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Integration of distributed energy sources with electrical power grid

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Abstract. The changes that have been taking place recently in the power sector, lead to an increasing share of distributed generation (DG) in the electric power production. Many different energy sources can be distinguished in this area and majority of them incorporate power electronic electrical energy converters interfacing with a power system. Connection of a large number of distributed energy sources (DES) changes the power system work conditions both in positive and negative sense. On the one hand, they emit disturbances to electric power network and on the other hand, they can be effective means of the compensation of such disturbances and also can be used to improve the quality of power delivery. Their additional capabilities are performed by power electronic converters.

Development of a modular universal interconnection architecture of these converters with standard functions for power conversion, power conditioning and quality, protection, controls, communications, ancillary services, and metering is the cornerstone of streamlined DG interconnection. Similarly, developing standard certification and testing procedures for the interconnection of DG converters, and then deploying and field testing many of the recently commercialised interconnection devices is a needed step in this process.

The main goal of this paper is to present the possibilities of application of the power electronic converters coupling DESs with supply networks to perform ancillary services resulting from supply network characteristics.

In the first part the interaction between DESs and networks is described and quantified. Then ancillary services are defined, as the new tasks that designers of converter can/should undertake as well as the standardization gap with respect to the converters that perform ancillary services. For the purposes of this paper the converter is considered to be a black box connected to the power system. The paper concerns DESs connected to distribution networks.

Key words: distributed energy source (DES), power electronic interface, power quality, ancillary services.

1. Introduction

In the recent years a number of changes have been observed in electrical power networks which aim at the increasing share of distributed energy sources (DESs) in total energy production. Distributed generation (DG) is characterized by some features which have not been present in traditional centralized systems: (i) rather free location in the network area, (ii) relatively small generated power and (iii) variation of generated power dependent on the availability and variability of primary energy.

The power of a source which would be numbered among DG is not precisely specified. In practice, one can meet "distributed" large wind power station of a few dozen or a few hundred MW installed power, connected to the high voltage (HV) network and centrally controlled, but also sources of significantly smaller power, operating in medium (MV) and low voltage (LV) networks. According to the regulations binding in Poland (the Decree of the Ministry of Economy dated 4 May 2007, concerning detailed rules of the functioning of the electrical power system. Law Gazette No 93, Item 623, 2007) one can assume conventionally that DG includes the sources of power below 50 MW, which are not subject to the central control. The production of energy in such sources does not need obtaining a special license from the Energy Regulation Office. However, this principle is not valid with reference to renewables if an energy producer wants to take the advantage of supporting instruments, which are provided for that type of sources, like green certificates (Act of 10 April 1997, Polish Energy Law. Law Gazette, 1997, No 54, Item 348, with late changes).

Main factors influencing the common application of DESs are costs and efficiency. Although investment costs are still high, energy produced from DESs may be cheaper than the one from conventional energy sources. In particular, it refers to renewables. At present, a number of technologies have already achieved a competitive prize and satisfactory efficiency. Moreover, the policy of EU is conducive to the development of DG. Thus, taking into account the circumstances of technical, economic or even political nature, the continuous development of DG and its increasing share in energy production should be expected. According to the EU Directive 2001/77, energy production from renewables in Poland in 2010 should reach the level of 7.5%, while in EU countries – 22% of the total energy production.

The connection of the bigger and bigger number of DESs to the electrical power network changes its operating condi-

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tions and may result in the appearance of phenomena which deteriorate the quality of energy delivery to customers. At the same time, these sources can be a potential measure for electromagnetic disturbances compensation and improving power system security. At present, the philosophy of DESs connection to the grid is "not harm". Connection requirements are formulated on the basis of the Decree of the Ministry of Economy (dated 4 May 2007, concerning detailed rules of the functioning of the electrical power system. Law Gazette No 93, Item 623, 2007) and should ensure power grid operation safety, required power quality and reliability of supply.

Technical requirements and recommendation for the production units of minimum 50 MW rated power, which are connected to 110 kV networks (so called "coordinated networks"), are defined by transmission network operator (TNO) (the Instruction of Transmission System Operation and Maintenance (IRiESP), 2006). Such sources are subject to central control and participate in frequency and voltage regulation, cooperating with superior control systems. For the units of smaller rated power connection requirements are established by distribution network operator (DNO). In particular, DNO decides on the level of grid voltage to which the unit will be connected, dependently on its power and the grid local operation conditions. Technical requirement do not take into account a positive impact that DES may exert on the supplying grid providing ancillary services for DNO.

The paper deals with the negative and positive interaction of DESs with the electrical power grid. Its aim is to point at those aspects of negative impact which can be essential problems for the integration of the big number of DESs with the grid. On the other hand, it shows how DESs connected to the grid by energy converters may be used for the solution of integration problems as well as for improving the quality of energy delivery to customers. In this aspect the objective is to define the new tasks, resulting from the needs of energy sources owners, distribution systems operators and end users that designers of converter can/should undertake as well as to point at the standardization gap with respect to the converters that perform ancillary services.

According to the assumed DG definition, the paper relates to the sources of rated power below 50 MW, connected to the distribution networks of MV or LV. For the purpose of this paper the converter interfacing the source with the grid is considered as a black box.

2. Influence of DESs on voltage quality of the supplying network

DESs influence power quality (PQ) in a similar way as disturbing loads. They may be the emitters of such disturbances as long and short duration voltage variations, voltage fluctuations (flicker), harmonics and unbalance. Voltage characteristics related to those disturbances and their limits are defined in standards or regulations.

In the further subsections the influence of DESs on voltage characteristics is described.

2.1. Voltage level. In conventional distribution networks of radial configuration positive voltage drop on the way of current flow to load devices results in negative deviation of voltage amplitude in the network nodes. In the network with DG both negative and positive deviations are possible, the latter one leads to node voltage increase.

Voltage drop between nodes 0 (distribution substation) and k, in the feeder from Fig. 1a, can be determined from the formula:

$$\delta U_{0k} = \sum_{i=1}^{k} \left(I'_{i-1,1} R_{i-1,i} + I''_{i-1,i} X_{i-1,i} \right), \tag{1}$$

where $I'_{i-1,i}$, $I''_{i-1,i}$ are the active and reactive currents of branch (i-1,i) and $R_{i-1,i}$, $X_{i-1,i}$ are the branch resistance and reactance, respectively.

Branch currents result from node currents:

$$\underline{I}_{i-1,i} = \sum_{j=i}^{k+1} \underline{I}_j \tag{2}$$

Taking the above into account one can obtain:

$$\begin{aligned} \delta U_{0k} = & \sum_{i=1}^{k} \left[\left(\sum_{j=i}^{k+1} I'_j \right) R_{i-1,i} + \left(\sum_{j=i}^{k+1} I''_j \right) X_{i-1,i} \right] = \\ & = \sum_{i=1}^{k} \left(I'_i \sum_{j=1}^{i} R_{j-1,j} + I''_i \sum_{j=1}^{i} X_{j-1,j} \right) + \\ & + I'_{k+1} \sum_{j=1}^{k} R_{j-1,j} + I''_{k+1} \sum_{j=1}^{k} X_{j-1,j}. \end{aligned} \tag{3}$$

Active and reactive currents can be expressed in relation to active and reactive powers, thus

$$\begin{aligned} \delta U_{0k} = \frac{1}{\sqrt{3}\, U_n} \Bigg[& \sum_{i=1}^{k} (P_i R_{0i} + Q_i X_{0i}) + \\ & + P_{k+1} R_{0k} + Q_{k+1} X_{0k} \Bigg], \end{aligned} \tag{4}$$

where $R_{0i} = \sum_{j=1}^{i} R_{j-1,j}$, $X_{0i} = \sum_{j=1}^{i} X_{j-1,j}$, $R_{0k} = \sum_{j=1}^{k} R_{j-1,j}$, $X_{0k} = \sum_{j=1}^{k} X_{j-1,j}$ are the resistances and reactances of feeder branches between nodes 0 and I or 0 and k, respectively.

Taking into account the reverse direction of active power generated in node k and assuming that the connected source can generate or consume reactive power, the formula (5) can be expressed as:

$$\begin{aligned} \delta U_{0k} = \frac{1}{\sqrt{3} U_n} \Bigg[& \sum_{i=1}^{k-1} (P_i R_{0i} + Q_i X_{0i}) - P_k R_{0k} \mp \\ & \mp Q_k X_{0k} + P_{k+1} R_{0k} + Q_{k+1} X_{0k} \Bigg]. \end{aligned} \tag{5}$$

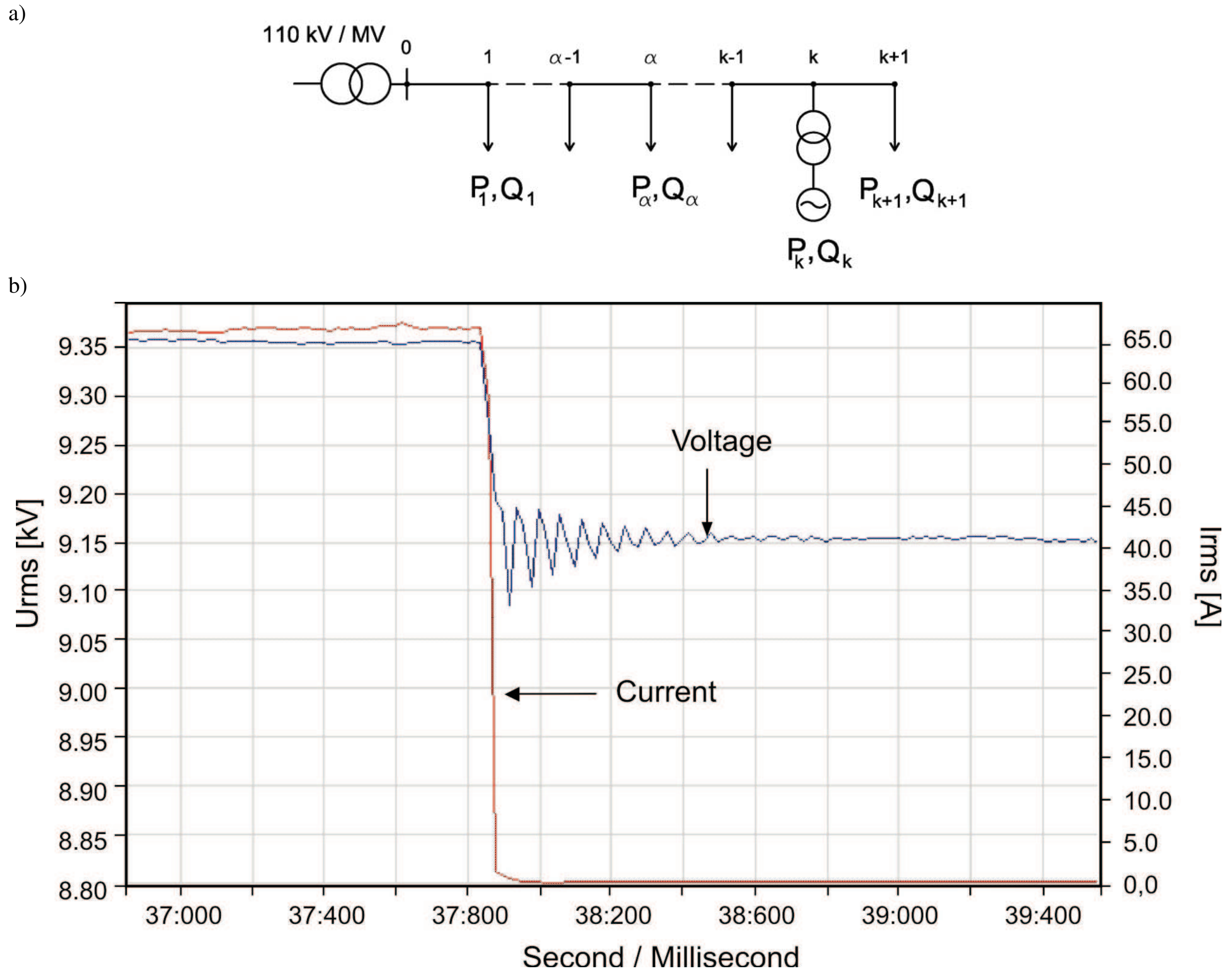


Fig. 1. (a) Energy source connected to MV network; (b) an example (one phase) of changes in the rms voltage value at the point of connection in response to switching-off a wind turbine

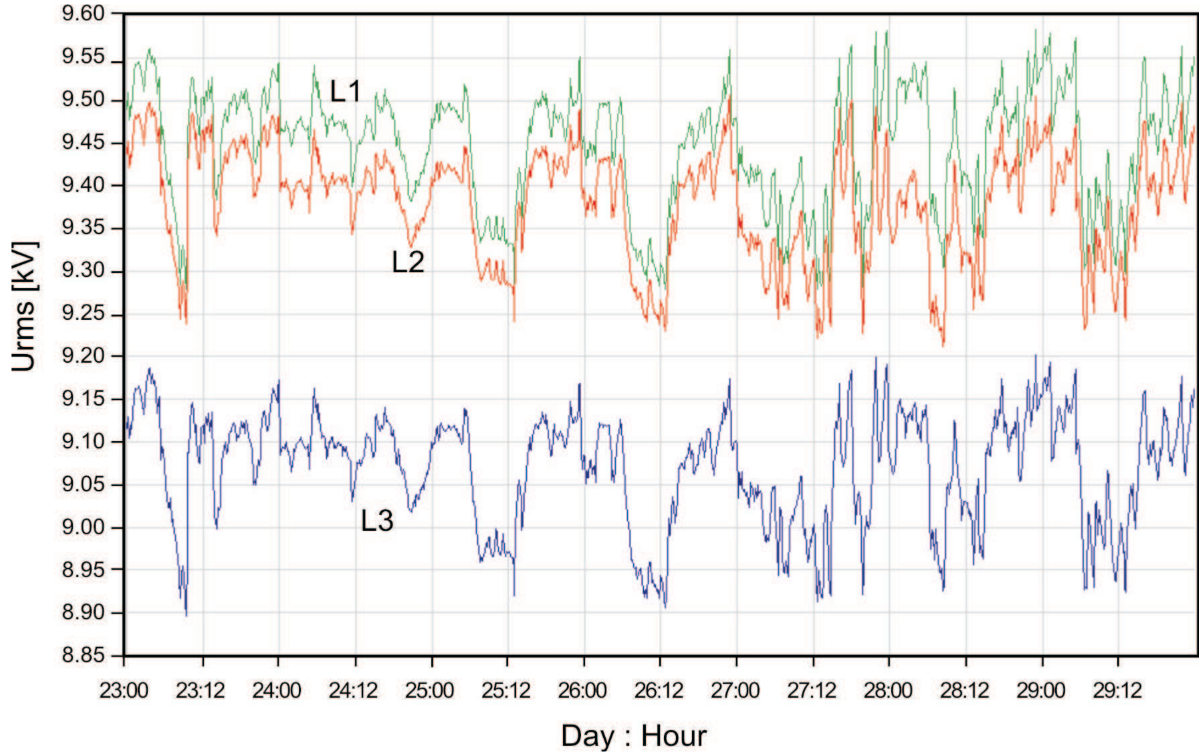
In high voltage networks the value of resistance R is relatively small in comparison with reactance X, therefore voltage levels in network nodes practically depend on reactive voltage drop component. However, in distribution networks the value of resistance is comparable or even bigger than the value of reactance, which causes that also the active power contributes to voltage drop and in consequence influences the voltage amplitude in the network nodes. Assuming that bus voltage at the distribution substation is set constant by a transformer tap changer, the change of voltage drop δU_{0k} after the source connection will result in voltage rise at the connection node (Fig. 1b):

$$\Delta U_{k\%} = \frac{100}{U_n^2}\left(R_{0k}\, P_k \pm X_{0k} Q_k\right). \tag{6}$$

The second element in the equation above is of little importance (in most cases $Q_k = 0$), so in practice the voltage rise depends on generated active power and the resistance of feeder from the connection point to the distributed substation. The smallest impact can be observed in the case of small power sources, which are connected near distribution substation. If energy sources are distributed far into the network than the voltage rise in the network nodes is bigger. In weak and heavily loaded networks it gives the positive effect of improving voltage profile. In some cases however, especially during small network loading voltage rise may result in node voltage being outside the acceptable range which may force the limitation of active power production. According to the network code (for example the Instruction of Distribution Networks Operation and Maintenace (IRiESD), Lodz Energy Company, 2006), value of voltage in the point of connection (point of common coupling – (PCC) should not exceed $\pm 5\%\ U_n$ in the full range of active power changes. Investigations showed [1] that the highest amount of DG that can be integrated to the network without the voltage limits being violated, so called "hosting capacity" [2], is approximately 2 MW for typical Polish MV network configuration. It should be noticed that reactive power compensation, which is required by DNO for sources which consume reactive power, may worsen the voltage profile.

2.2. Voltage variations/fluctuations. Voltage fluctuations (flicker effect) are introduced to the network by some types of DESs, first of all wind generators, whose output voltage varies dependently on wind velocity and direction (Fig. 2).

a)



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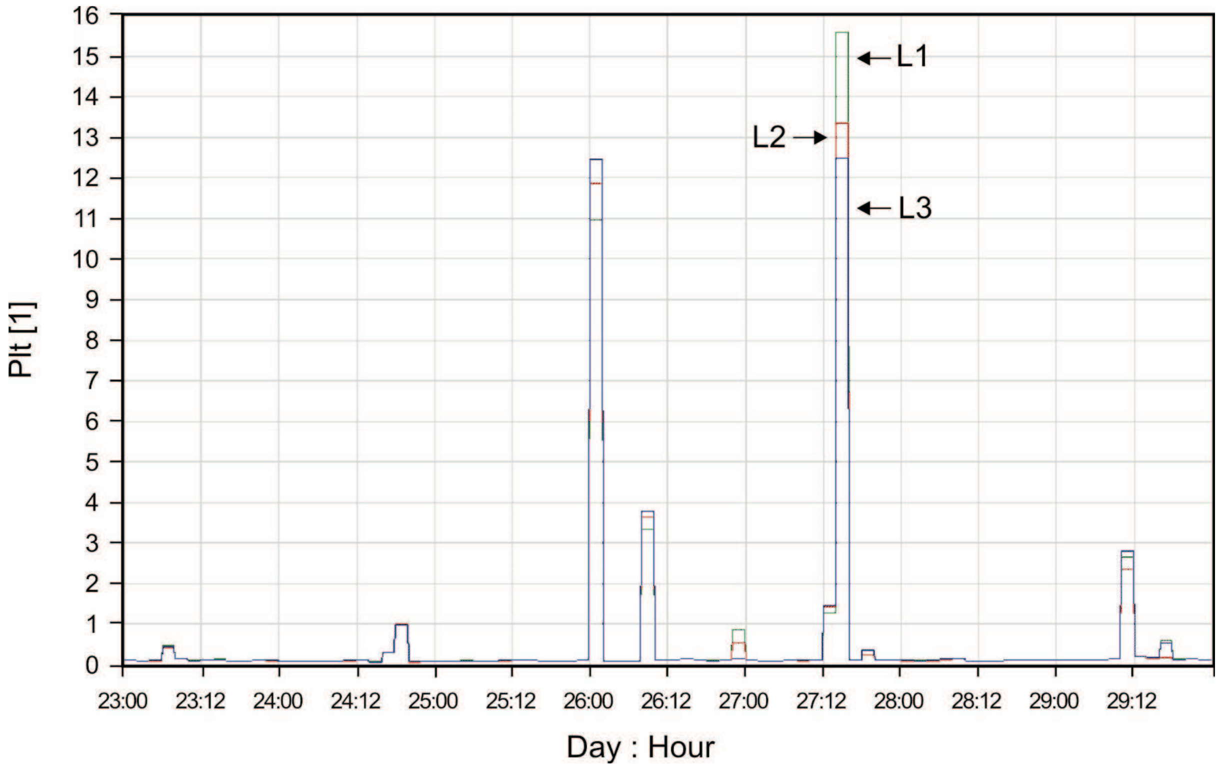


		L1	L2	L3
P_{lt}	CP95%	1.45	1.42	1.29
	max	12.49	13.34	15.59

Fig. 2. An example of the time-waveform of the rms voltage value at wind farm terminals (7 days) and the long-term flicker severity index P_{lt} measurement results

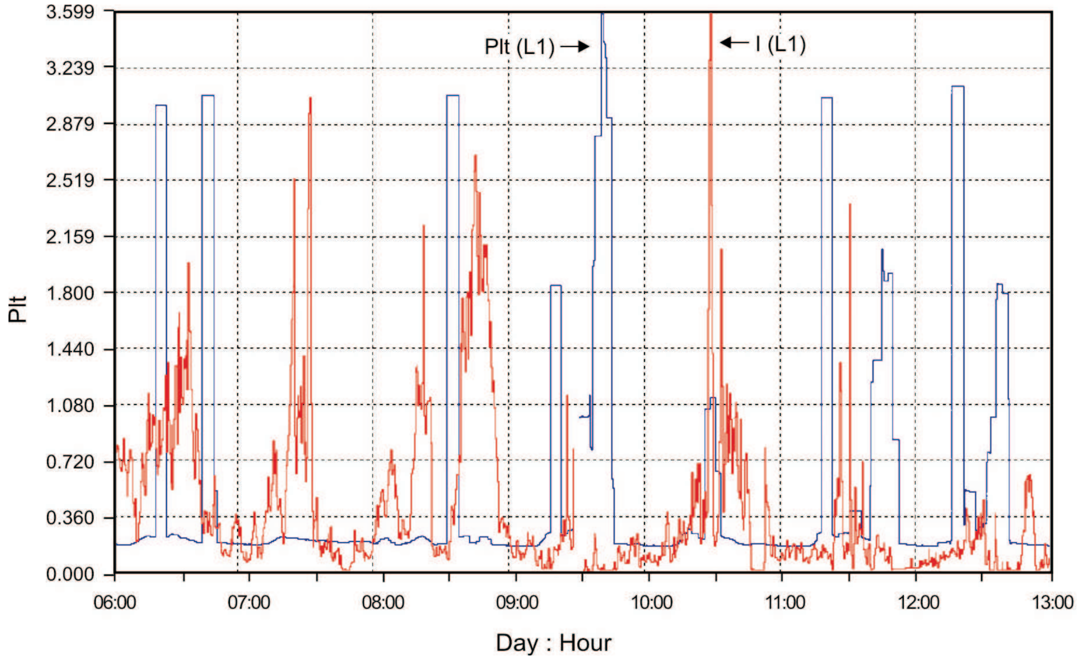


Fig. 3. The looking for correlation between the current and the P_{lt} index at the wind turbine terminals shows that in the analyzed case the wind turbine is not the source of voltage fluctuation

The assessment of flicker at the stage of connection design should be performed according to EN 61400-21 ("Wind turbine generator systems". Part 21: Measurement and assessment of power quality characteristics of grid connected wind turbines, 2002) for wind power stations connected to HV and MV networks for continuous operation as well as for switching states under start-up and nominal wind velocity. Flicker indices P_{st} and P_{lt} should be evaluated from the formula:

$$P_{st} = P_{lt} = c(\psi_k, \nu_a) \, \frac{S_n}{S_k''}, \tag{7}$$

where $c(\psi_k,\, \nu_a)$ is wind farm flicker coefficient obtained from wind turbine tests, ψ_k is network impedance phase angle, ν_a is annual average wind speed, S_n is wind farm rated power and S_k'' is short-circuit power at the PCC.

The determination of flicker coefficient $c(\psi_k,\, \nu_a)$ needs short-circuit analysis to be performed for the network and short-circuit impedance at the PCC to be calculated. Permissible values of P_{st} and P_{lt} for the MV network are equal to 0.45 and 0.35 respectively and are set by DNO.

The problem that often remains to be solved during measurements is a technical proof that the considered source is the actual cause of voltage fluctuation (Fig. 3). An appropriate assessment method for emission of individual working installation should be also urgently developed. This method should enable on-line determining (without the necessity of disconnecting the installation) the actual contribution of the converter installation to the total voltage fluctuation occurring at the point of its connection.

2.3. Rapid voltage changes. The connection of certain types of DG units to the distribution grid may lead to the occurrence of voltage changes due to switching operations in the DG installation. Currently there is no precise definition (at the international level) of the rapid voltage change and uniformed limit values for this disturbance.

There are diverse limit values of the rapid voltage change caused by DG operation, e.g. switching operations in the DG installation (usually start/stop operations of equipment, switching a capacitor bank etc.). This variety of limit levels (e.g. 3% (IEC 61000-3-3: Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems, for equipment with rated current $\leq$ 16A per phase and not subject to conditional connection, 2008.), 6% (IEC 61000-2-2: Compatibility levels for low-frequency conducted disturbances and signaling in power supply systems, 2002)) can be expected to be uniformed.

2.4. Unbalance. Single-phase DG units connected to LV networks contribute to unbalance phenomena. It seems that presently in most cases there is no danger of increase the negative-sequence components unbalance. However, where small-scale DESs, installed at the customer's site, has become more popular and taken up a significant share of the electricity production, the situation can be different. Many of these relatively small units, such as photovoltaic installations, are connected to the grid at LV by means of single-phase power electronic inverter units. The connection point has a relatively low short-circuit power level which lead to a potentially larger unbalance of the voltage compared with connections at higher voltage level.

For systems with the neutral point directly connected to earth, the zero-sequence unbalance ratio can be relevant.

It may occur that in the near future specific limits for distributed generators will be necessary. An assessment of the DES-inverters contribution to total unbalance is not a simple task since unsymmetrical loads are connected to the same network. However, methods to calculate this contribution as well as a suitable testing arrangement and simulated testing grid may soon be needed.

2.5. Harmonics DES which uses power electronic equipment may be a source of current harmonics and accompanying voltage distortion[1]. Nevertheless, it seems that because of the DG-converters specificity (a generating system producing rather than consuming energy) there is the need for modifications specified in this standard with respect to:

- Limit values. For instance, considering that modern DG inverters are capable of active shaping their output current, the limits for inverters, according to IEC 61000-3-2 (Limits for harmonic current emissions (equipment input current $\leq$ 16A per phase, 2009) can be lowered (Fig. 4). This feature of inverters is currently not taken into account in test procedures, whereas it should be.
  Additionally, standards (e.g. IEC 61000-3-2: Limits for harmonic current emissions (equipment input current $\leq$ 16A per phase), 2009) cover frequencies only up to 2 (2.5) kHz, for any higher frequency, currents shall not exceed 0.5% of the device nominal current at fundamental frequency[2]. Currently, when fully controlled semiconductor devices operated at high switching frequencies are commonly used in converters, the operating frequency band should be much more precisely defined.
- The required response of the inverter to voltage harmonics at the point of common coupling. Conventional generation will contribute to load harmonics (a feature of its inherent electrical response to network voltage distortion). The requirements for inverter connected DESs in such conditions are undefined. Depending on its control, the inverter has the capacity to shape its output current and contribute to harmonic loads. Standards/guide-lines on preferred inverter behaviour under such conditions are required.
- Test methods and procedures to measure current harmonics of DES-converters. In many such inverters, harmonic currents seem to have a significant dependency on the harmonic voltage content of the AC-system voltage. In this case, the current standard test conditions as defined in the above mentioned IEC international standards do not consider real system conditions with respect to the harmonic voltages in system voltage. According to these standards, tests should be performed with an ideal grid. In the result the measured currents are very often comparatively lower than under the condition of real system operation.
  The same happens when a large number of generators are connected to the network. For example, large number of inverters on low-voltage feeders can give power quality problems, even if the inverters individually comply with relevant emission standards. As harmonic current pollution of inverters depends on the voltage pollution of the grid, some inverters can produce higher than expected current harmonics, simply calculated from the inverter configuration.
  Since some inverters degrade the harmonic content when operated in non-ideal (realistic) grids, this characteristic should be respected in the tests. Tests should be performed on grids with defined harmonics: the simulated grid must not introduce disturbances. An adequate simulation grid must be used during test.
  Finally, the harmonic currents differ much under different generation conditions, e.g. there is a great difference between high generation and low generation. The assessment for grid connection of DG-converters shall take also into account this fact.

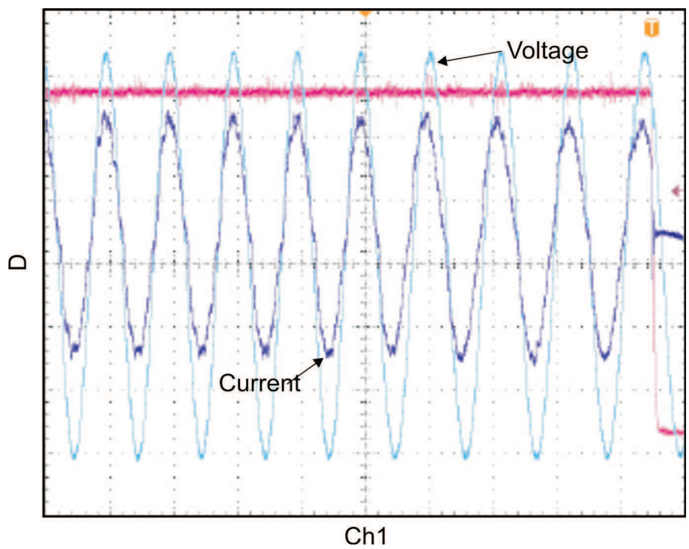


Fig. 4. Example waveforms of the current and output voltage of a photovoltaic power source

[1]For countries where standards IEC and EN series 61000 are applicable, DG units can in principle be considered as loads.
[2]Providing harmonic capability from the inverter interface may require high bandwidth power electronics leading to a reduced efficiency.

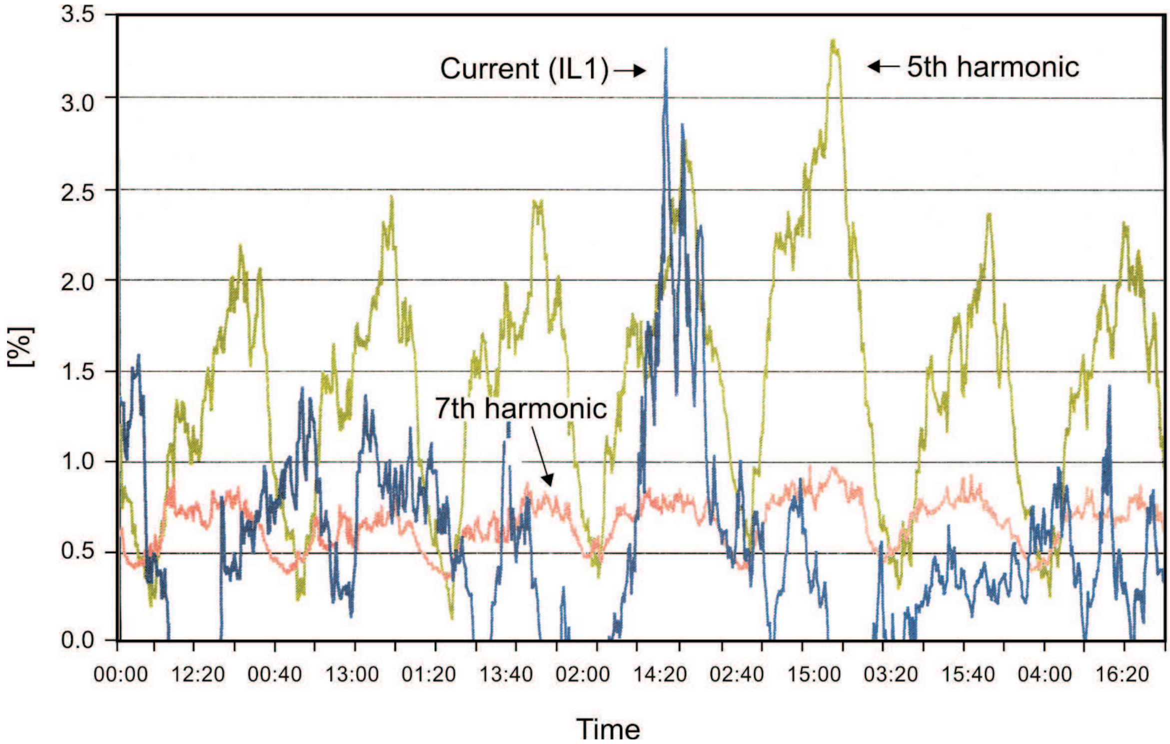


Fig. 5. Example time-characteristics of the 5th and 7th voltage harmonics at the wind farm supply terminals (20 MW, ten turbines with power electronic converters) and the rms current (110 kV). The lack of correlation between the characteristics shows that the wind farm is not the source of distortion

- Assessment method for emission of working installations. Taking into account the current approach used by network operators whose purpose is to share emission rights between network users based on subscribed power, very urgently should be developed an appropriate assessment method for emission. This method should enable on-line determining (without the necessity of disconnecting the installation) the actual contribution of the converter installation to the total voltage distortion at the point of its connection (Fig. 5).

In the case of older wind turbines with induction generators a short-duration harmonic emission may occur during starting using a power electronic softstart system (Fig. 6).

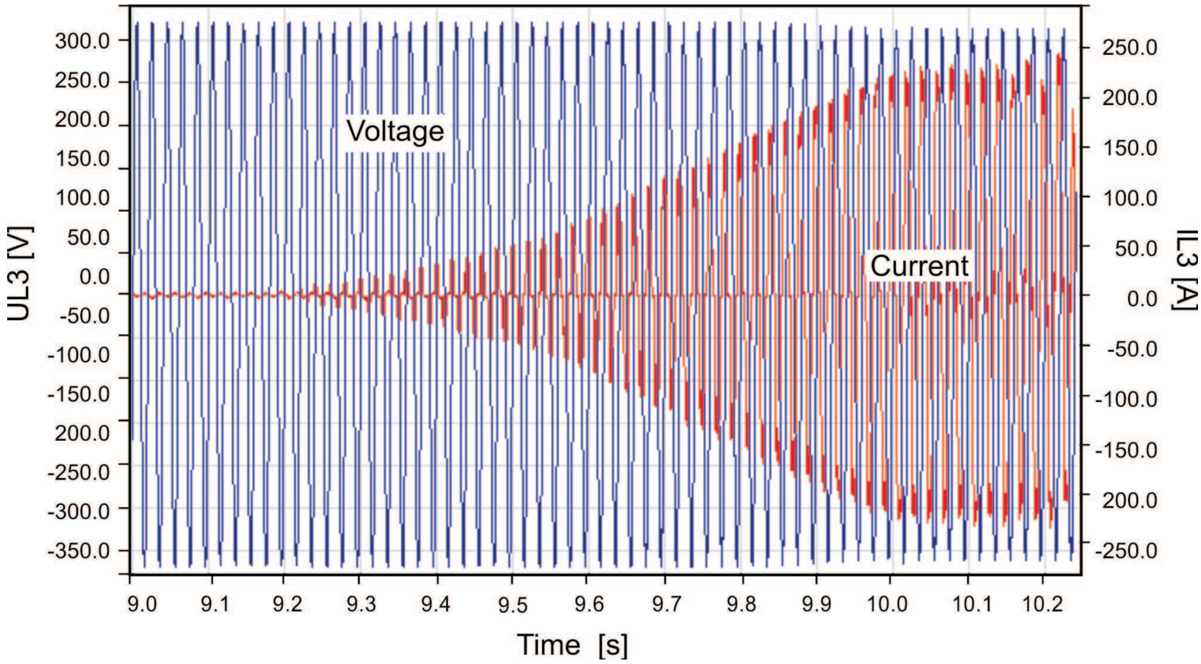
The voltage and current oscillations caused by reactive power compensation capacitors switching, as well as the overcompensation occurring in wind farms with extensive cable networks, may also be a problem (Fig. 7).

2.6. DC Injection. The injection of DC current by distributed generators into distribution networks has received increasing attention. There is a concern that transformer less inverters may inject sufficient current into distribution circuits to cause distribution transformer saturation. The possibility that a DC-component (offset) on voltage or current will appear and flow into the grid has therefore to be considered. Thus there exists a need for determining in IEC standards both: the limit values and the procedure of measuring DC current component for different types DG-converters (e.g. IEV 161-07-11: International Electrotechnical Vocabulary, IEC 2009, http://dom2.iec.ch/iev; IEEE 1547: Standard for interconnecting distributed resources with electric power systems, 2003)[3].

2.7. Case study. It seems that problems with power quality may arouse first of all in weak rural LV networks, where installing DESs, particularly the renewable ones, is most probable. Electricity production from his own source may be an attractive mean for the investor, aiming at the decreasing of costs and increasing effectiveness of his farm or household. Favourable field conditions and easy location outside high density zones will be conducive to the development of such sources. On the other hand, the rural network of radial configuration, in general, are not adjusted to installing new sources. They are supplied from the transformers of relatively small capacity and deliver electrical energy to customers who utilize mostly single-phase load devices. These networks are usually underinvested and their power quality characteristics are often pushed to the limits. In such conditions connecting the single-phase sources of power comparable or even greater than the power of other investor loads may cause power quality characteristics to go outside the limits. Moreover, dynamics of the variations may be significant because of the stochastic variations of generated power as a function primary energy amount available at the moment.

[3]The use of converters employing the symmetrical control, as defined in (IEV 161-07-11) is exclusively permitted. For instance, in LV networks the use of systems, which due to their structure may inject a DC component into the network, is prohibited for co-operation with DESs (IEEE 1547).

a)



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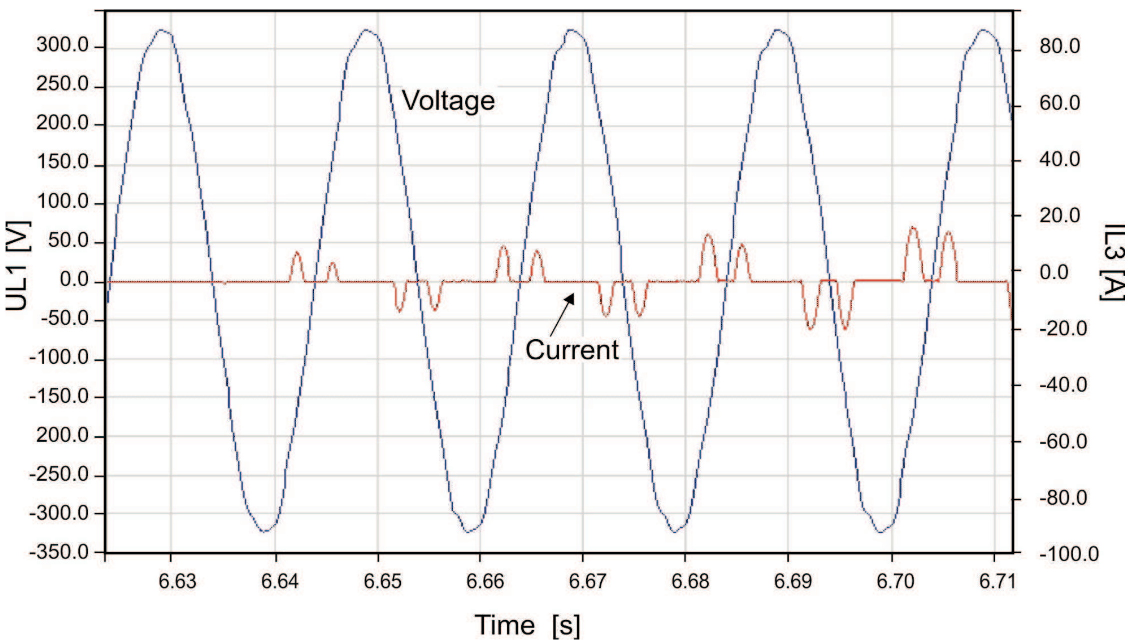

Fig. 6. An example of soft starting of a turbine with induction generator

The following example of particularly unfavorable but possible situation has been considered to illustrate the impact of DESs on the supplying network [3]. An overhead rural LV network is supplied from the distribution transformer of 63 kVA rated power. It is assumed that wind and solar energy sources are installed at the end of Al 4×25 mm^2, 500 m long feeder, as the most probable and easy in utilizing by an unqualified owner. The wind turbine of 5 kW rated power is connected to phase A and produces active power in the range (30–110)% of its rated power with constant tg$\phi = 0.4$. The photovoltaic source of 3 kW is connected to phase B and produces active power in the range (20–100)%. In the phase C a single-phase load is connected which maximum active power is 4 kW and reactive power 1.5 kVAr. Furthermore, other loads connected to the transformer substation are taken into account, which charge the distribution transformer with balanced 3-phase load of 30 kW and 12 kVAr. Simulation of the network operation was performed using the network simulator worked out in PSCAD/EMTDC environment. Power quality at the point of the sources connection was assessed according to the (EN50160: voltage characteristics of Electricity Supplied by Public Distribution Systems, 2007), however the time scale was different. Averaging time was assumed 0.5 s instead of 10 min and the time

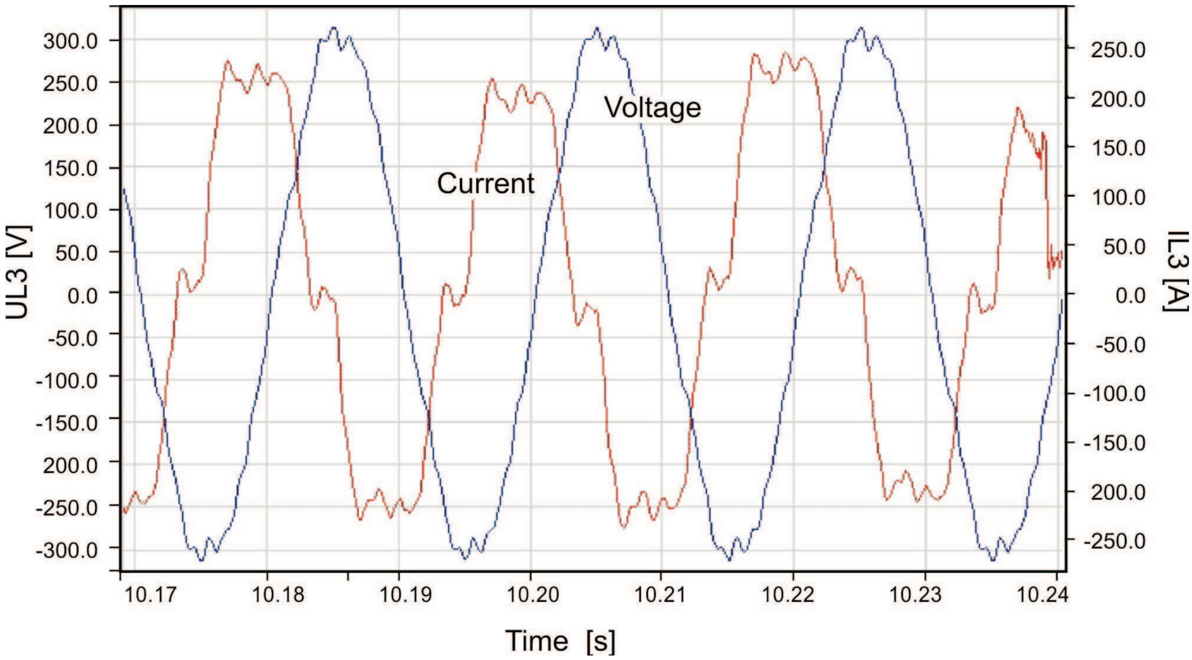

Fig. 7. Overcompensation, which often occurs in a wind farm power supply lines due to the cable line capacitance

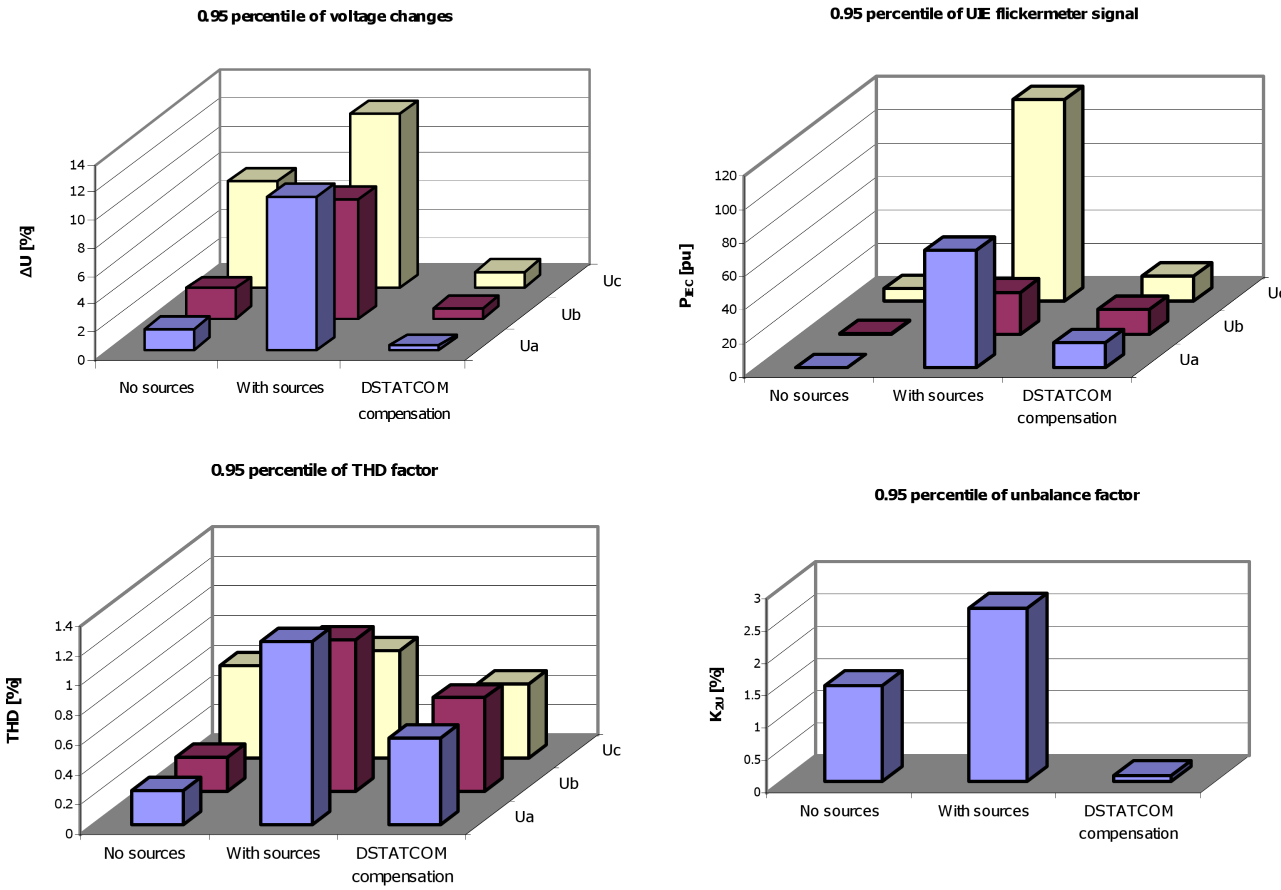

Fig. 8. Voltage characteristics at the PCC showing the impact of RESs on the supplying LV network – case study simulation

of assessment was 50 s instead of one week. In Fig. 8 the results of simulation are shown in the form of 0.95 percentiles of voltage characteristics. One can observe significant increase of PQ indices after the sources connection. This negative impact can be mitigated by additional electronic equipment connected to the PCC, like DSTATCOM compensator. The effect of compensation is also shown in the Figure.

3. Employing DESs for power quality improvement purposes – ancillary services

According to the International Electrotechnical Vocabulary (IEV) (http://dom2.iec.ch/iev) "ancillary services" are the tasks to be performed by operators and customers/users for increasing the quality, safety, reliability and efficiency of supply. In relation to the DESs, the sense of the term "ancillary services" has been expanded to all additional functions of grid-coupling converters, beyond their basic task, i.e. transferring active power/energy to the grid in the form suitable to be converted into other forms of energy, adequate for intended purposes. This approach allows concluding that converters can be employed for the purposes essential for:

- energy producers – effective energy generation, increasing the reliability of electric power supply,
- network operators – increasing the functionality and efficiency of electric energy conversion and distribution, increasing the reliability of electric power supply, improvement of voltage quality,
- end-users – increasing the reliability of electric power supply[4], power supply conditioning (sinusoidal, balanced voltage, without voltage events), reduction of electromagnetic disturbances emission from the users' equipment (from the perspective of the electric power supplier the user can be perceived as a linear, balanced load of resistive character), increased effectiveness of energy conversion.

Ancillary services have always been a part of the electric industry, but only in recent years and supported by liberalization, their relevance has been recognized and they have been considered to be traded on a market basis. There is potential for distribution network ancillary service markets in parallel with the increase in electricity generation from DES and it is worth reiterating the importance of anticipating future ancillary services in the specification of requirements for grid inverters.

Grid side services on distribution level apply first of all to supply quality improving by the compensation or mitigation of power quality events introduced to the grid in normal and fault network operation conditions. They also include power factor correction and reactive power compensation.

Contribution of DESs to voltage support during faults needs reactive power management. From an economic perspective two main cost categories have to be distinguished with regard to reactive power supply: investment costs and variable operational costs. Operational costs of reactive power supply are caused mainly by additional losses in the grid-coupling converter. Investment costs occur if the converter has to be oversized in order to guarantee a certain reactive power capacity in all operational situations. The result of the costs-benefit analysis is that it is economically attractive to use distributed generators for reactive power supply in many situations. Most important for network operation is the enhancement in reactive power reserves required to control and maintain network voltages within prescribed limits. In many applications the relative short time of work with the energy source peak power, allows to employ a converter for the purposes of providing ancillary service without considerably increasing its power.

Table 1
The problems occurring in distribution networks and power electronic equipment most commonly used to solve them after Ref. 4

	Voltage disturbances	Converter systems used to fulfil the task
Variations	Voltage level, slow changes in voltage magnitude	DVR, SVC (TSC, TCR, FC /TCR, TCR/TSC), DSTATCOM, UPFC STCSB, AC/AC Continuous Voltage Regulators
	Voltage fluctuations	SVC (TSC, FC/TCR, TCR/TSC) DSTATCOM
	Voltage and current unbalance	SVC, DSTATCOM, UPFC
	Voltage and current distortion	APF
Events	Fast voltage changes,	DVR, DSTATCOM
	Voltage dips and swells	DVR, STS
	Short interruptions	STS, ESS, DVR
	Long interruptions	ESS
APF	– Active Power Filter	
DVR	– Dynamic Voltage Restorer	
SVC	– Static Var Compensator	
TSC	– Thyristor Switched Capacitor	
TCR	– Thyristor Controlled Reactor	
FC	– Fixed Capacitor	
STATCOM	– Static Synchronous Compensator	
UPFC	– Unified Power Flow Controller	
STCBS	– Static Tap Changers Series Booster	
STS	– Static Transfer Switch	
ESS	– Energy Storage System	

[4]Application of converters as a part of stand-by power supply sources has also a considerable importance at the system operators' level.

Power electronic energy converters interfacing DESs applied to accomplish ancillary services could be in the nearest future the alternative solutions to power electronics systems currently used in supply networks (custom power equipment/FACTS) in order to eliminate different electromagnetic disturbances. Table 1 [4] summarizes various possible problems that can occur in distribution networks in both: the steady and transient states, as well as common methods for their solution, indicating those employing power electronic equipment (not necessarily co-operating with DES).

The provision of ancillary services can, for example, be made compulsory by law (e.g. fault ride through requirements), and the services can be paid for on the basis of available capacity or by use or the services could be market-based and paid for at market prices (e.g. balancing services). Different approaches (payments by the TSO/DNO to the providers for recovering the costs when the services are mandatory, negotiated or auctioned contracts, open market with bidding, etc.) can be explored in the search for an optimum solution, taking into account that, in general, it would be very difficult, if not impossible, to develop business cases for investing in DG solely on the basis of ancillary service income. This issue needs a separate discussion and will not be taken in this paper.

4. General converter requirements for ancillary services

The following requirements concern practically all converters that perform ancillary services, regardless of their function, topology, voltage, etc.

- Considering the field of application, there will always be the tendency towards increasing individual power of equipment. This trend is characteristic for power electronic equipment applications to electric power engineering (cf. converters for wind turbines, growing powers of static compensators, etc.). There is thus a constant demand for new semiconductor devices with increasing ratings – voltage, current and switching frequency. The alternative solution is the modular design of converters, as the large-power units are, as a principle, built from smaller modules. High-power and very high power converters provided with additional functions may influence configuration of distributed power sources, e.g. wind turbines, since it may turn out that the construction of a single "network" AC/DC converter with a power sufficiently large to supply a whole wind farm can be more cost effective than installing individual converters for each turbine. Such central static energy converter can – apart from transferring active power to grid – perform various functions of FACTS and CUSTOM POWER systems. For the above reasons (large powers) there will always be trend towards increasing the efficiency of energy conversion resulting from the necessity for both: the reduction of losses and elimination of forced cooling (particularly under continuous operation conditions). Development of new technologies in this field would significantly change prospects for applications.
- A 3-phase 4-wire inverter would be most useful for LV applications, because it allows controlling in each phase independently (neutral balance capability). This also concerns four-wire output converter structure such, as not to convey the load unbalance to the side of local generators and therefore protect them from zero sequence and negative sequence components of currents and fluxes.
- In many applications (e.g. mitigation of voltage fluctuation, active filtering, reduction of the number of voltage events, etc.) a short time of converter response to a disturbance is very needed.
- The high switching frequency of semiconductor devices used in the converter structure enables more precise reproduction of the voltage and current reference signals and therefore improve the quality of an ancillary service being provided. The high switching frequency is often the cause of higher order harmonics emission.
- One of the expectations is certainly the reduction of their price. Very often decisions are made to resign from very good converter solutions to passive ones[5] that offer worse performance but are considerable cheaper. For the same reasons a purchaser often resigns from additional functionality, serving e.g. power quality improvement.
- As far as technology is concerned, the trend is toward an invisible (i.e., a plug-and-play) interconnection. Larger DES units typically have more stringent utility interconnection requirements as well as greater sitting complexity. Thus, there may eventually be two distinct DES markets: one for type-tested, plug-and-play, residential and small commercial units and one for larger site-specific DES.

5. Expectations for standards

As it was described in the previous sections, depending on the primary energy source and on the technology used for the conversion process, the connection of DG units to the grid may reduce the quality of supply on the network, increasing the electromagnetic compatibility problems. The impact of the phenomena depends largely on the short-circuit power available at the connection point of the DG unit. This may be one of the limiting factors that determine the number and size of DG units that can be connected. It seems that in this field is the strongest need for amendments and modifications to the existing standards. The practice shows that some corrections or amendments to these standards should be made because of the DG specificity.

5.1. Emission standards. Low frequency emission limits differ significantly in different countries' standards. Table 2 [4] shows example of standards most frequently used at LV level in different countries. The need for standards' unification at the international level with regard to limits is evident.

[5]For example: resignation from active filtering to cheaper (less effective) passive filters.

Table 2
Some DES specifications and EMC emission requirements applied in different countries after Ref. 4

	Flicker	Harmonics	DC Injection
Austria	$P_{LT} = 0.46$ at the PCC mostly affected	Individual calculated when inverter is used	5% or rated current not exceeding 1A Ref 5.2 (EN 50438)
Belgium	IEC 61000-3-3 IEC 61000-3-5	IEC 61000-3-2 IEC 61000-3-4	$<$ 1% of rated current; $1 > 1\%$, trip after 0.2 s
Canada	IEEE 519 or IEC 61000 series	IEEE 519, TDD = 5%	IEEE 1547: $<$ 0.5% rated current
France	Limited such that DSO can meet its commitments in terms of power quality $P_{LT} \leq 1$	Harmonics emissions should be limited	
Germany	IEC 61 000-3-3 IEC 61 000-3-11	IEC 61000-3-2 IEC 61 000-3-12	1 A max trip after 0.2
Greece	IEC 61000-3-3 IEC 61 000-3-11	IEC 61000-3-2 IEC 61 000-3-4	Under consideration; $<$ 1%
Italy	IEC 61000 series	IEC 61000 series	IEC 61000 series
Japan	ΔV_{10} must be < 0.45 in general	THD $<$ 5% each harmonic $<$ 3%	To prevent DC current from flowing out of inverter
Malaysia	$P_{ST} = 1$ $P_{LT} = 0.8$	THDV = 8% at 415 V	None
Netherlands	during one week 95% of time: $P_{LT} < 1$; always $P_{LT} < 5$	THD $<$ 8% during one week for 95% of time	
Portugal	IEC 61000 series	IEC 61000 series	EN 50438
Spain	IEC 61000 series	IEC 61000 series	IEC 61000 series
Australia	AS/NZS 61000 series	AS/NZS 61000 series	IEC 61000 series
USA	IEEE 519	IEEE 519	Varies among utilities
U.K.	BS EN61000	BS EN61000	20 mA G83 recomended level

5.2. Immunity standards [6]. The increasing presence of harmonics and interharmonics superimposed on the grid voltage due to distributed generation has to be taken into account also to guarantee that DG-inverters can continue working properly. Distributed generators should be able to withstand disturbances without false trips of the grid interface protection, overcurrents or other problems. On the pattern of tests proposed in standard (IEC 61000-4-13: Harmonics and interharmonics including mains signaling at a.c. power port, low frequency immunity test, 2002) similar test for other converters with various power and voltage ratings should be developed.

Practical experience shows that in power electronic systems there exists the problem of mutual adverse impact of converters on each other, long ago known in low-voltage systems. Often the cause is lack of immunity to commutation notches from other converters. It is worth to give attention to investigation and standardization of converters immunity.

5.3. Type testing. Today, the utility interconnection requirements and processes at the sitting of DES are far from plug-and-play. Type testing has not yet been accepted by most utilities. In most cases it may only be possible to achieve plug-and-play status for smaller DES units. Larger units will likely continue to be designed, engineered, installed, interconnected, and tested on a site-specific basis. This greatly increases the cost compared with what it would be if the interconnection system was both plug-and-play and pre-certified for installation for particular DER units.

It is anticipated that precise defining of requirements concerning the DER-converters (DER interconnection equipment in general) leading to interconnection equipment standardization will greatly assist marketplace deployment of DES units by lowering installation costs.

One of the main goals might be to design interconnection equipment sufficiently flexible that they not only meet certifications and receive type testing approval but also can be used in a variety of installation applications. The procedures need to be established that support type testing of specific equipment.

It seems that relatively quickly should/can be defined classes of equipment intended not only to feed active power to the grid, but also to contribute to the local power quality of the grid due to their inherent active capabilities. It seems purposeful to introduce converter classes (e.g. A, B, C, ...) adopting harmonic emission level and/or the converter capability of providing additional functionalities as classification criteria; these functionalities may result from local needs for improvement of voltage quality.

[6]The issue of the converters immunity to voltage dips, short supply interruptions and frequency variations have not been considered.

6. Conclusions

The assessment of distributed generation impact on the grid and quality of power supplied to consumers is not unambiguous. On the one hand, distributed energy sources emit disturbances to electric power network, but on the other hand they can be an effective means of compensation of such disturbances.

Development of a modular universal interconnection architecture with standard functions for power conversion, power conditioning and quality, protection, DES and load controls, communications, ancillary services, and metering is the cornerstone of streamlined DES interconnection.

Component integration is the single most important step in streamlining interconnection. Research is needed to help increase component integration capabilities, with the focus on developing a functional system architecture. This approach is indifferent to equipment specifications and seeks the development of a set of plug-and-play functional components that readily work with one another, regardless of who makes the component. Equipment performance improvements (e.g., increasing the efficiency, surge capacity, and reliability of inverters so they become less expensive to operate and have a mean time to first failure of greater than 10–15 years) and the design of more reliable, smaller, and more durable packaging for combining the interconnection components can hasten interconnection simplification.

For smaller units, complete power electronic subsystems may be assembled as a single unit that can be readily integrated with either a high-speed engine or high-frequency alternator to produce output power in the assume voltage and frequency range. Expanding on this approach, it may be possible to develop a simple plug-and-play interconnection package for smaller DES units. The ideal is a package with two power cords. In this vision, one cord plugs into the DES unit. The other cord has a standard 230-V plug that fits into the electrical power network via a standard 230-V socket.

Similarly, developing standard certification and testing procedures for interconnection components, also converters, and then deploying and field testing many of the recently commercialised interconnection devices is a needed step in the process.

It is clear that for the EU to fulfil its political objectives of ensuring sustainable and secure electricity supplies, it will be essential to provide an appropriate policy framework supporting system operation in the near future. If DES only displaces the energy produced by central generation but not the associated flexibility and capacity, the overall cost of operating the entire system will rise. In addition, the provision of ancillary services by DES will improve the viability of the DG projects.

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