offset of 4.5 °C guaranteed a peak load reduction of 21% to the Air Conditioning unit.

To further illustrate the potential of the SLC, the case of the New York City was analysed, where each °C of cooling requirement adds 350 MW to the load. An end-use load control based on a maximum SLC action of 3 °C 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.

### 3.8 Unintentional islanding

The topic of “unintentional islanding” where a part of the network can be unintentionally maintained live by local generation when the primary network is disconnected, has received attention from both the PV and electricity industries over a number of years. 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. As it is well known, for an island to occur there has to be a 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. This phenomenon has been analysed to date using the ‘fault tree’ methodology of Risk Standard (IEC 61508, 1998).

Most countries have adopted their own recommendations/ standards for anti-islanding measures (IEA-PVPVS-Task 5, 2002b; DISPOWER, 2006) and are implementing these on their networks. Most national requirements specify “type testing” of sample inverters on a “resonant” test circuit designed to simulate the situation of a dense population of inverters. This is typically a functional test, with the methods used in the inverters to achieve a pass usually being left open. These recommendations and national requirements are now being harmonised as far as possible into international and European standards (Draft IEC 62116 for the anti-islanding test circuit, and Draft CENELEC prEN 50438 on the settings required in the various countries). 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.

- **Theoretical and experimental evidences**

Several theoretical and experimental studies have been carried out on the topic of unintentional islanding from PV-DG.
An Islanding analysis based on the ‘fault tree’ methodology of Risk Standard found that the risk of electric shock associated with islanding of PV systems under worst-case PV penetration scenarios (PV rating reaching approximately six times the minimum night-time load, or 2/3 of the After-Diversity-Maximum-Demand) to both network operators and customers was very low, typically $<10^{-9}$ per year (IEA-PVPVS-Task 5, 2002c). Thus, the additional risk presented by islanding did not materially increase the risk that already existed as long as the risk was managed properly, which means, amongst others, that appropriate anti-islanding schemes were included in the inverters.

Another theoretical study based on experimental measurements done within the IEA-PVPS in 2002 (IEA-PVPVS-Task 5, 2002c) found that the probability of ‘balanced’ conditions for islanding in a typical low voltage Dutch residential area was very low (well below $10^{-6}$ to $10^{-5}$). The probability of encountering an island was therefore virtually zero, so that Islanding was not considered a technical barrier for the large-scale deployment of PV system in residential areas.

The DISPOWER project (DISPOWER, 2006) analyzed also experimentally an 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 both residential and public buildings. Most relevant results were the following:

- Concerning PV penetration levels, it was found that the ratio between the actual load and the generation had a fundamental influence on the probability for balanced conditions: at levels below 0.5 the probability tends to approach zero, with the maximum occurring at penetration levels between 1 and 2.
- With the PV inverters operating at unity or lagging power factor and no other reactive power supply present, balanced conditions never occur. However, in a future situation where inverters could provide reactive power for network support, the probability of balanced conditions would increase. This fact leads to the conclusion that the additional ‘Loss of Mains’ function already specified by most countries in addition to voltage and frequency threshold ‘windows’ is to be recommended.

Also within the DISPOWER project (DISPOWER, 2006) experimental tests were done in state-of-the-art inverters designed for the German market, mostly equipped with a grid impedance measurement facility for the detection of islanding, together with grid voltage and frequency monitoring. The results indicated that while the protection systems worked well under normal grid conditions with rather low impedance, less ideal conditions (higher grid impedances) lead to problems for the devices. This issue is currently not satisfactorily addressed in the according standards which define the requirements for protection systems.

As a general conclusion by the DISPOWER project, it is considered that when taking into account the proposed 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.

### 3.9 Added value capabilities of modern inverters

- **Active power quality improvement**

  Modern PV inverter technology allows multifunctional operation: in addition to feeding PV power into the public grid, a modern inverter can act as active filter for harmonic distortions to improve grid power quality, *i.e.* effectively reduce grid voltage harmonics. There are

- **Power factor regulation, reactive power control and voltage level control**

  When an inverter is equipped with energy storage (which may be relatively small, such as a capacitor) and with an adequate control system, it is possible to actively control the inverter in such a way that, in addition to delivering active power, reactive power is produced or absorbed at its grid interface. The inverter can thus compensate excess or lack of reactive power in the grid, and thus also contribute to voltage control. This might, for example, pay off in case of large PV systems, where grid interconnection tariffs cover active power (VA) and reactive power (VAR): the inverter can be used to optimize reactive power at the point of grid connection. Also, when grid voltage level becomes critically high, reactive power control may be an option to continue delivering active power while avoiding further increase of line voltage at the same time. (Schmitt 2007, Nietsch 2007, Kremer 2006, Degner 2006, Wakao 2005)

![Figure 5. Dynamic power factor correction: provision or compensation of reactive power (Kremer 2006)](image)

- **Phase symmetry control by purposefully asymmetric phase currents**

  When a three-phase inverter is equipped with energy storage (which may have a small capacity, such as a capacitor) and with an adequate control system, it is possible to actively control the inverter in such a way that, in addition to delivering active power, actively improves grid power quality by equalization of the three grid phase voltages with respect to each other: purposefully delivered asymmetric phase currents result in a residual current through the neutral conductor. (Nietsch 2007, Kremer 2006)
Figure 6. Dynamic phase correction for equalization (symmetry) of the three voltage vectors (Kremer 2006)

- **Grid stabilization and operation as uninterruptible power supply (UPS)**

  It would be desirable that irradiated solar energy keeps being made available by the PV system in case of grid deterioration or failure, rather than simply shutting off. This requires merging technology approaches for grid-connected and stand-alone systems. When an inverter is equipped with an energy storage (which needs to have some energy buffering capacity in proportion to the energy requirements, such as a storage battery), and with an adequate control system, possibly in coordination with local energy management, it is possible to actively control the inverter in such a way that it can:
  
  - Contribute to grid voltage, frequency and power quality stabilization;
  - Contribute to local controlled islanding operation (UPS for selected loads);
  - Act as an UPS for selected loads such as essential computer systems;
  - Continue operation of specific applications such as water pumping (where a reservoir can be seen as storage for pumped water — hence, applied energy).

  Market potentials definitely exist for such technologies, especially in industrial context and in countries with unreliable public grids and emerging economies, where frequent brownouts or blackouts impair business severely, and lead to increased system downtime of pure grid-connected PV systems. In such regions, coping with recurrent grid failures and considerable fluctuations in grid voltage and frequency is a major issue to be tackled. (Jahn 2007, Vandenberg 2006, Dutta 2005, Omari 2005, Schmid 2001)
Participation in distributed grid-forming or grid-supporting modes of operation

Active integration of decentralized PV systems into conventional electric grids may involve the distributed inverters into the overall management, control and formation of the grid. Local storage capacitors or batteries, added to grid-connected PV systems, would enable the PV inverter to participate in grid-forming or grid-supporting modes of operation, which may even include contributions to fault clearing capacity, i.e. to get the grid up again after a blackout. With a view on this, the abstract generic functionalities (e.g. control of voltage and frequency, balancing of active and reactive power) which are required in a grid, as well as various options for their allocation (e.g. centrally or decentrally) and implementation (e.g. rotating machines, solid state converters) can be reassessed in order to restructure the overall approach, to accommodate very high and growing levels of renewable (stochastic) and distributed energy generation and consumption, part of which may be remotely and decentrally controlled. (Vandenburg 2006, Dutta 2005, Omari 2005, Koeln 2005, Schmid 2001)
3.10 Impact on grid design and operation

- **Grid capacity, structure and control**

  The electricity network structure and control is expected to be completely reshaped within the next thirty years. The distribution grids need to get ready for drastic increase of dispersed energy generation, and corresponding reductions in central generation. This involves radical overhauling of grid design and dimensioning, as well as its operation and control. As half of the electrical energy consumed is tapped from low voltage distribution grids, the evolution and optimization of these grids, in the wake of massively rising fractions of dispersed generation, is a crucial issue. For example, grid control and safety approaches need to be made fit for downstream as well as upstream energy flows, resulting from central and dispersed points of generation. Distributed management and control of grid interfaces, generation and consumption can evolve into major mainstays — and even a bedrock — of grid formation, control, stability, and resilience. In this scenario, dispersed generation and control will eventually take over these roles entirely from conventional and outdated central power stations and control systems. There is definitely a need to review and, where appropriate, to alter and
adapt the structures and procedures which are active nowadays. (Nietsch 2007, Kitzing 2006, Kurokawa 2005, Koeln 2005, Bendel 2005)

![Figure 9. Expansion of grid capacity for distributed generation (Nietsch 2007)](image)

- **New basic approaches towards grid operation and control**

On our way towards predominantly renewably supplied energy demands, our entire energy infrastructure will have to undergo metamorphosis and transformation. In the long term perspective, increasingly decentralized patterns of production and consumption call for novel and decentralized —but integral, systemically all-embracing— approaches to energy and power management in production, transmission, storage, and consumption of energy. Such approaches need to be developed and tested. Many views, concepts, bits and pieces, which already exist, need to be combined into a big picture that points the way forward. Approaches are required for economic assessment (cost models) and optimization (algorithms), and for true grid integration of decentralized power devices (technology). (Omari 2005, Koeln 2005, Erge 2005)

![Figure 10. Distributed generation in distribution grid systems (Erge 2005)](image)
- **Distributed devices combined into “Virtual power plants”**

  Increasing penetration of the distribution grid with dispersed generators increases the demand and opportunities for active energy and operations management. Stochastic and controllable generation units can be aggregated into “virtual power plants”, which in turn can be integrated into the existing structures for control of generation and transmission. (Kitzing 2006)

  ![Figure 11. Virtual power plant concept for integration of control, including distributed generation (Kitzing 2006)](image)

- **Grid costs distribution models need review and update to accommodate dispersed generation**

  The cost of distribution grid operation is almost entirely fix cost, with a virtually negligible utilization dependent fraction. When all users become potential producers, the conventional grid cost distribution model is increasingly inadequate and needs reconsideration. Also, there is a paradigm clash between (a) the general pressure towards liberalization and unbundling on one side, and (b) a protected and subsidized renewable energy market segment on the other hand. Quality and availability is endangered by cost reduction pressure. With a view on the long time period required for investment and buildup, a Europe-wide energy concept, —and its assertion in the face of liberalization, privatization and cost pressure— is overdue. (Lewald 2004)

- **Variable tariffs for optimized distributed control of generation and consumption**

  Variable tariffs, e.g. updated every minute according to the current balance of energy availability and demand, can be used as a tool for overall optimized distributed control of generation, storage, and consumption. Technically, fluctuations of the grid frequency within a narrow band could be allowed to represent such a tariff, as grid frequency naturally responds to the balance of energy generation and demand, and is directly available everywhere as a carrier of information, without need for further information infrastructure. The entire philosophy of grid structure and operation is worth to be reconsidered and changed in order to accommodate massively increasing fractions of renewable (stochastic) energy generation. (Koeln 2005, Schmid 2001)
Figure 12. Strategy for the development of variable electricity prices in the “Mini-Grid-Kit” project (Schmid 2001)
4 Impacts of Distribution networks on PV-Distributed Generation

In this section, the impacts of Distribution networks on PV Distributed Generators are described; these are relatively frequent events that can affect negatively the operation of PV-DG in quantitative terms (final yield, useful output) as well as qualitatively (power quality).

4.1 Voltage dips

Voltage dips (or sags) in electrical systems are defined as sudden reductions of the voltage followed by a voltage recovery after a short period of time, ranging from a few cycles to a few seconds. They are generally characterized by their magnitude and duration\(^{16}\); other influencing parameters are the point of the voltage waveform where the dip initiates/finishes, and the phase angle jump occurring when the dip occurs. 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.

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 rather complex phenomena to be accepted as an intrinsic feature of public electricity supply systems. 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, they might 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 could adversely affect the stability of the network in case of sudden 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).

- **Theoretical evidences**

Simulations have been done within a large European R&D project (DISPOWER, 2005) in a weak network scenario (island with average annual load of 600 kW and strong seasonal fluctuations) with several renewable resources (PV and wind, distributed), conventional diesel generators and batteries.

One of the scenarios considered involved the installation of 10 identical PV systems distributed across the grid, with a total installed power of 1.3 MWp. Stability of the network was analyzed by investigating the effects of PV-DG on the grid transient behaviour. In particular, the

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\(^{16}\) The majority of voltage dips have a magnitude of about 80 % of nominal voltage and duration of 4 to 10 cycles.
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 behaviour provided that sufficient spinning reserve existed, provided by the existing diesel generators.

Due to the high cost of the energy produced by the diesel generators, further simulations were carried out with the PV inverters showing disturbance ride-through capability\textsuperscript{17}. Results indicated that, in this way, it should be possible to operate the power system with a lower spinning reserve without any safety risk.

- \textbf{Experimental evidences}

Experimental tests have been carried out within a large R&D project (DISPOWER, 2004) on 12 state-of-the-art single-phase inverters representative of the European market (low-frequency transformer, high-frequency transformer and transformerless types) operating under different voltage dips. Most inverters appeared to be very sensitive, with under-voltage protection trip being the most common disconnection cause. Also relevant was the high sensitivity to relatively small phase angle jumps (only 5º)\textsuperscript{18} that were interpreted as frequency deviations. Ride-through capability against voltage dips was shown only by 25% of the units, designed with quick current control loops. Regarding the effects of voltage dips in the inverters, a large number of them showed current peaks at voltage recovery; stability of the current control loop was also affected in some cases.

Most inverters exhibit weaknesses and flaws in their dynamic behaviour, being exceedingly sensitive to, and easily derailed by, grid disturbances such as voltage dips and surges or superimposed sinusoidal signals of other frequency (e.g. remote control signals). Required improvements include:

- Dynamic input voltage (DC side) control including accuracy and speed of maximum power point tracking (MPPT) recovery from deviations (caused by irradiation swing or AC current irregularities).
- Dynamic output current (AC side) control including efficient and robust response to abnormal grid conditions (e.g. fluctuations in grid voltage level and waveform, grid voltage sags or surges, short interruptions and automatic re-closure).
- Robust ride-through capabilities and quick fault recovery.
- No emission but rather active compensation of harmonics.
- Efficient overload and over-temperature behaviour.

Very few inverters, however, show excellent behaviour. But they demonstrate the proof of technological feasibility of high immunity and robustness without major additional cost. (Bründlinger 2006, Bletterie 2005, Bletterie 2004-2)

\textsuperscript{17} Disturbance ride-through capability means, among other things, that the inverter grid interface should stay connected during the disturbance or be reconnected quickly after the disturbance is cleared.

\textsuperscript{18} Phase angle jumps of up to 60º can be found in voltage dips; dips originated in distribution networks have generally larger phase angle jumps as those originated in transmission networks.
As a conclusion, it was stated that PV inverters do not have a simple behaviour under-voltage dips, their “voltage tolerance characteristic” curves being rather different from those of general electric equipment. High sensitivity to voltage dips can have a negative effect on the inverters (and PV plants) performance, components lifetime (induced stress) and, ultimately, the network. Implementation of the mains monitoring is seen to be determinant in the inverters sensitivity to voltage dips.
Experimental tests were also carried out in a 200 kW Test field for Photovoltaic systems in Japan, where different voltage dips were created on distribution lines (IEA-PVPVS-Task 5, 1999). During those events, inverters of the current control type continued stable operation without generating over-currents; voltage control type inverters, on the contrary, generated over-currents and operation was interrupted by the over-current relays.

Measurements done 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 problems regarding the reliable operation of the plant but furthermore also be a source of power quality disturbances in the network (Bletterie, 2004).

4.2 Voltage swells

Voltage swells in electrical systems are temporary increases of the voltage above a threshold, typically 1.1 times the nominal value. They 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.

- **Experimental evidences**

  Experimental tests have been carried out within a large R&D project (DISPOWER, 2004) on 12 state-of-the-art single-phase inverters representative of the European market (low-frequency transformer, high-frequency transformer and transformerless types) operating under voltage swells. Inverters proved to be very sensitive to these events; 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 relatively small voltage swells (whereas it was not the case with voltage dips).

4.3 Short-circuits in electrical installations

Short-circuits in electrical installations represent a severe stress situation for equipment connected to the same branch where the fault has happened. A particular threat exists if the short-circuit is interrupted by a branch fuse or circuit breaker; in that 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 fault by the protective element.

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.

- **Theoretical evidences**
The consequences of short-circuits for active elements of Distributed Generation systems such as inverters are:

- The voltage dip following the short-circuit results in a fast voltage variation and large associated over-current, 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.

- Fast interruption of the short-circuit current will make the energy stored in the inductive part of the network impedance to be released and dissipated in capacitances. The resulting voltage transient will be also seen by the inverter and therefore might cause stress on the electronic components of the output circuit.

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

- **Experimental evidences**

  Experimental tests have been carried out within a large R&D project (DISPOWER, 2004) on 8 state-of-the-art single-phase inverters representative of the European market (low-frequency transformer, high-frequency transformer and transformerless types) operated under different inductive grid impedances and exposed to output voltage transients equivalent to those of quick fuses (worst case). Measured over-current values were up to 20 times the nominal output, which in some cases created severe stress for the components carrying those currents and led to device defects. Concerning the internal over-voltage protection of the inverters, although with the usual protections were limited up to 2.5 times the peak amplitude of the nominal grid voltage, at low limitation-voltages high energies had to be absorbed and high over-currents resulted.

  Analysis of the inverter defects in the experiment reveal that in practise there are still problems regarding the proper implementation of the protection against short-circuits, with some important factors being:

  - 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 event.

  - 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). Also, special care has to be taken to ensure that the over-voltage protection is working during all operating conditions (also at night time).

In general, it was stated that highly sophisticated protective designs do not seem to be necessary for DG components used in residential applications. However, in special cases and especially under rough operation environments, additional external protection might become necessary.

4.4 *Superimposed harmonics and interharmonics on the grid voltage*

The grid voltages in public supply systems are never pure sinewaves. 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 are sinusoidal voltages or currents having frequencies that are integer multiples of the frequency at which the supply system is designed to operate (termed the fundamental component)\(^\text{19}\);
- Interharmonics 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.

The main sources of harmonics existing in the networks are nonlinear loads present in the MV and LV levels. 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. Also, linear loads might 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.\(^\text{20}\)

Concerning interharmonics in the networks, they are typically created whenever there is an amplitude modulation of load current (e.g. transient changes in operating conditions of loads), or where transformers are subject to saturation.

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 voltage variations and flicker, thermal effects on transformers, increased losses in rotating generators and motors, disturbances in electronic equipment and protection systems, interference with communication systems (telephone, control and data transmission signals), stress on insulation materials, transformer saturation and system resonances. Regarding the impact of harmonics on electricity meters there is one reported case where electricity meters have been burned, allegedly due to harmonics from PV inverters (Spain, medium voltage (MV) grid level). (Caamano 2006)

- **Theoretical evidences**

  DG inverters are potentially sensitive to voltage disturbances (harmonics and interharmonics), particularly the following components:

  - 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.

\(^{19}\) Typically 50 or 60 Hz.

\(^{20}\) Harmonic current distortion levels above 100% occur often for single phase loads, but harmonic voltage distortion above 8% is very unlikely.
Experimental evidences

Experimental tests have been carried out within a large R&D project (DISPOWER, 2004) on 12 state-of-the-art single-phase inverters representative of the European market with different design concepts (low-frequency transformer, high-frequency transformer and transformerless types) operating at pre-defined levels of voltage distortion. Main results were the following:

- Inverters were relatively insensitive towards harmonics present on the grid voltage. However, specific harmonics could induce over-currents that might cause unintended tripping of their internal over-current protection. The implementation of the AC current control strategy has a major influence on the behaviour of the inverter in terms of power quality (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 current distortion. Interestingly, one inverter even partially compensated the voltage distortion (active filter behaviour); in other cases no compensation occurred. As a general trend, the inverters with very low/low current distortion under normal conditions were only slightly influenced by the high levels of voltage distortion. There were also 2 cases where the devices were highly influenced by superposed interharmonics in the 100-1000 Hz range.

- Superposed interharmonics at levels of the mains signalling used in many European countries (the so-called “Meister Curve”) created severe troubles for the large majority of the tested inverters.

- Adequate implementation of the grid monitoring is critical to achieve a high level of immunity against interharmonics. Frequency measurement schemes working on a period-by-period base appear to be very sensitive to interharmonic components on the grid voltage. On the contrary, too narrow frequency limits leading to frequent disconnections are counterproductive to achieve high immunity levels.

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21 Tests were based on European standards dealing with harmonics and interharmonics (EN 61000-4-13), for electromagnetic environments applicable to Points of Common Coupling. Also, tests were conducted to evaluate the impact of different types of mains signalling used in many European countries.

22 The most critical components influenced by the disturbances being the frequency and impedance measurements of the grid monitoring unit.
5 Standardization, research and development needs

This section summarises the standardization, research and development needs identified in the literature survey to overcome the still existing technical barriers, as well as to increase the values of PV Distributed Generation leading to a higher penetration of PV electricity in distribution networks.

The following tables summarise, respectively, the standardization, R&D needs for the impacts summarised in sections 2 and 3. In all cases the time-frame for addressing the specific need (short, medium or long term) is identified.
**IMPACT** | **STANDARDIZATION NEEDS (time-frame)**
--- | ---
*PV-DG on Distribution networks* | 
**Voltage rise, Voltage fluctuations** | 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. (Short / medium term) 
**Current harmonics** | 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. (Short term)
**DC from inverters** | PWM inverters may in principle generate symmetrical DC currents during normal operation in the presence of even harmonics in the grid voltage. This point should be addressed in future standardization activities, where meaningful limits should be adopted; too severe limits resulting in unjustified constraints for equipment manufacturers (technical barriers) should be avoided. (Short term)
**Ground faults** | Current standards dealing with PV systems installed in buildings do not address completely fault protection by automatic disconnection of supply on the DC side of systems. The existence of many PV systems in buildings nowadays, and the growing penetration of PV-DG worldwide brings the necessity to address this topic. (Short / medium term)
**Capacity leakage of PV with transformerless inverters** | Design of transformerless inverters for PV systems should pay close attention to the potential leakage currents. Product standards for transformerless inverters should consider limit values for the DC capacity, since AC voltages with a large harmonic content across earth are often injected into their DC side. (Short term)
**Contribution to short-circuit capacity** | In order to prepare the markets for a higher penetration of DG technologies, specific standards for inverters should be developed covering, amongst others, limits for short-circuit current contribution. (Short / Medium term)
**Power value, Capacity value** | For PV systems to contribute with effective capacity to distribution networks, standards should be developed which establish the associated minimum technical requirements and constraints. (Medium / long term)
Unintentional islanding

Although two recent standards have been approved concerning the anti-islanding test circuit for PV inverters and the settings required in the various countries, there is still widespread discrepancy concerning interconnection practices, protection systems and the probability of occurrence and persistence of distributed resource islands. It is advisable that future revisions of those standards enable a consistent policy amongst network operators, as well as consensus with their customers, developers and operators of DG. (Medium / long term)

Added value capabilities of modern inverters: islanding management

Although, up to now, islanding operation is considered to be avoided at all cost, it has been demonstrated that live islanding management, with smooth disconnect and reconnect and remote management of DG devices via frequency is possible. The fact that inverters can be designed to smoothly change between grid-connected and stand-alone operation mode will have to be reflected in corresponding rules and standards. (Medium / long term)

* Distribution networks on PV-DG

| **Voltage dips** | Future technical requirements for the interconnection of DG technologies should consider immunity issues in order to 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. (Short / medium term) |
| **Voltage swells** | Future technical requirements for the interconnection of DG technologies should consider immunity issues in order to positively contribute to safety and quality goals without imposing significant additional constraints on DG equipment. Current standards of inverters lack detailed requirements of decoupling protection against voltage swells. (Short / medium term) |
| **Short-circuits in electrical installations** | Specific standards for PV inverters should include testing under realistic short-circuit conditions on the AC side. (Short / medium term) |
| **Harmonics and Interharmonics on the grid voltage** | Current immunity standards seem to be adequate for grid-connected inverters. However, for DG to play a fundamental role in future distribution networks, the desired behaviour of inverters during network disturbances should be standardized. (Medium / long term) 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 should be developed to guarantee quality of performance and proper integration in the networks. (Short / medium term) |

Table III. Standardization needs on the mutual impacts of PV Distributed Generation and Distribution networks
<table>
<thead>
<tr>
<th>IMPACT</th>
<th>RESEARCH &amp; DEVELOPMENT NEEDS (time-frame)</th>
</tr>
</thead>
<tbody>
<tr>
<td>* PV-DG on Distribution networks</td>
<td>* Voltage rise, Voltage fluctuations: More studies and measurements are needed on the effect of wide-spread 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. (Short / medium term)&lt;br&gt;Multiple generator modelling studies are also considered necessary, in order to identify and correct eventual problems arising from the operation of small multiple generators. (Short / medium term)&lt;br&gt;Also, R&amp;D on new voltage control techniques are necessary, which enable to maintain network voltage control with Distributed Generation technologies. (Short / medium term)&lt;br&gt;&lt;br&gt;Current harmonics: Although inverters may individually comply with existing standards, cumulative effect of harmonics when multiple inverters operate simultaneously is difficult to predict (many influencing factors, both of the inverter and the network). Although some work in this field has been done (see list of publications), more research on the understanding of harmonics is needed in this respect, as well as measurements on real projects. (Short / medium term)&lt;br&gt;&lt;br&gt;DC from inverters: State-of-the-art inverters without galvanic separation and with appropriate control designs are able to regulate the DC component, even in distorted grids. No specific R&amp;D needs on this subject are identified, except improvement of control techniques for operation in highly distorted electrical environments. (Short / medium term)&lt;br&gt;Although not specifically related with PV inverters, further experimental research (testing) is necessary on the effects of DC currents on the networks (transformers, RCDs, electronic and electromechanical energy meters). The same applies to DC components coming from small appliances (lighting ballasts, switched mode power supplies, Class D devices – e.g. mobile phone chargers –, etc.). (Short / medium term)</td>
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<tr>
<td>IMPACT</td>
<td>RESEARCH &amp; DEVELOPMENT NEEDS</td>
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<tr>
<td>Ground faults</td>
<td>Measurements of ground faults currents in grid-connected PV systems (especially if installed in buildings or public spaces) 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. (Short / medium / long term)</td>
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<tr>
<td>Capacity leakage of PV with transformerless inverters</td>
<td>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. (Short / medium term)</td>
</tr>
<tr>
<td>Contribution to short-circuit capacity</td>
<td>Effective means of limiting short-circuit current contribution by voltage-control type inverters. (Short / medium term)</td>
</tr>
<tr>
<td>Power value, Capacity value</td>
<td>Further R&amp;D is needed on the capacity of PV systems to contribute to the grid capacity through added-value benefits such as uninterruptible power supply and backup power. The potential of this combination can be particularly interesting in industrial environments and locations with unreliable or weak grids, where frequent brownouts or blackouts occur. (Short / medium / long term)</td>
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<td></td>
<td>Demand Side Management functionalities such as those provided by Distributed Intelligent Load Controllers and DG technologies (for example, PV in urban areas), and their integration into central network operation strategies. (Short / medium / long term)</td>
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<tr>
<td>Unintentional islanding</td>
<td>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. In particular:</td>
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<td>- R&amp;D support to standardisation committees IEC 62116 &amp; CENELEC prEN 50438 (Short term)</td>
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<td></td>
<td>- Monitoring of ‘islanding’ conditions logged on real networks (Medium term)</td>
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<td></td>
<td>- Review of methods as networks become more ‘actively’ managed, and as maintenance practices change, to check that they are still appropriate (Long term)</td>
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<tr>
<td>Impact on grid design and operation</td>
<td>For future (30 years from now) electricity distribution networks to incorporate large fractions of DG, profound changes should be done in grid design, dimensioning, operation and control. There is a need to review and, where appropriate, to alter and adapt structures and procedures which are used nowadays. New approaches are also required for economic assessment (cost models, variable tariffs), optimization (algorithms), and for true grid integration of decentralised power systems (technology). The addition of stochastic and controllable generation units into “virtual power plants” has already demonstrated; however further R&amp;D is</td>
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**Table IV.  Research and Development needs on the mutual impacts of PV Distributed Generation and Distribution networks**

<table>
<thead>
<tr>
<th>IMPACT</th>
<th>RESEARCH &amp; DEVELOPMENT NEEDS (time-frame)</th>
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<tbody>
<tr>
<td>** Distribution networks on PV-DG**</td>
<td></td>
</tr>
<tr>
<td>Voltage dips</td>
<td>Adequate and realistic immunity requirements for inverters against voltage dips. (Short / medium / long term)</td>
</tr>
<tr>
<td>Voltage swells</td>
<td>Adequate and realistic immunity requirements for inverters against voltage swells. (Short / medium / long term)</td>
</tr>
<tr>
<td>Short-circuits in electrical installations</td>
<td>Inverters should increase their reliability against short-circuits on the AC side, phenomena that cannot be excluded in electrical installations. This is especially important for inverters operating under rough electrical environments, where additional protections might become necessary. (Short / medium / long term)</td>
</tr>
<tr>
<td>Harmonics and Interharmonics on the grid voltage</td>
<td>Harmonic and interharmonics superposed on the grid voltage are usually not properly considered during the design phase of inverters. A high level of robustness against these phenomena is however very important, given their increasing presence in electricity networks. (Short term)</td>
</tr>
</tbody>
</table>
6 Summary and conclusions

In general, from the present experience of two of the European countries with more PV systems connected to distribution networks (Germany and the Netherlands), it can be concluded that the present inverters perform reasonably well, and that application EU-wide should not really be a problem. Uniform specifications (for example, simple islanding detecting and uniform connectors) would lower the costs. Proper design of the LV-grid and future demand side management, preferably with storage (with advanced batteries such as Li-ion type) would allow for a high economical value and avoid most of the technical problems identified so far.

In particular, after the extensive literature review done on the mutual technical impacts of PV Distributed Generation and Distribution Networks, the following conclusions can be drawn:

IMPACTS OF PV-DISTRIBUTED GENERATION ON DISTRIBUTION NETWORKS:

- **Voltage rise and voltage fluctuations**
  
  There are several solutions to cope with the voltage rise concern of distribution companies when considering the interconnection of PV grid connected systems. Some imply behavioural changes in inverters (effective power limitation, voltage regulation function) when voltage rises reach pre-defined over-voltage levels. More general solutions can be applied within maintenance schemes of the distribution networks (e.g. adapt the transformers to the expected periods of load demand so that overvoltages by PV-DG can be virtually excluded) or at the planning stage (by limiting the amount of DG allowed at each customer or transformer site). In this context, it is crucial to mention the advantages of load management and control as an effective strategy for mitigating voltage rise and facilitating the penetration of DG technologies in distribution grids (and therefore PV), especially under tarification schemes with different buying and selling prices of electricity.

  Concerning voltage fluctuations, although the evidences found have shown its relatively low importance (slow speed of output changes, with total fluctuation largely decreased and levelled-off compared with individual fluctuations), under high penetration levels of PV-DG it may become an issue requiring countermeasures to maintain adequate voltage levels.

- **Current harmonics**
  
  Up to now, inverters to be used in grid-connected PV systems (or by any other DG technology) have no specific product standard related to current harmonics emissions, with generic standard for electrical equipment (only for rated currents up to 16 A per phase) being generally applied. It is of utmost importance to develop specific product standards for inverters of different sizes (powers).

  Experiences have shown that although inverters generally comply individually with applicable standards, their multiple operation (interaction) may have undesirable effects under specific conditions. In particular, depending on the nature of the inverter control and the strength of the grid, low order harmonics may superimpose (especially in weak grids), so that the harmonic distortion tend to increase as the number of inverters increases. Harmonics are however very complex phenomena, and their presence in electricity networks is to be mainly related to the increasing presence of non-linear loads.

- **DC from inverters**
State-of-the-art inverters representative of the European market operating in realistic voltage conditions have shown that they do not produce relevant DC current components. Even under adverse network conditions (positive-negative imbalance on the voltage waveform, equivalent to even order harmonics), modern design possibilities enable the suppression of DC-components on the inverters output. Therefore, it can be concluded that the injection of DC current by inverter-based generators should not be a limiting issue for the integration of PV-DG in distribution networks.

- **Ground faults**

Although in PV grid-connected systems, due to their electrical nature and their particular location, insulation failures between current-carrying conductors and ground (ground faults) cannot be totally excluded during their lifetime, the combination of adequate standards, good designs and components and good maintenance schemes can result to reliable PV systems in terms of safety.

Notwithstanding this, the increasing integration of PV-DG in buildings, ground-fault detection and elimination are still issues to look upon, given the particular interaction between the PV system, the building and building users, and the electricity network.

- **Capacity leakage of PV systems with transformerless inverters**

Due to the presence of parasitic capacities on the DC and AC parts of PV systems, leakage currents can flow over the ground (protective) wire of the systems, which may cause undesirable situations for personnel safety or unintended trigger of protection devices. Of the different influencing factors, contact pressure (in case of PV generator touch) and, above all, the inverter topology have the greatest influence on the amount and the shape of the leakage currents.

From the theoretical and experimental evidences found of leakage currents in PV systems with transformerless inverters, it can be concluded that the problematic of ground wire currents should be kept in mind when PV systems with many inverters are planned, since the currents can add up to values that can exceed the limit values given by the standards, or they can represent a potential for danger if the ground wire is interrupted.

- **Contribution to short-circuit capacity**

Although it is generally considered that PV generators connected to distribution networks do not contribute significantly to short-circuit faults when such events occur on the distribution system side, a concern exists that under high penetration of PV-DG and particular fault conditions (faults occurring at the end of long distribution lines with a high resistance), the PV systems might supply a significant fraction of the fault current and therefore hamper fault detection by existing protections (distribution network, customers).

Theoretical analysis and experimental tests lead to conclude that there is ample precedent for considering modern current-controlled inverters as insignificant short-circuit current contributors. However, the fault impact of DG inverters should to be re-evaluated in case the DG controls were changed to accomplish other functions such as voltage support, or in weak lines. In any case, coordination of the different protections (network, customers, PV-DG) at different fault current levels is critical to guarantee protection against short-circuits.

- **Power value, capacity value**

Traditionally, system operators hesitate to rely on PV as a firm peaking capacity component.
However, a critical test in support of PV is to look at PV availability during instances of major grid stress and supply shortfall events, particularly the world-wide increasing summer-peak, heat wave-driven events often characterized by rolling blackouts, which represent the highest possible stress on the networks. The capacity value of PV generation can be greatly improved when complemented by the availability of backup energy (to make up for any deficit to meet loads above a given threshold) and Demand Side Management measures (mitigation of loads in response to a wider effective capacity context, for example, a substation or a regional load and dispersed set of PV-DG).

- **Unintentional islanding**

  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.

  From the theoretical and experimental experiences known up to date, it is widely recognised that in addition to standard voltage and frequency monitoring, further Loss-Of-Mains detection should be part of the interface protection of PV-DG, which should not have a non-detection-zone under realistic network conditions (including weak grid sections). Furthermore, it is important that the schemes also work in case of multiple generators connected to the network. This protective function should be implemented based on a certain safety integrity level in order to guarantee its “function-on-demand” during the whole technical life time of the system and reduce the risk of malfunctions. In this sense, two different approaches have been proposed depending on the size of the PV system:

  - For small-scale PV-DG standardised, integrated protection systems should keep the system and interconnection costs on a reasonable level and 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 need to be included into the qualification procedures and interconnection standards.

  - For larger PV-DG units, protection should be designed on basis of a rigorous assessment of discrimination and risk. Potential to derive appropriate solutions has been identified in the areas of frequency/speed governing systems, source impedance, earth impedance, voltage phase shift and rate of change of frequency, and filtering methods that allow good discrimination.

- **Added value capabilities of modern inverters**

  Modern PV inverter technology allows multifunctional operation. In addition to feeding PV power into the public grid, modern inverters can perform additional functions such as:

  - Active power quality improvement: active filter to effectively reduce grid voltage harmonics.

  - Power factor regulation, reactive power control and voltage level control. In addition to delivering active power, reactive power can be produced or absorbed at the inverter’s grid interface; the device can therefore compensate excess or lack of reactive power in the grid, and thus also contribute to voltage control.

  - Phase symmetry control. When a three-phase inverter is equipped with energy storage (which may have a small capacity, such as a capacitor) and with an adequate control system, it is possible to improve grid quality by equalization of the three grid phase voltages with respect to each other, by purposefully delivering asymmetric phase
currents.

- Grid stabilization and operation as uninterruptible power supply. When the PV system is equipped with an energy storage (which needs to have some energy buffering capacity in proportion to the energy requirements), in coordination with local energy management it can supply local demand (selected loads) in case of grid deterioration or failure (local islanding operation). By applying the corresponding control, the inverters can also contribute to grid voltage, frequency and power quality stabilization. This function is especially interesting in industrial electrical environments and in locations with unreliable grids affected by recurrent grid failures and considerable fluctuations in grid voltage and frequency.

- Participation in distributed grid operation. By adding local storage (capacitors, batteries) to grid-connected PV systems, these can contribute to grid-forming or grid-supporting modes of operation, which may even include fault clearing capacity, *i.e.*, to get the grid up again after a blackout.

- Islanding and safety new approaches. Up to now, islanding operation is mostly viewed as a safety threat to be avoided at all cost. Nowadays, inverters can be designed in such a way that they are able to smoothly change between grid-connected and stand-alone operation modes. It has been demonstrated that live islanding management with smooth disconnect and reconnect, and with remote management of DG devices via grid frequency control, is possible.

### Impact on grid design and operation

The electricity network structure and control is expected to be completely reshaped within the next thirty years. For the distribution grids to experience drastic increase of dispersed electricity generation, radical overhauling of grid design, operation and control are necessary. As half of the electrical energy consumed is tapped from low voltage distribution grids, the evolution and optimization of these grids is a crucial issue.

- Grid capacity, structure and control. Grid control and safety approaches need to be made fit for downstream as well as upstream energy flows, resulting from central and distributed sources of generation. Distributed management and control of grid interfaces, generation and consumption can evolve into major mainstays of grid formation, control, stability, and resilience.

- Distributed devices aggregate. Increasing penetration of the distribution grid with dispersed generators increases the demand and opportunities for active energy and operations management. Stochastic and controllable generation units can be aggregated into “virtual power plants”, which in turn can be integrated into the existing structures for control of generation and transmission.

- Grid costs distribution models need review and update. When a lot of electricity users become potential producers (*e.g.* by means of DG), the conventional grid cost distribution model (characterised by almost fixed costs) is increasingly inadequate and needs reconsideration. In the context of the prevailing pressure towards liberalization and unbundling of electricity services on one side, and a protected and publicly supported renewable energy market segment on the other hand, quality and availability are endangered by cost reduction pressure.

- Variable tariffs for optimized distributed control of generation and consumption. Variable tariffs (*updated according to the current balance of energy availability and demand*), can be used as a tool for overall optimized distributed control of generation, storage, and consumption. Technically, it has been demonstrated that fluctuations of the grid frequency within a narrow band could be allowed to represent such a tariff. The entire philosophy of grid structure and operation is worth to be reconsidered and changed in
order to accommodate massively increasing fractions of renewable (stochastic) energy generation.

**IMPACTS OF DISTRIBUTION NETWORKS ON PV-DISTRIBUTED GENERATION:**

- **Voltage dips**

  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). For DG technologies, in addition to the possible internal effects that voltage dips might have, they might also cause network disturbances through their effect on DG systems. 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. 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). With the increasing penetration of PV-DG both in urban and rural networks, ride-through requirements might be sensible in the near future.

  Experimental tests done with state-of-the-art PV inverters of the European market based on different design concepts have revealed that inverters are generally very sensitive to voltage dips. High sensitivity to these disturbances can have a negative effect on the inverters and PV systems performance, components lifetime (induced stress) and, ultimately, the networks. Proper implementation of the mains monitoring is determinant in this sense.

- **Voltage swells**

  As it is the case with voltage dips, experimental tests done with state-of-the-art PV inverters of the European market have revealed their high sensitivity to voltage swells, their decoupling protection method (overvoltage protection) being a decisive factor in the devices behaviour.

- **Short-circuits in electrical installations**

  Short-circuits in electrical installations represent a severe stress situation for equipment that cannot be excluded in real operation. The consequences of short-circuit events for active elements of DG systems such as inverters are double-fold: the voltage dip following the short-circuit results in a fast voltage variation and large associated over-current, in case no current limitation exists in the device; the fast interruption of the short-circuit current by existing protections will induce a voltage transient also seen by the inverter that might cause stress on the electronic components of its output.

  Experimental tests done with state-of-the-art PV inverters of the European market have revealed that there are still problems regarding the proper implementation of the protection against short-circuit. In general, it can be concluded that highly sophisticated protective designs are not necessary for DG components used in residential applications. However, in particular cases and especially under rough operation environments, additional external protections might become necessary.

- **Superimposed harmonics and interharmonics on the grid voltage**

  The grid voltages in public supply systems are never pure sine waves. Disturbances in form
of harmonic and interharmonic voltages superposed on the grid voltage are indeed some of the main steady state power quality phenomena. Inverters are potentially sensitive to voltage harmonics and interharmonics disturbances, particularly the current control unit, the grid interface and related protections. Particularly inverters which rely on a high accuracy of the zero-crossings of the voltage signal for grid monitoring will be affected.

Experimental tests done on state-of-the-art single-phase inverters representative of the European market with different design concepts (low-frequency transformer, high-frequency transformer and transformerless types) operating at typical European levels of voltage distortion showed that inverters are relatively insensitive towards harmonics present on the grid voltage; however, under specific harmonics particularly high over-currents can be induced in the devices, which might unintended tripping of their over-current protection. The implementation of the current control strategy has a major influence on the inverters behaviour in terms of power quality (harmonic current distortion) and critical over currents.

Concerning interharmonics, tests done with interharmonic levels associated to the mains signalling used in many European countries show that most inverters were greatly affected. In this case, the implementation of the grid monitoring (particularly frequency and impedance measurement methods) is critical to achieve a high level of immunity against interharmonics phenomena.

STANDARDIZATION NEEDS:

Section 4 of this document presents in a table-format the standardization needs identified after the literature review, concerning PV-DG. They can be grouped as follows, depending on whether they affect inverters, PV systems in general or electricity distribution networks:

- **Inverters**
  - To improve PV-DG impacts on Distribution networks, product standards for inverters should include limits for current harmonics emissions (also for devices with phase currents higher than 16 A.), DC currents, DC capacity (only in transformerless inverters) and short-circuit contribution.
  - To improve PV-DG immunity against network events, product standards for inverters should consider decoupling protections against voltage dips and swells, and testing under realistic short-circuit conditions on the AC side.
  - Also, for inverters to perform new functions (voltage regulation, active filtering), specific product standards are needed.
  - Rules as recently developed for wind energy converters should also be adopted in inverters in order not to enhance system instability in case of a network fault or overload.

- **PV Systems**
  - Ground faults on the DC side of PV systems installed in buildings are not completely covered by international standards. This topic should be addressed.
  - For PV systems to contribute with effective capacity to distribution networks, standards should be developed which establish the associated minimum technical requirements.
  - Concerning unintentional islanding, there is still widespread discrepancy concerning interconnection practices and protection systems required in the various national grid codes or standards, as well as regarding the probability of occurrence and persistence.
of distributed resource islands. 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.

On another hand, the concepts of live islanding management, with smooth disconnect and reconnect and remote management of DG devices via frequency has already been demonstrated. The fact that modern inverters can be designed to smoothly change between grid-connected and stand-alone operation mode should be reflected in corresponding rules and standards.

- **Electricity distribution networks**
  - For future electricity distribution networks to incorporate large fractions of DG, profound changes should be done in grid design, dimensioning, operation and control. There is a need to review and, where appropriate, to alter and adapt structures and procedures which are used nowadays.

**RESEARCH AND DEVELOPMENT NEEDS:**

Section 4 of this document presents in a table-format the research and development needs identified. They can be grouped as follows, depending on whether they affect inverters, PV systems, multiple operation of PV systems or the electricity distribution networks:

- **Inverters**
  - Improvement of current control techniques for inverters operating in highly distorted electrical environments.
  - Measurements of leakage currents in PV systems with transformerless inverters and different module types on a long time basis, in order to gain further experience and produce technical recommendations for the inverters design.
  - Adequate and realistic immunity requirements for inverters against voltage dips and voltage swells.
  - Reliability against short-circuits on the AC side, especially for inverters operating under rough electrical environments.
  - New voltage control techniques to maintain network voltage control with Distributed Generation technologies.
  - Effective means of limiting short-circuit current contribution by voltage-control type inverters.

- **PV systems**
  - Capacity of PV systems to contribute to the grid capacity through added-value benefits such as uninterruptible power supply and backup power. The potential of this combination can be particularly interesting in weak grids.
  - Combination of Demand Side Management functionalities with PV systems, and integration into central network operation strategies.
  - 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 penetrations.

- **Multiple operation of PV systems**
- Multiple generator modelling and analysis, in order to identify and correct eventual problems regarding voltage rise and fluctuations arising from the operation of small generators.
- Effect of wide-spread 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.

### Electricity distribution networks

- New approaches are required for economic assessment (cost models, variable tariffs), optimization (algorithms), and for true grid integration of decentralised power systems (technology). The addition of stochastic and controllable generation units has already demonstrated in the “virtual power plants” concept. However further R&D is needed to incorporate PV-DG added value capabilities in the networks operation and control.
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