Unintentional islanding in distribution grids with a high penetration of inverter-based DG: Probability for islanding and protection methods

R. Bründlinger and Benoît Bletterie

***Abstract*—Unintentional islanding in distribution networks due to the presence of DG is one of the major safety concerns for the grid interconnection of generators. The present paper looks at the current protection and safety requirements and new activities in selected European countries with a focus on inverter based generation. By means of a field study carried out in a real LV network with a high DG penetration, occurrence and persistence of balanced load/generation conditions - which are the basic prerequisite for islanding - are analyzed and the according probability is calculated based on different penetration scenarios protection settings and load characteristics.**

The results show that under realistic conditions the probability to encounter an island is not negligible. Thus additional protection methods to the standard voltage and frequency monitoring are required in order to detect a loss of mains at the generator and ensure the safety of customers and maintenance personnel.

***Index Terms*—unintentional islanding, distributed generation, probability, islanding protection**

I. Nomenclature

DG Distributed generation
PV Photovoltaic(s)
DISPOWER "Distributed generation with high penetration of renewable sources", European Commission project
ENS/MSD Mains monitoring with allocated switching devices, anti-islanding protection required according to the German draft standard VDE 0126:1999 which based on measurement of the grid impedance
LOM Loss-Of-Mains
NDZ Non-Detection-Zone

II. Introduction

The possible occurrence of unintentional islands in distribution networks with distributed resources (loads and generation) has been one of the major issues in connection with the ongoing growth of distributed generation (DG) in Europe [1]. Furthermore it is anticipated that the rapid deployment of DG in recent years has substantially increased the likelihood and concerns associated with this phenomenon – especially among network operators.

However, there is still widespread discrepancy not only concerning interconnection practices and protection systems required in the various national grid codes or standards [2], but also regarding the probability of occurrence and persistence of distributed resource islands. It also has been recognized that today existing standards often do not deliver consistent policy among network operators or consensus with their customers, developers and operators of distributed generation.

Though it is not inherently a problem, the unintentional creation of an island has a number of implications for the safe operation of the islanded section of the network [3]. The main hazards and problems associated with unintentional islanding are:

- *Exceeding of the acceptable limits* for voltage, frequency, unbalance, harmonics, flicker and other PQ parameters which can lead to malfunction or damage of network and customer equipment. Usually this hazard is restricted by the tripping limits of protective relays (voltage and frequency) implemented at the generator site
- *Uncleared faults* (earth or phase faults) due to too low short-circuit capacity or unearthed operation. Possible damage of network equipment, or sustained fault currents.
- *Out-of-phase re-closing* of circuit breakers may damage circuit breaker equipment and cause high transient inrush currents which may damage the generator. Of particular relevance for networks with an automatic re-closing facility.
- *Electric shock* due to touching of live conductors assumed to be dead. Only relevant for LV networks and depending on the safety practices applied for working on the line.

For the reasons mentioned above it is necessary to disconnect all distributed generation in case of islanding in order to prevent sustained operation under these conditions. Since it is the network operator's contractual obligation to operate the network in a safe way it is also the network operator's duty to make sure that suitable protections are installed.

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R. Bründlinger and B. Bletterie are with the Business Unit Renewable Energy Technologies, arsenal research, A-1030 Vienna, Austria (web: http://www.arsenal.ac.at, e-mail: roland.bruendlinger@arsenal.ac.at)

III. PROTECTION REQUIREMENTS IN EUROPEAN COUNTRIES

A. Current situation

Within an extended survey on grid interconnection standards for DG in European countries carried out in the framework of the European project DISPOWER [2], also the requirements for protection against unintentional islanding were analyzed and compared to those outside Europe, particularly the U.S. American requirements.

It turned out that there is a broad diversity among different standards and the requirements for distributed generators when it comes to protection and unintentional islanding. Particularly for small scale generation in the range of a few kW such as PV, micro CHP or fuel cells, the lack of common standardized “plug-and-play” interconnection requirements and certification procedures has been identified as an important barrier for a future mass market of DG [1].

Due to the extensive growth of DG in recent years, dedicated standards or guidelines for the interconnection of small-scale generation – usually in the range up to 5 kW – are meanwhile available in most European countries (Table I). However, the national standards are far from providing consistent requirements across Europe.

TABLE I
OVERVIEW OF REQUIREMENTS FOR THE CONNECTION TO LV-NETWORKS IN EUROPEAN COUNTRIES AND THE U.S. WITH RESPECT TO PROTECTION AGAINST UNINTENTIONAL ISLANDING

	Generic protection requirements			**Specific protection for small scale DG**
	Voltage monitoring	**Frequency monitoring**	**Additional requirements**	**(*max. capacity*)**
Germany [10], [11]	required, single stage over and under voltage tripping	required single stage over and under frequency tripping	accessible disconnection switch;	*<4.6 kVA single phase <30 kVA, 3-phase:* ENS/MSD, type tested protection device with voltage, frequency and impedance monitoring according to [11]; then accessible disconnection switch is not required.
Austria [12], [13]	required, single stage over and under voltage tripping	required single stage over and under frequency tripping	accessible disconnection switch; vector shift relay (for larger generators)	*<4.6 kVA single phase <30 kVA, 3-phase:* Usage of non-islanding inverters according to [13] or ENS/MSD according to [11]; in both cases, no accessible disconnection switch required.
Belgium [14]	required, single stage over voltage, two stage under voltage tripping	required single stage over and under frequency tripping	accessible disconnection switch Either vector-shift relay or RoCoF relay or frequency relay with tighter limits; detection of asymmetry	*<10 kW:* Automatic isolation system according to AREI/RGIE: Type tested device with voltage and frequency monitoring plus active islanding protection; ENS/MSD according to [11] accepted with modified settings. No accessible disconnection switch.
The U.K. [15], [16]	required, single stage over and under voltage tripping	required single stage over and under frequency tripping	accessible disconnection switch; additional protection such as RoCoF or vector shift relays	*<generators 16 A* Type tested “small scale embedded generator” according to [15], with voltage and frequency monitoring and an additional active loss-of-mains protection; Impedance monitoring is not accepted.
Netherlands [17]	required, single stage over voltage, two stage under voltage tripping	required single stage over and under frequency tripping	none	*< 5kVA* 1-phase voltage and frequency monitoring with single trip levels for inverter based generation, fixed settings
Italy [18], [19]	required, single stage over and under voltage monitoring	required single stage over and under frequency tripping	accessible disconnection switch; RoCoF relay if generator capacity is in the range of network load	*PV <5 kW 1-phase <20 kW 3-phase* Type tested protection integrated in the inverter according to [18] and [19] consisting of voltage and frequency monitoring and optional RoCoF; accessible disconnection switch
Spain [20]	required, single stage over and under voltage monitoring	required single stage over and under frequency tripping	accessible disconnection switch	*for PV systems <100 kW:* Voltage and frequency monitoring may be integrated in the inverter, settings and function certified by the manufacturer; accessible disconnection switch
France [21], [22]	required, single stage over and under voltage monitoring, standardized relay types	required single stage over and under frequency tripping, standardized relay types	accessible disconnection switch	*for PV systems <5kVA:* ENS/MSD, type tested protection according to [11] is accepted, impedance monitoring may be disabled; accessible disconnection switch.
U.S. [23], [24]	required, single stage over voltage, two stage under voltage tripping	required single stage over and under frequency tripping	accessible disconnection switch; additional active islanding protection e.g. type tested according to [24]	No specific requirements for small scale generation; equipment type tested according to [24] fulfils the requirements of [22]

Whereas e.g. in countries as The Netherlands, Italy, Spain or France passive protection by monitoring voltage and frequency is seen as sufficient for small-scale generation, additional active protection methods are required in Germany, Austria, Belgium, the UK and also the U.S. The German situation is somehow special in this context, since it has meanwhile become the only country where impedance monitoring is virtually mandatory and no other active methods can pass the required test procedures. However there are several other European countries, such as France, Belgium and Austria where the German ENS/MSD is accepted as well – but not mandatory.

B. Barriers to European harmonization

This lack of consensus among European countries is the main barrier to reach a harmonization of the current requirements in Europe. Also recent attempts to create a common European product standard for small-scale CHP [25] are suffering from the fundamentally different national requirements and views. The only solution which turned out to be acceptable in the case of the micro CHP standard was the definition of national deviations and individual interface protection settings for each of the countries. However this does neither resolve the unsatisfactory situation for equipment manufacturers, which have to design their products specifically for each national market nor provide a real breakthrough in the current discussion towards a compromise which has the potential for a real harmonization in Europe.

C. Recent activities in Europe

Besides the efforts on the CENELEC level to establish a standard for micro CHP [25] ongoing since 2002 also many European national standards and guidelines recently underwent fundamental changes. Activities are reported e.g. from Germany, France or Austria. Related to islanding protection, the newly revised Austrian national guidelines for the grid connection of PV [13] now permit the use of alternatives loss-of-mains protection methods to impedance monitoring and also the latest drafts of the German standard [11] adopted an alternative approach for conformance testing of LOM protection. This would allow manufacturers to use other protection methods than impedance monitoring and could be an important breakthrough towards a European compromise.

IV. Probability of Islanding in LV Networks

An important issue in the context of islanding is the still existing lack of knowledge when it comes to the probability and duration of the event. Although probability and occurrence of islanding in distribution networks have been investigated by several studies, the results did not provide consistent conclusions, especially on the persistence of a local power island. Furthermore some of the theoretical studies suffer from simplified assumptions made for the analysis and are therefore often given little attention. In order to provide data on the base of a real situation a study was carried out in the framework of the Task V of the IEA Implementing Agreement on PVPS [5], where load and generation (a 100 W PV system) in a residential area were correlated to identify possible islanding conditions. The main conclusion was that balanced load conditions occur very rarely even at high penetration levels of PV and thus the probability of encountering an island is virtually zero. However, it has been shown that several results of the study need to be reinterpreted to allow a better estimation of the probability under realistic conditions [6].

Against this background, a measurement campaign has been initiated in the framework of the European project DISPOWER, which aims at filling these gaps in the knowledge and provide further information on load and generation characteristics in a typical distribution network.

V. Balanced Load/Generation Conditions in LV Distribution Networks – the Gleisdorf Case Study

A. Load/generation balance and basic conditions for unintentional islanding

Principally, for an unintentional island to occur, the load flow in the network prior to the initiation of the island must be such that the generation does not realize the loss-of-mains. In this context the match between load and generation in a section of the network is the most crucial factor, if just voltage and frequency monitoring are present at the generator and no further protection methods are applied. Then it is possible for both, voltage and frequency to remain within the limits of the protection and the islanding situation would persist until either load or generation variations drive voltage or frequency outside the limits.

Thus the probability of unintentional islanding to occur may be directly correlated to the number and duration of balanced load/generation conditions in a certain part of a network which can form a possible island zone.

On this basis the idea of the presented study is to simultaneously measure and record the active and reactive power of the loads and the DG at a high time resolution of 1 second. By correlating the recorded load and generation profiles for active and reactive power, possible islanding situations can be identified under different boundary conditions, e.g. protection settings, or penetration levels. The resulting probability can be then calculated by summing up the duration of all balanced conditions and relating the figure to the total time.

B. Description of the area

The basic criterion for the selection of a representative LV-network for the field study was on one hand the presence of a strong – in comparison with the network capacity – distributed generation unit with a fluctuating generation profile. On the other hand, a good mixture of residential, commercial, public and light industrial loads and last but not least the accessibility for the required measurements was the basis for the choice of the network.

The selected area is located in a suburb of an urban community in Austria, about 20 km east of the city of Graz in the Province of Styria, Austria. The load structure with mainly single-family residential homes, some public buildings and a few multi-dwelling houses provides a good mixture of different loads. Furthermore the selected network is a good model for an area where high penetration levels of DG can be expected in the future.

Figure 1 shows a map of the area. The border describes the extent of the local LV-network, which is supplied from the transformer substation located in the upper middle of the area. Located on the southern border of the network, close to the A2 highway, the “MLA control station” hosts the controls for the “Multi-functional noise barrier” systems (over-head information displays, monitoring and traffic control) as well as the point of coupling for the PV-system, which is mounted on top of the noise barrier along 1.2 km of the A2 highway.

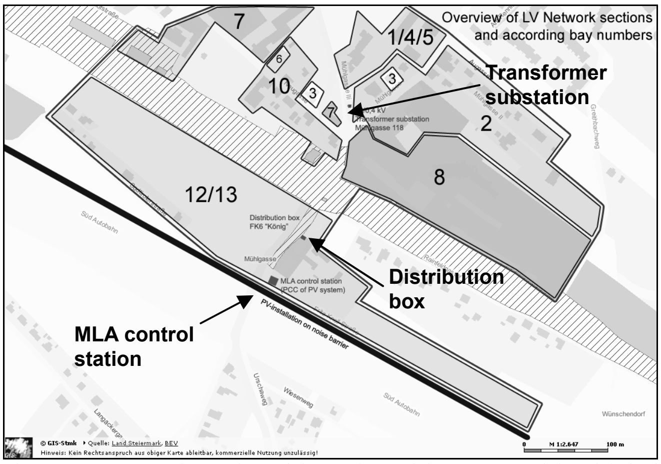

Fig. 1. Area map and overview of the sections of the LV network in Gleisdorf with according bay numbers (see also Tab. II); Dark grey line: 101 kW PV installation on highway noise barrier

C. Characteristics of the network and DG connection

The local electricity supply system (Fig. 1 and Fig. 2) consists of a single MV/LV distribution transformer situated in a substation. From there, the electricity is directly distributed via cables to customers in the near surroundings of the substation. Farther customers are supplied via several remote distribution boxes, situated close to each group of buildings. In total there are 13 bays at the transformer substation. Table I gives an overview of the customers and loads connected to the different bays at the substation and their characteristics.

TABLE II
CHARACTERISTICS OF THE CUSTOMERS CONNECTED TO THE LV-NETWORK

Bay No.	No of customers connected to the bay	Customer type
1	45	Residential (apartment buildings)
2	22	Mixed (residential/commercial)
3	2	Residential (2 single family houses)
4	14	Residential (apartment building)
5	14	Residential (apartment building)
6	1	Commercial (Joiner's workshop)
7	12	Mixed (residential/public)
8	2	Commercial + Petrol station
9	-	N.C.
10	25	Residential (single family houses)
11	-	N.C.
12 13	23	Residential/Public service PV generation (MLA)
Total	160	Mixed

Since the distance between the location of the MLA and the substation is approximately 300 m, the connection is made indirectly via a distribution box (black dot in the centre of Fig 1) where also loads are connected to the network (section 12/13 in Fig. 1).

The PV system itself (see bottom left of Fig 2) consists of about 1 800 modules (1/3 of the installed power multi-crystalline and 2/3 amorphous silicon modules) which are integrated into the 1 300 m length of the noise barrier. They are connected to 55 string inverters (single-phase transformer-less type) which feed the produced electricity into the network at the control station of the MLA. The total rated power of the inverters equals 101 kW.

D. Measurement and data acquisition system

The measurement and data acquisition system consists of two independent measuring stations which are located inside the transformer substation and the MLA control station. At both stations the parameters active and reactive power, voltage and current of the individual bays are measured by power transducers and recorded with the help of a PC at a resolution of one second. In total 140 parameters are recorded which gives a data volume of approximately 70 MB per day and 25 GB for a whole year. To synchronize the measurements both stations are equipped with a GPS time receiver.

E. Possible island zones

According to the topology of the network, different points where a possible power island may be initiated were identified. These points are usually circuit breakers or fuses, which can separate parts of the network from the main system. Fig. 3 shows the zones for the Gleisdorf case.

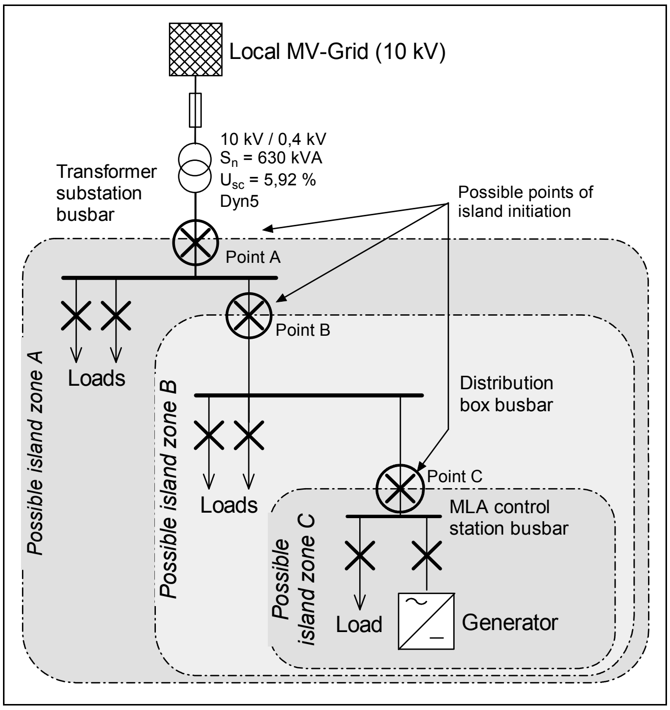

Fig. 2. Local electricity supply, network topology and different scenarios for unintentional islanding with possible island zones in the Gleisdorf LV network

The smallest possible island zone C consists solely of the Control Station of the Multifunctional Noise Barrier where the PV-System and the technical systems of the highway displays are connected. Since this zone has a rather limited extent and the local load has very specific characteristics, this case was not evaluated in further detail. Islanding in the second zone can be initiated by opening the circuit breaker which supplies the distribution box and the Control station (Point B in Fig. 3). Besides generation, zone B (section 12/13 in Fig. 1) comprises about 23 residential and public customers connected via the distribution box.

Finally the possible island zone with the largest extent consists of the whole LV part of the network and can be initiated by tripping of the main circuit breaker at the transformer substation (Point A).

F. Determination of Non Detection Zones

For a generic inverter based generator, the size of this so called "Non Detection Zone" (NDZ) as described e.g. in [6] can be calculated depending on the protection's voltage (U_{max} and U_{min}) and frequency window (f_{max} and f_{min}) with

$$P_{L,\min} = \frac{U_{grid}^2}{U_{\max}^2} \cdot P_{Gen} \text{ and } P_{L,\max} = \frac{U_{grid}^2}{U_{\min}^2} \cdot P_{Gen} \quad (1)$$

for the minimum ($P_{L,min}$) and maximum ($P_{L,max}$) active power which may be drawn by the load and

$$\begin{aligned} Q_{L,\min} &= \frac{P_L \cdot f_{\min}}{P_{Gen} \cdot f_{grid}} \cdot Q_{Gen} + \left(\frac{f_{\min}^2}{f_{grid}^2} - 1 \right) \cdot Q_r P_{Gen} \\ Q_{L,\max} &= \frac{P_L \cdot f_{\max}}{P_{Gen} \cdot f_{grid}} \cdot Q_{Gen} + \left(\frac{f_{\max}^2}{f_{grid}^2} - 1 \right) \cdot Q_r P_{Gen} \end{aligned} \quad (2)$$

for the minimum ($Q_{L,min}$) and maximum ($Q_{L,max}$) reactive power respectively. P_{Gen} and Q_{Gen} correspond to the active and reactive power fed by the generator. Q_r is the Quality factor of a tuned resonance circuit which is used as a substitution for the load. The quality factor is defined as the ratio between reactive and active power stored in the circuit and therefore has a crucial impact on the size of the according NDZ.

Based on typical voltage and frequency windows stated in various standards the NDZs have been calculated for three different cases (Table IIIA). Case A represents a rather tight window for both, voltage as well as frequency whereas case B has a wide window for both parameters. The last case used for the calculations has a wide window for the voltage, but very narrow limits for the frequency. For Q_r, Table IIIB shows the selected values respectively.

TABLE III

A) VOLTAGE/FREQUENCY WINDOWS AND QUALITY FACTORS

Case	Voltage window	Frequency window	Reference Standard
A	0.9 to 1.10 U_N	0.99 to 1.01 f_N	IEEE P1547
B	0.8 to 1.15 U_N	0.94 to 1.02 f_N	VDE0126, OVE E2750 (partly)
C	0.8 to 1.20 U_N	0.994 to 1.006 f_N	DK5950

Case	Quality Factor Q_r	Reference Standard
Q_{r1}	0.5	ER G83
Q_{r2}	1	Draft IEEE P1547.1
Q_{r3}	2	OVE E2750, UL 1741 (2.5)

G. Calculation of balanced conditions in the network

To illustrate the existence of balanced conditions in the network, a simplified probabilistic approach was be used. This method is based on determining the probability distribution of the ratio between load and generation for active as well as reactive power in the considered zone.

Fig. 3 shows the results for Zone B for each of the three phases. Each of the individual peaks of the distribution curves is at a ratio below one. This reflects that there is often a surplus of generation in the zone. The difference of the peak ratios between the individual phases indicates a notable divergence of generation and load in the three phases. In the specific case this was caused by a significantly lower generation in phase L1 compared to the other phases as well as a slightly lower load in phase L3.

The probability distribution is influenced by the seasonal variations in load and generation profiles. Thus when moving from summer to winter, the peak-ratios flatten and move towards higher values. This can be explained by a significantly lower generation and a higher load during the winter time.

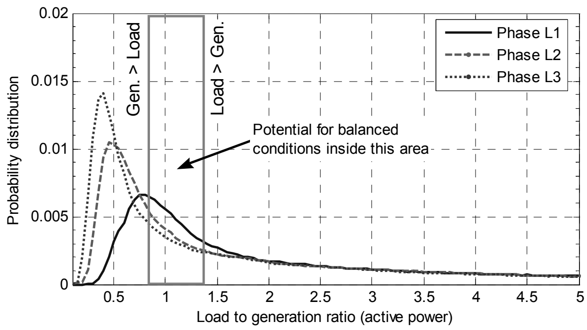

Fig. 3. Island Zone B: Probability distribution of the load-to-generation ratio (active power) for the individual phases.

Another important parameter that can be derived from Fig. 4 is the maximum DG capacity for which balanced conditions in the selected island zone never occur. This figure can be estimated by multiplying the lowest Load to Generation Ratio where the probability becomes zero with the DG peak power. For zone B, assuming a peak generation of 30 kW per phase, the evaluation gives a maximum capacity of 6 kW per phase.

Since stable balanced conditions in a network require both, active and reactive power to be balanced, the probability distribution was likewise calculated for the reactive component.

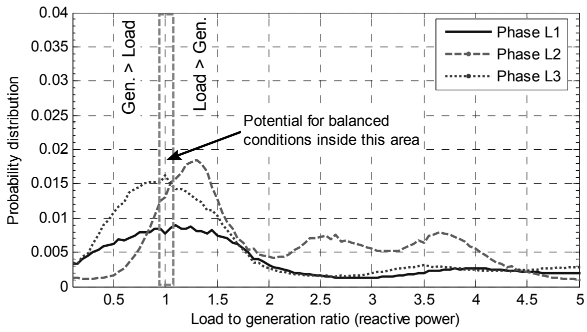

Fig. 4. Probability distribution of the load-to-generation ratio (reactive power) for the individual phases.

The location of the three curves in Fig. 4 clearly indicates the existence of balanced conditions also for reactive power; however, the peaks are not as distinctive as in Fig. 3. Since for both parameters, the probability around ratios of 1 is not zero the conclusion can be drawn that there is a basic potential for balanced conditions in Zone B. However, this does not implicate that islanding conditions actually exist in the network, since for these conditions both active and reactive power have to be balanced at the same time.

To allow an identification of islanding conditions in Zone B, first the NDZ in terms of active and reactive power of the generator was computed for each second and each of the different cases (see Table III) by using (1) and (2). In a second step, the power drawn by the loads was compared with the resulting NDZ-band and all points where the power was within the band were marked. In order to identify a possible islanding condition – defined (e.g. in [8]) as a balance that persists over at least two seconds – all points which represented only a single balance were eliminated.

By applying "penetration" factors, different DG scenarios were simulated to assess the impact of the installed generation capacity in relation to the loads. A factor of 1 represents a level of DG where the active load-to-generation ratio has its maximum. The other factors were set to 0.5 and 2 for a low and a high penetration level, respectively.

Fig. 5 presents the results of this analysis for three levels. For the protection settings, the margins of Case B with rather wide windows for voltage and frequency were chosen.

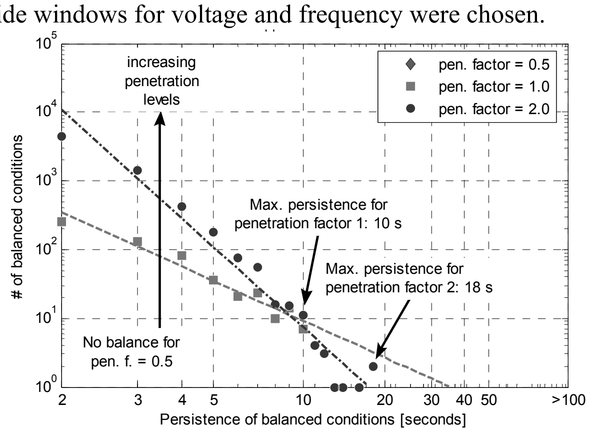

Fig. 5. Number and persistence of balanced conditions for a single phase at different penetration levels (Voltage and frequency window B, $Q_r = 0.5$)

It can be clearly seen that the number of balanced conditions grows at increased penetration levels. Moreover, Fig. 5 also shows an increase of the maximum persistence of a balance. On the other hand, when the penetration level is below a critical level, no balances occur at all (factor 0.5).

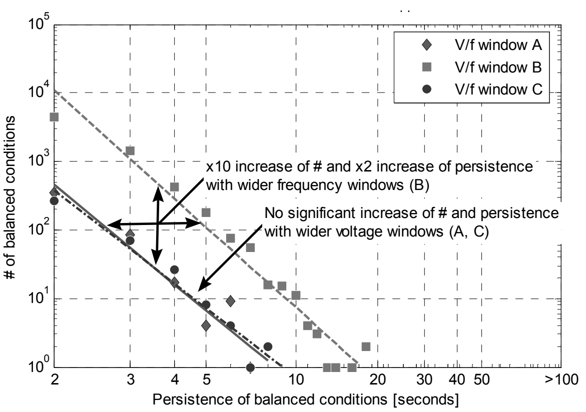

Fig. 6. Number and persistence of balanced conditions for a single phase for different Voltage and frequency windows ($Q_r = 0.5$, penetration level 2)

Fig. 6 shows the impact of different protection settings. A comparison of the case B with A and C indicates that a wide frequency band has a significantly higher impact than a wide voltage band.

VI. Conclusions

The rapid deployment of DG in recent years has substantially increased the concerns associated with unintentional islanding – especially among network operators.

The analysis of requirements for protection against unintentional islanding made within a European wide survey on grid interconnection standards showed that there is a wide diversity among different requirements for DG. Particularly for small and micro scale generation in the range of a few kW such as PV or micro CHP, the lack of common "plug-and-play" procedures represents a major barrier for the establishment of a future mass market.

Specific standards or guidelines for small-scale generation, usually in the range of a few kW have meanwhile become available in most European countries. However, despite the efforts made at the CENELEC level, a common procedure accepted all across Europe is not foreseeable at the moment, since there is still no broad consensus regarding adequate protection methods and testing requirements [9]. Especially the impedance method virtually mandatory in Germany is currently under discussion, due to two factors, its susceptibility to disturbances coming from the network and the disturbances introduced by the measurement itself. Against this background the latest drafts of the national standards in Germany and Austria also permit the application of alternative methods.

One of the crucial factors when it comes to the assessment of the relevance of the phenomenon is the probability of its occurrence. In a certain section of the network and islands can only occur if load and generation are balanced.

To obtain real data on the frequency and persistence of these islanding conditions, a measurement campaign has been performed in an LV distribution network in Austria with a high penetration of DG. By recording the power flows in the sections of the network on a one second base and simultaneously correlating them to the generation, balanced conditions were identified and their frequency was calculated.

The evaluations, which have been performed for different possible island zones, protection settings and penetration scenarios, show that under realistic conditions the probability of balanced conditions depends on the following key factors:

- *DG penetration level*: The DG must be able to supply sufficient active power for the loads in a certain network zone.
- *Reactive power supply*: With a DG operating at unity or lagging power factor and no other reactive power supply present, balanced conditions never occur.
- *Protection settings*: The frequency margins define the possible reactive power imbalance, under which balanced conditions can stabilize and have thus a crucial influence on both, frequency and persistence of balanced conditions.

- *Generator control*: The supply of active and reactive power during variations in grid voltage and frequency fundamentally influences the stability of a balanced condition.

Considering these factors, it is possible to assess the risk of islanding for maintenance personnel or customers in a certain part of a network, as described e.g. in [7]. Generally it can be concluded that in certain network environments, the probability for balanced load/generation conditions and thus also the unintentional creation of an island shall not be regarded as virtually impossible. Especially with increasing penetration levels and DG which are intended to supply reactive power to the network, the potential risks associated with this event may not be neglected.

Hence additional protection methods to the standard voltage and frequency monitoring are required in order to detect a loss of mains at the generator and ensure the safety of customers and maintenance personnel.

VII. Acknowledgment

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VIII. Disclaimer

The authors are solely responsible for this publication, it does not represent the opinion of the European Commission and the European Commission is not responsible for any use that might be made of data appearing therein.

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X. Biographies

Roland Bründlinger studied at the Technical University, Graz, Austria and the Royal Institute of Technology in Stockholm and received his M. Sc. degree in Electrical Energy Engineering in 2000. Since 2001 he is with the Business Unit Renewable Energy Technologies at arsenal research in Vienna Austria. The focus of his work is on testing and conformity assessment of grid interfaces for DG. His main interest lies on specific issues of inverter based DG and the interactions between protections and the grid. R. Bründlinger is member of the CIGRE TF C6.04.01 "Connection Criteria at the Distribution Network for DG".

Benoit Bletterie received a M. Sc. degree in Electrical Engineering from Ecole Supérieure d'Electricité (France) and from the Technical University of Madrid in 2001. Since 2003 he is working as a researcher at the Business Unit for Renewable Energy Technologies at arsenal research, Vienna. His work in European and national research projects is focused on the integration of distributed generation, particularly on power quality issues.