Technical University of Lodz
Institute of Electrical Power Engineering

INTEGRATION OF DISTRIBUTED ENERGY SOURCES WITH ELECTRICAL POWER GRID

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Presentation contents

- Introduction – distributed generation definition and characteristics
- Impact of distributed generation on the supplying network
  - Network component load capacity
  - Voltage profile
  - Voltage quality
  - Short-circuit conditions
- Impact of the supplying network on distributed energy sources
  - Voltage dips
  - Tripping
- Using distributed energy sources for improving the quality of supply / Ancillary services
  - Inverters operating in current control mode
  - Inverters operating in voltage control mode
- Final remarks

Distributed generation

Distributed generation (DG) is characterised by:

- Rather free location in the network area
- Relatively small generated power
- Variation of generated power dependent on the availability and variability of primary energy
- Not subject to the central control
- The sources of power below 50 MW

[The Decree of the Ministry of Economy, 2007]

Two kind of sources can be distinguished in distributed generation:

- Sources using non-renewable fuels, mainly natural gas: microturbines, combustion engines, fuel cells (power in the range from a few kW to a few MW)
- Sources using renewable energy of wind, sun, water or biofuels, as well as geothermal energy: thermal-, wind-, water-, gas turbine, photovoltaic cells, fuel cells (power in the range from a few kW to dozens MW)

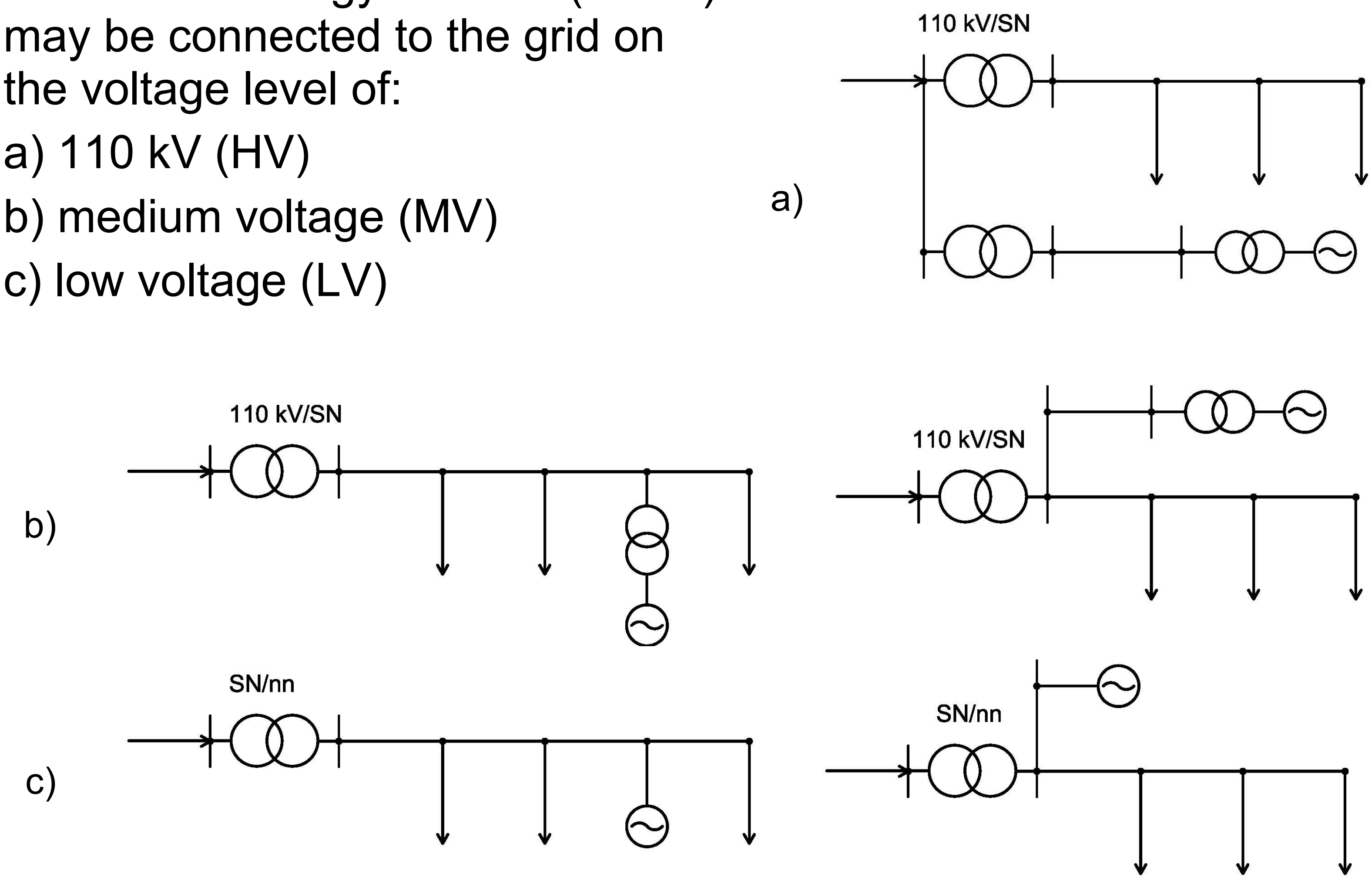
Connection to the grid

Distributed energy sources (DESs) may be connected to the grid on the voltage level of:

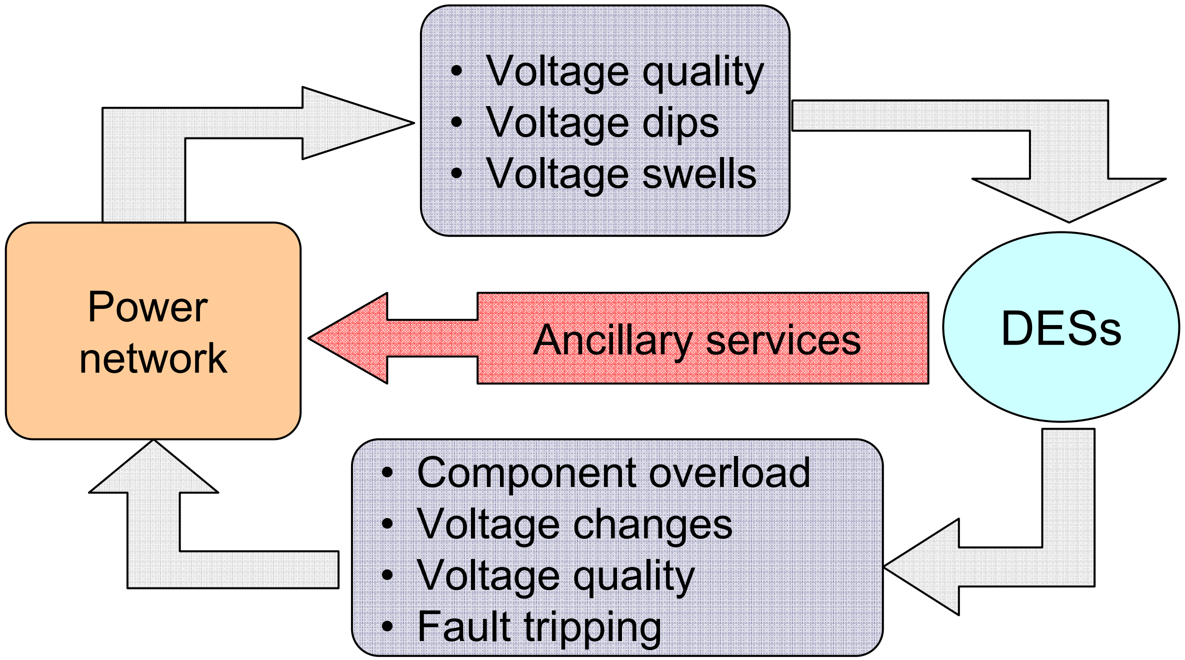
a) 110 kV (HV)

b) medium voltage (MV)

c) low voltage (LV)



Interaction between the power grid and DESs



The connection of big amount of DG power to electrical power grid changes its operating conditions and may result in the deterioration of the quality of energy delivery to customers and threaten the safety operation of the grid.

At the same time, DESs can be a potential measure for electromagnetic disturbances compensation and improving the power system security.

Connection requirements

The present philosophy of DESs connection – „no harm"

- Connection requirements should ensure:
  - Power grid operation safety
  - Maintaining the required power quality and reliability
  - Protection of the power system against damages caused by the improper operation of connected devices
  - Protection of the power system against damages in case of a fault or limitation in energy delivery
- For the DES of P_n>= 50 MW connected to coordinated 110 kV networks technical requirements are formulated by TNO (IRiESP –[8])
- For other DESs connection requirements are established by DNO (IRiESD – [9])

Hosting capacity approach

The question is: „What is the amount of DG power that can be connected to the grid with „no harm"?

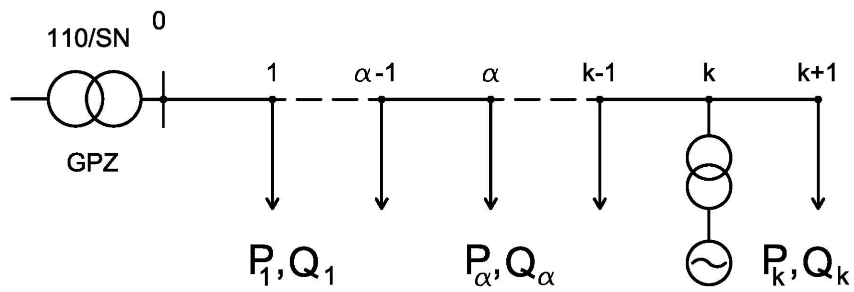
The answer is not easy, depends on:

- grid characteristics
- way of connection
- kind of a source and its power

- Hosting capacity - the highest amount of DG that can be integrated to the grid without violation of the limits defined for different aspects of the network safe operation in normal and fault network operation conditions [2].
- Performance indicators:
  - voltage levels at the network nodes
  - voltage quality indices
  - grid component load capacity
  - protection settings
  - power losses.....

Network component load capacity

MV distribution network



Energy source connected to MV network

$$P_{\alpha-1,\alpha} = \sum_{i=\alpha}^{k-1} P_i - P_k + P_{k+1}$$

$$Q_{\alpha-1,\alpha} = \sum_{i=\alpha}^{k-1} Q_i \mp Q_k + Q_{k+1}$$

If $P_k > P_{loads}$ than the power flows to the supplying network.
Usually, the connection of DES to MV network decreases network components loading what results in reduction of network losses.

Network component load capacity

Simplified criterion: $I_{ddmin} > I_{kmax}$

I_{ddmin} – min line load-carrying capacity

I_{kmax} – maximum current of the source

Hosting capacity for typical 15 kV grid:

cable lines s_n=120 mm^2 Al. – I_{ddmin}=285 A ⟹ S_k<=7,40 MVA

overhead lines AFL-6 70 mm^2 – I_{ddmin}=253 A ⟹ S_k<=6,64 MVA

Practical problems:

- Component overload may be expected in parts of the network designed for small loads – remote rural areas.
- Overload may occur during the time period of minimum load.

Network component load capacity

<u>Transmission network</u>

Because of the meshed configuration the analysis of load conditions is more complicated and it is difficult to foresee what the effect of a source connection will be without an exact load flow calculations.

Practical problems:

- The winds farms of relatively big power concentrated in the region of profitable wind conditions (e.g. the north part of the country where the network infrastructure is rather weak)
- Fault conditions - „n-2” criteria:
  - The security of power transmission should be guaranteed if a single component is lost - „n-1” criterion (no limitation in transmitted power)
  - The safety operation of the system should be guaranteed if one single component is switched off and one is lost (limitation in power acceptable)

Voltage profile

Distribution network

As opposed to conventional distribution power networks, in networks with DG the negative voltage drop is observed which lead to the increase of node voltages

$$\delta U_{0k} = \frac{1}{U_n}\left[\sum_{i=1}^{k-1}\left(R_{0i}P_i + X_{0i}Q_i - R_{0k}P_k \mp X_{0k}Q_k + R_{0k}P_{k+1} + X_{0k}Q_{k+1}\right)\right]$$

$$R_{0i} = \sum_{j=1}^{i} R_{j-1,j} \qquad X_{0i} = \sum_{j=1}^{i} X_{j-1,j}$$

The change of voltage at the PCC $\quad \Delta U_{k\%} = \frac{100}{U_n^2}\left(-R_{0k}P_k \mp X_{0k}Q_k\right)$

Assuming Q_k=0, the hosting capacity is $\quad P_k \le \frac{\Delta U_{k\%\min} U_n^2}{100 R_{0k}}$

$\Delta U_{k\%min}$ – the permissible value of voltage change

Voltage profile

- Voltage change after DES connection depends on:
  - distance between a source and GPZ
  - kind of a feeder and its load
  - the value of active power produced by a source
- The upper limit of voltage at PCC is +/- 5% U_n (IRiESD – [9])
- A study indicated [4] that the connection of DESs to MV network may cause the voltage rise on LV side of the transformers MV/LV of about 20-30 V. Hosting capacity is about 2 MW.
- Small amount of DG power can mitigate undervoltages in a heavy loaded network.
- Overvoltages are likely to occur in the conditions of light loading.
- DESs connected to distribution networks are not required to contribute to voltage control. The relatively small value of network reactance would need the considerable amount of inductive reactive power to get an effect of voltage decrease.

Voltage profile

<u>Transmission network</u>

- With minor amount of DG power there is no problems with node voltages, and even positive impact is visible during faults in the power system.
- With high amount of DG power network overloading may occur which lead to excessive node voltage decrease – a threat to voltage stability.
- DESs connected to the transmission networks should contribute to voltage regulations.
- In some cases voltage control through the reactive power changing of DES connected in MV may need active power production to be reduced.

Voltage quality

- DESs may introduce to the network disturbances such as voltage variations, flicker and current harmonics. According to the principle of electromagnetic compatibility the level of the disturbance introduced by a source should be lower than a defined limit value.
- Permissible values of voltage variations, flicker and voltage harmonics at the PCC with DES connected are set by DNO and apply to 0,95 percentile of the values measured during one week.
- For wind turbine generators emission levels are measured according to [EN 61400-21] (WINDTEST certificate).
- To assess how DES connection will influence voltage quality at the PCC voltage quality indices are determined on the basis of the WINDTEST, dependently on the short-circuit power of the network.

Voltage variation assessment

Flicker indices at the PCC for a single wind turbine generator

Continuous operation:

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

P_{st} – short term flicker severity

P_{lt} – long term flicker severity

$c(\psi_k, \nu_a)$ – wind generator flicker emission coefficient as the function of network phase angle ψ_k, and average wind velocity ν_a

S_n – wind generator power

S''_k – short-circuit power at the PCC

Switching states

$$P_{st} = 18 \cdot N_{10}^{0,31} k_f(\psi_k)\frac{S_n}{S_k''} \qquad P_{lt} = 8 \cdot N_{120}^{0,31} k_f(\psi_k)\frac{S_n}{S_k''} \qquad \Delta U_{dyn}[\%] = 100 k_u(\psi_k)\frac{S_n}{S_k''}$$

N_{10} – number of switching occurring during 10 min

N_{120} - number of switching occurring during 2 hours

$k_f(\psi_k)$ – step flicker emission coefficient

ΔU_{dyn} – voltage variation due to switching

Results of assessment - example

Excerpt from the expertise of the impact of 10 MW wind farm connected to 110 kV network

No	S''_{kmin} at PCC [MVA]	Ψ_K	k_f	$c(\Psi_K, v)$	Limits		P_{st}	P_{lt}
					P_{st}	P_{lt}		
Continuous operation $P_{st} = P_{lt}$, v = 7,5 m/s								
1	132.84	58.80	-	2.01	0.45	0.35	0.057	0.057
Switching states under nominal wind velocity, v = 12,0 m/s								
3	132.84	58.80	0.06	-	0.45	0.35	0.026	0.024

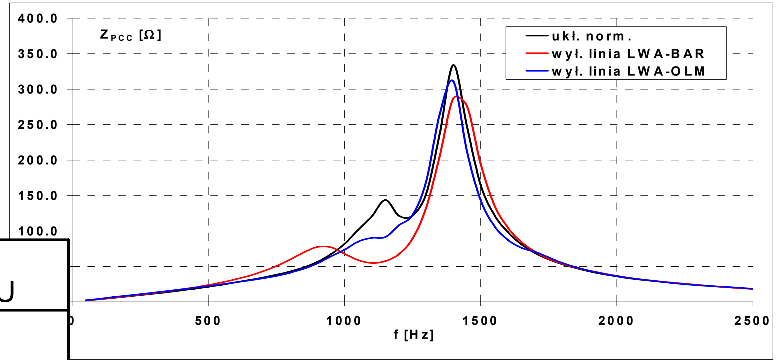
No	S''_{kmin} [MVA]	Ψ_K	k_u	ΔU_{dyn} [%]	Limit $\Delta U_{dyn}\|_{dop}$ [%]
Normal configuration					
1	132.84	58.80	0.54	0.8189	2.5

Voltage distortion assessment

The assessment of voltage distortion due to current harmonics introduced to the network by a source needs the frequency characteristic of the network impedance to be determined in different network configurations.

Practical example – 10 MW wind farm connected to 110 kV

h	$U_h/U_h\|_{dop}$	U_h/U_h	$THD_U\|_{dop}$	THD_U
-	[%]	[%]	[%]	[%]
5	1.5	0.13	4.0	0.830
7	1.5	0.12		
11	1.5	0.38		
13	1.5	0.42		
17	1.5	0.44		
19	1.5	0.14		
23	1.5	0.31		

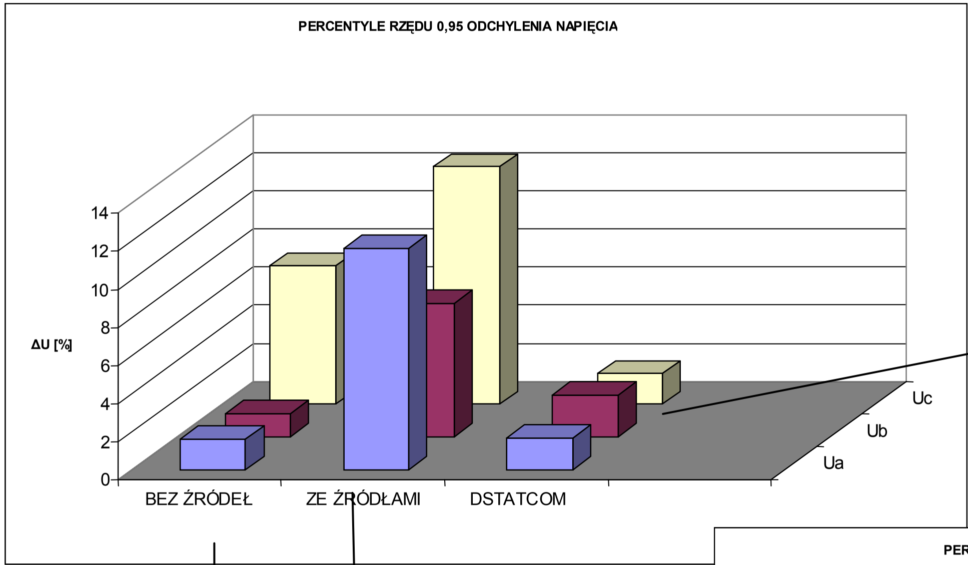


Example of network impedance frequency characteristic

Power quality - case study

- Network under study:
  - Overhead, rural LV feeder, supplied from the transformer of 63 kVA
  - Typical feeder Al 4x25 mm^2, 300 m long
  - Two RESs connected at the end of the feeder:
    - phase A - wind turbine of 10 kW rated power, produces active power in the range (30-110) % P_n with constant $tg\varphi = 0,4$.
    - phase B - photovoltaic source of 5 kW, produces active power in the range (20-100)%.
  - A single-phase load connected in phase C, which maximum active power is 4 kW and reactive power 1,5 kVAr.
- Power quality assessment at the PCC performed according to the PN-EN 50160 [3] – simulation time 50 s, averaging time 0,5 s

PQ assessment at the PCC for the case study

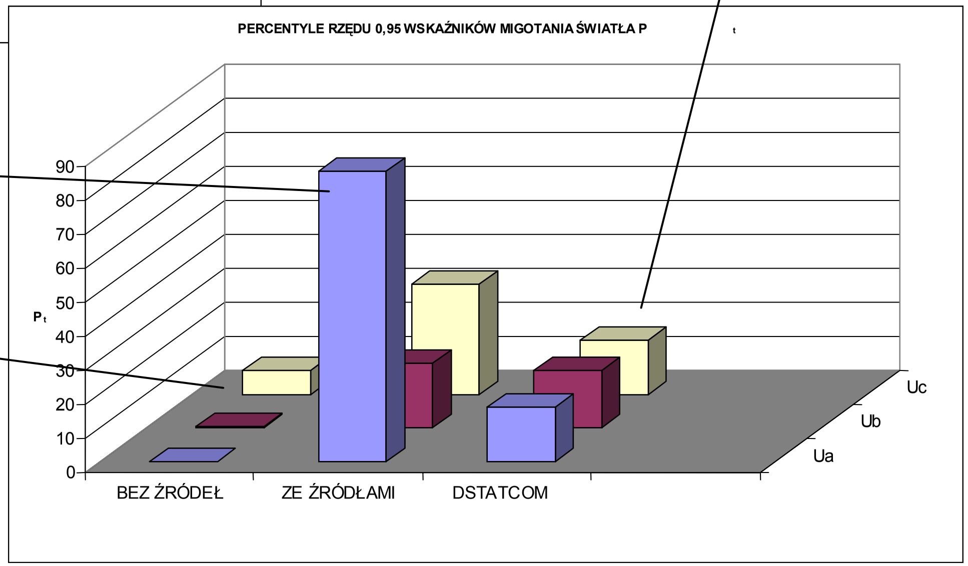


0,95 percentile
of voltage changes

Compensation by
DSTATCOM

With
sources

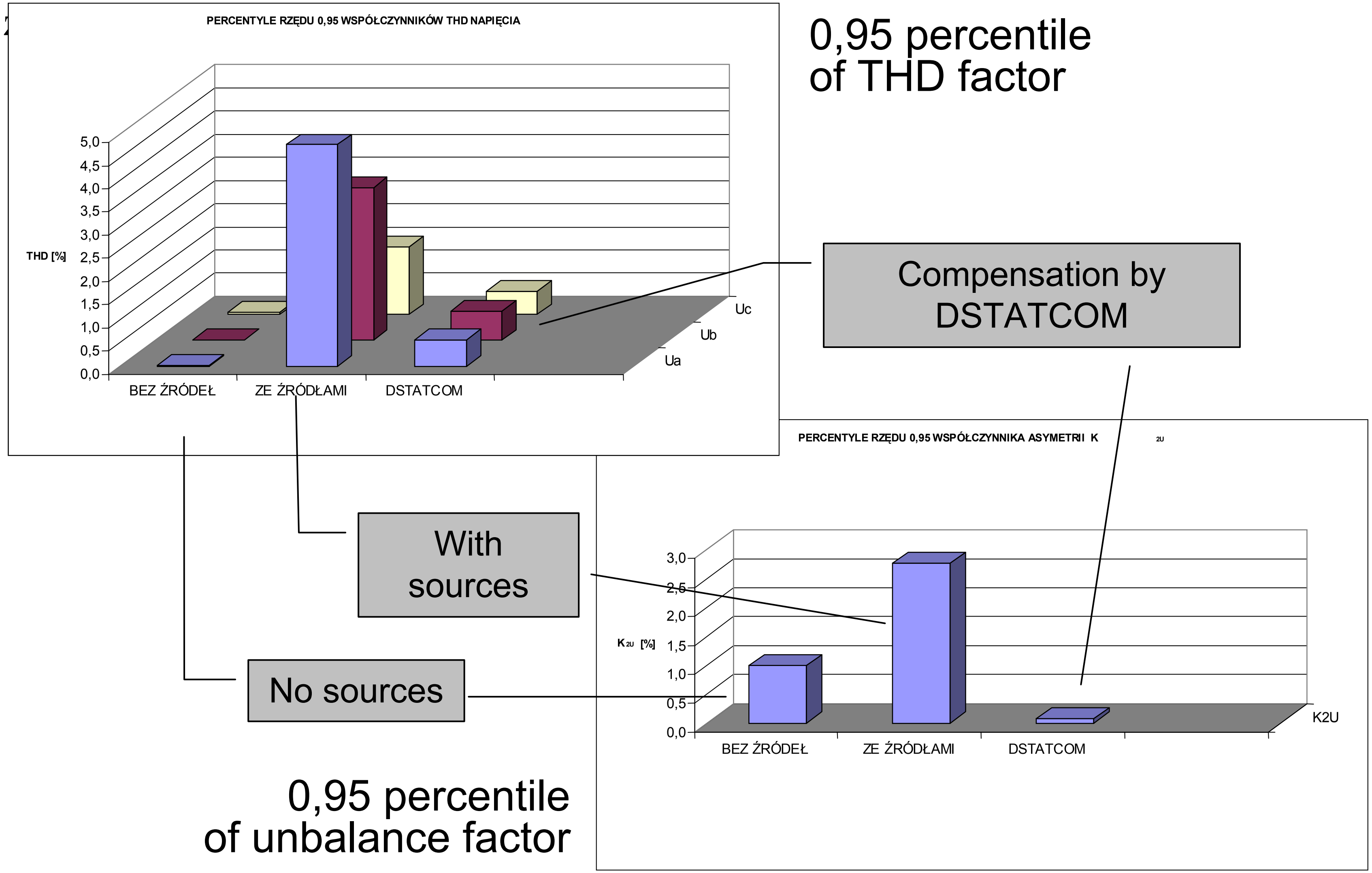
No sources



0,95 percentile
of flicker coefficient

PQ assessment at the PCC for the case study

0,95 percentile
of THD factor



0,95 percentile
of unbalance factor

Short-circuit conditions

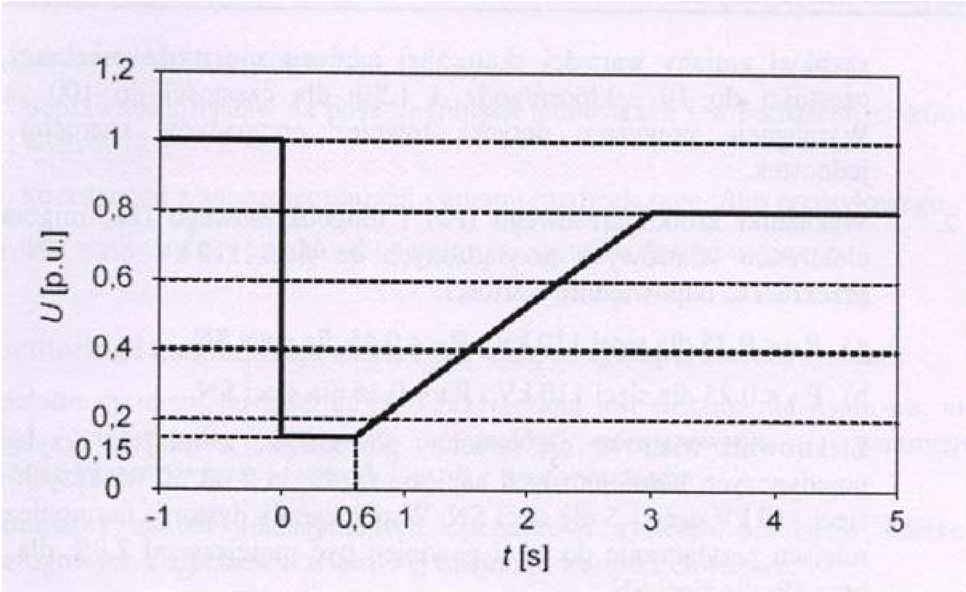
- DESs connected to electrical power network, in particular synchronous generators, contribute to short-circuit currents in the networks.
- In most cases it does not cause exceeding the short-circuit parameters of the equipment however, as reported in [4], such a situation may occur in LV networks.
- Increasing values of short-circuit currents may need network protection settings to be changed. Analysis of the protection performance is another problem to be considered if a feeder contains a high amount of DG. Incorrect protection operation will result in higher number of interruptions.
- Generator protections (IRiESD requirements) should be coordinated in network protection in order to obtain sensitive and selective performance in different network configurations and operation conditions.

Impact of the supplying network

- Bad voltage quality has similar impact on energy sources as on load equipment: reduction of the lifetime, increasing losses, erroneous tripping and damage.
- The permissible levels of disturbances in normal operation conditions are defined in compatibility standards or set by TSO, DNO as planning levels.
- A fault in the network may cause the generator tripping. To protect the grid against uncontrolled islanding operation the trip is forced in the time shorter than the time of overcurrent protection of the feeder.
- Tripping the source in distribution network may worsen voltage conditions in the grid.
- In the transmission network the tripping of big DES may upset the balance between generation and demand, thus influence stability of the network.

Voltage dips

The immunity of DES unit against voltage dips is imposed by DNO.



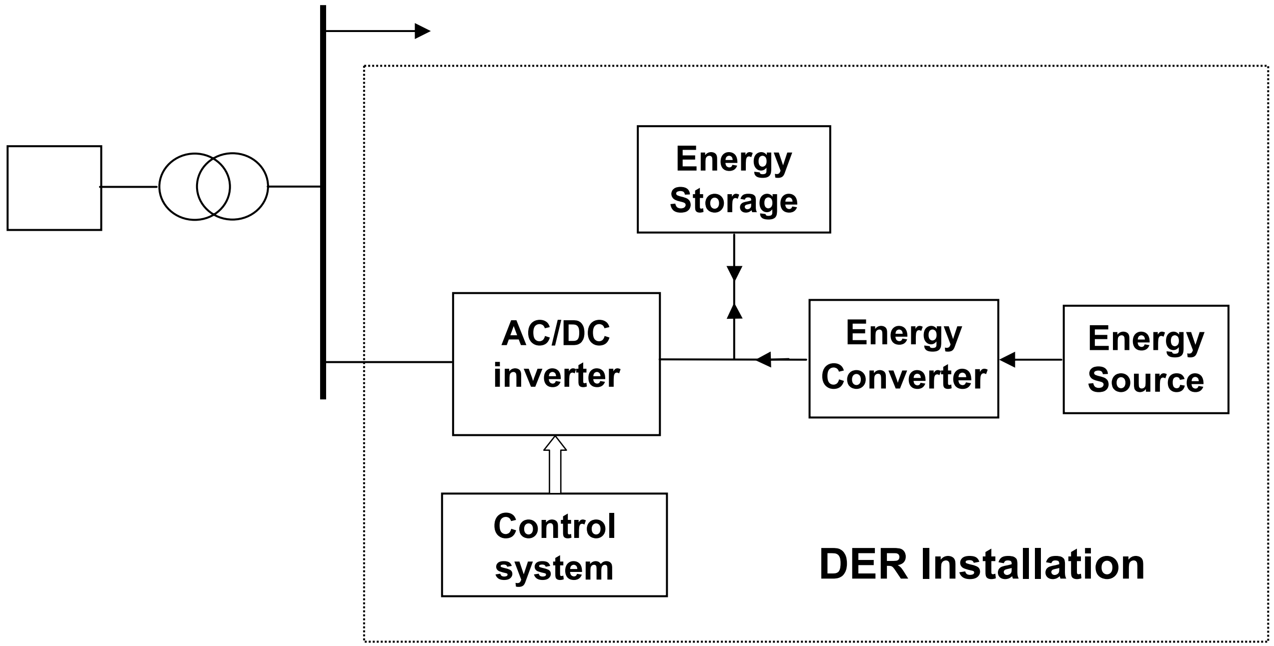
Fault-ride-through curve for wind farms [9]

DNO requires reactive power generation from wind farms connected to the transmission networks to support the voltage during faults in the grid.

Ancillary services provided by DESs

Many different DESs are connected with the grid by inverters. Their main task is active power exchange with the grid.

Ancillary services can be defined as additional tasks which DER inverters can provide to the network operator for increasing the quality, safety, reliability and efficiency of supply.



Ancillary services

Two points of view are put together in discussion on ancillary services:

- What are the network needs and real problems to be tackled?
- What are inverter capabilities ?

The main concern in the transmission systems is to maintain frequency and voltage stability in steady- and transient states. These are key issues for big power stations rather than distributed energy sources MV and LV connected, which can contribute to the system stability in a minor level.

The main task for the distribution network is electricity supply to consumers with high power quality and reliability. The network operation is influenced by disturbances, sources of which may be loads, distributed energy sources and the supplying network as well. Grid side services apply then to the improving supply quality and reliability in normal and fault operation conditions.

Ancillary services - supply quality

- Supply quality improving means the compensation or mitigation of power quality events introduced to the grid:
  - Voltage variations
  - Voltage dips or swells
  - Harmonics
  - Unbalance
  - Flicker

Other tasks: reactive power compensation or power factor correction

- The relatively short time of maximum power production may create for inverters an extra capacity to be used in ancillary services without increasing their ratings.
- High switching frequency inverter which can generate any set of three current or voltage waveforms is very suitable for ancillary services applications. For LV applications 3-phase 4-wire inverter would be most useful, because it allows controlling in each phase independently.

Inverter ancillary services example – a case study

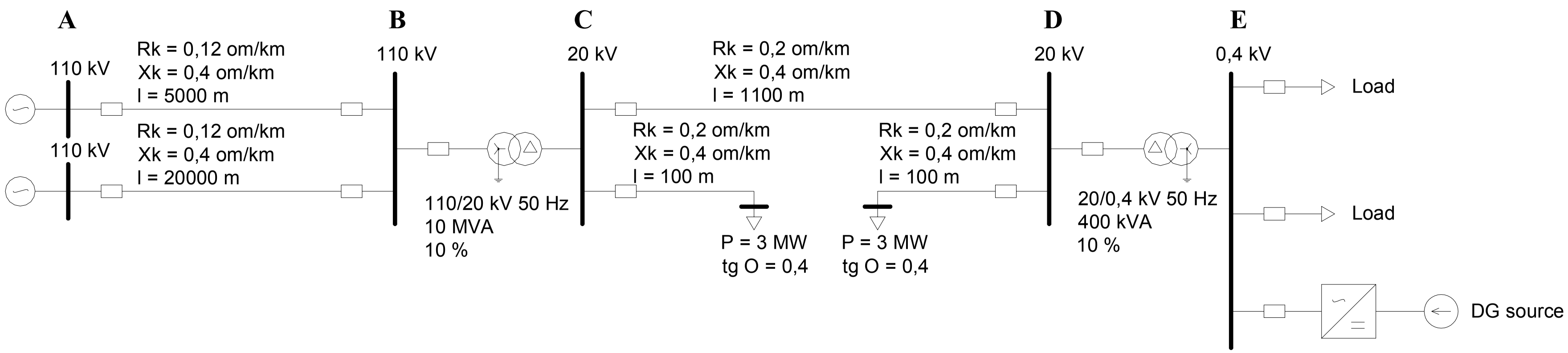
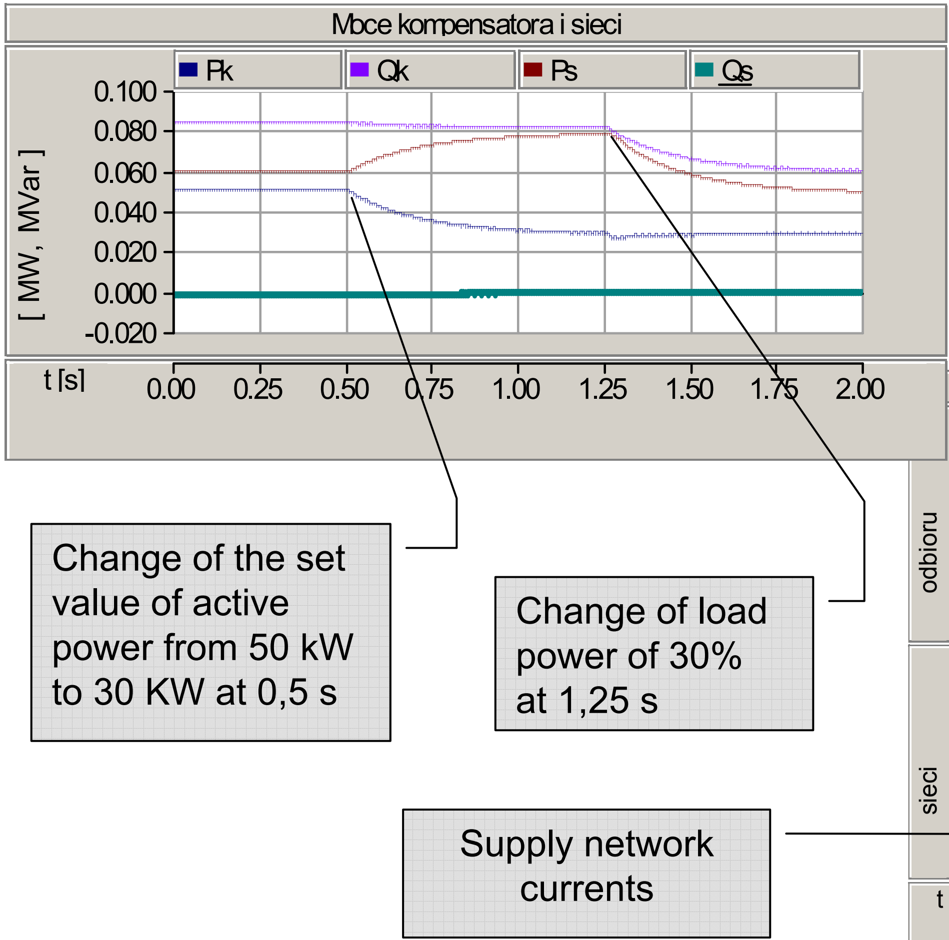


Fig.1. The network under study

1. Compensation of disturbances introduced by loads – DES inverter operates in current control mode
2. Compensation of dips coming from the supplying network - DES inverter operates in voltage control mode

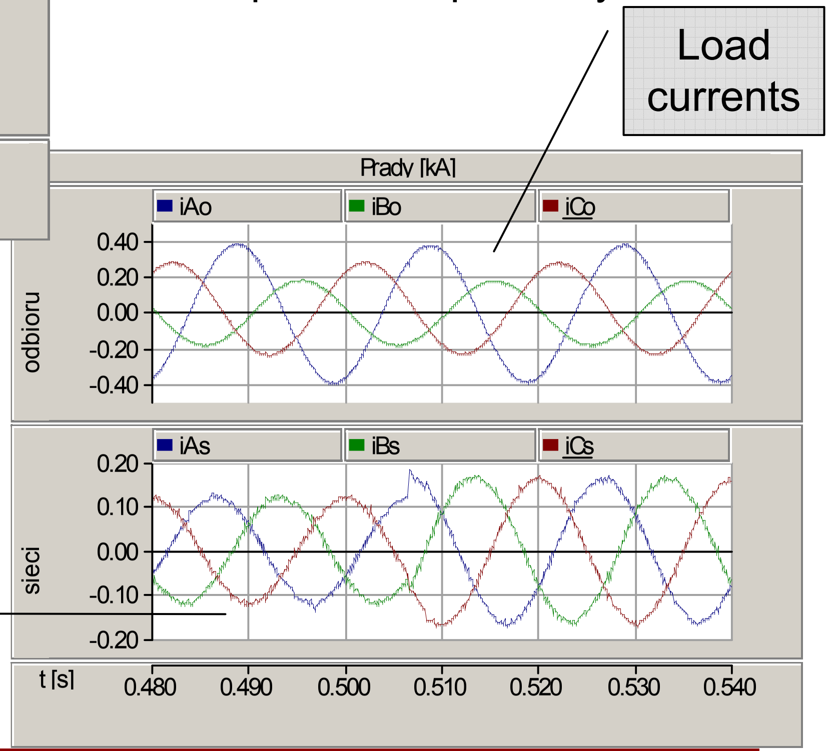
Inverter ancillary services – load compensation

The compensation of load unbalance and reactive power

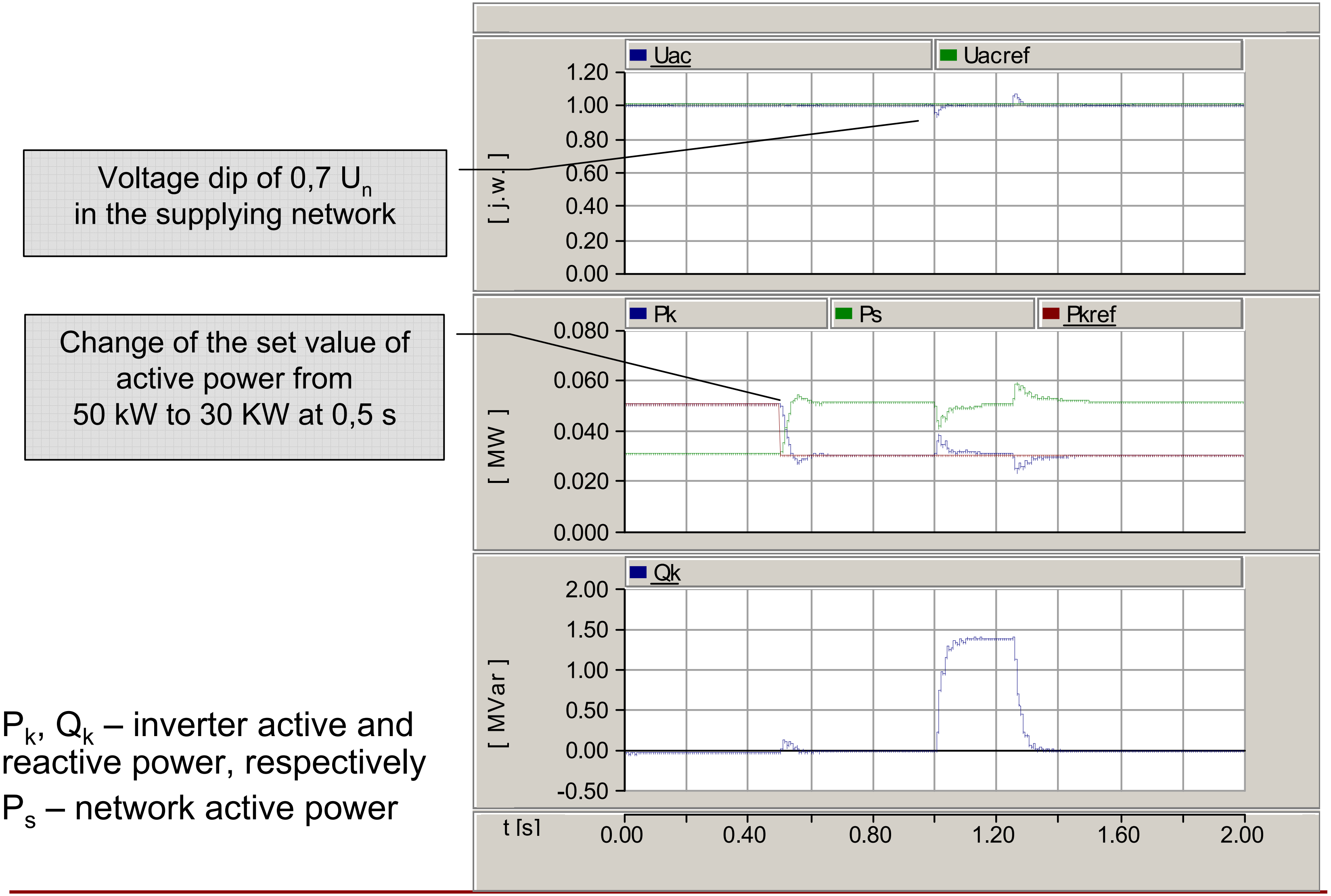


P_k, Q_k – inverter active and reactive power, respectively

P_s, Q_s – network active and reactive power, respectively



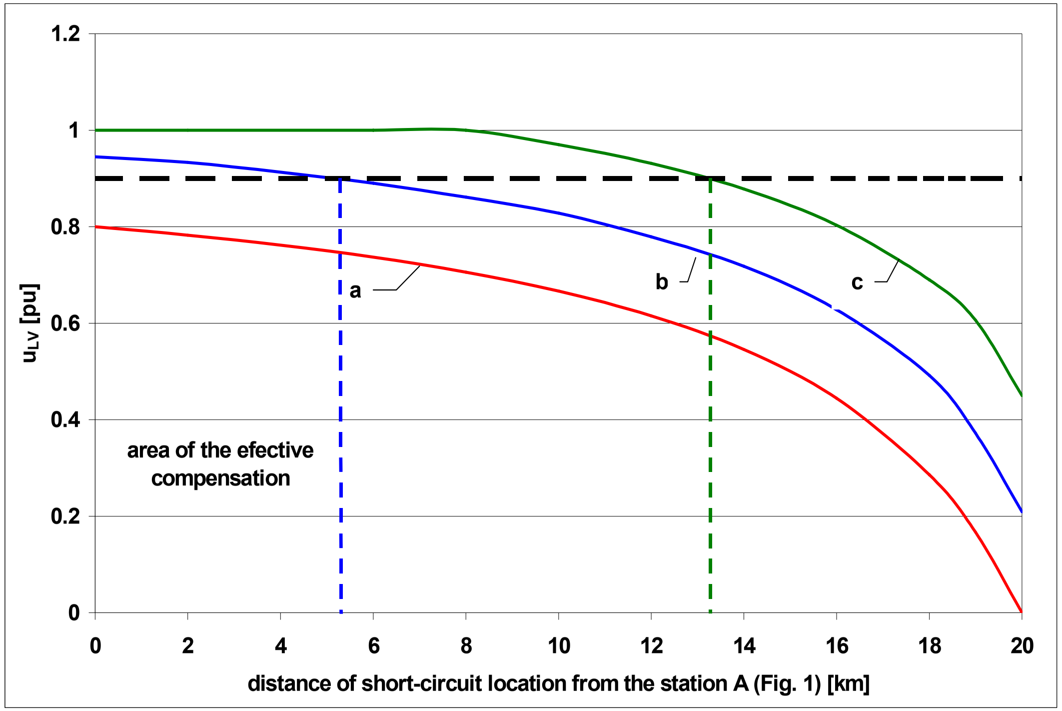
Inverter ancillary services – dip compensation



P_k, Q_k – inverter active and reactive power, respectively

P_s – network active power

Voltage dips reduction by DES



Three phase voltage dip compensation with DG inverter (L_D = 1 mH):

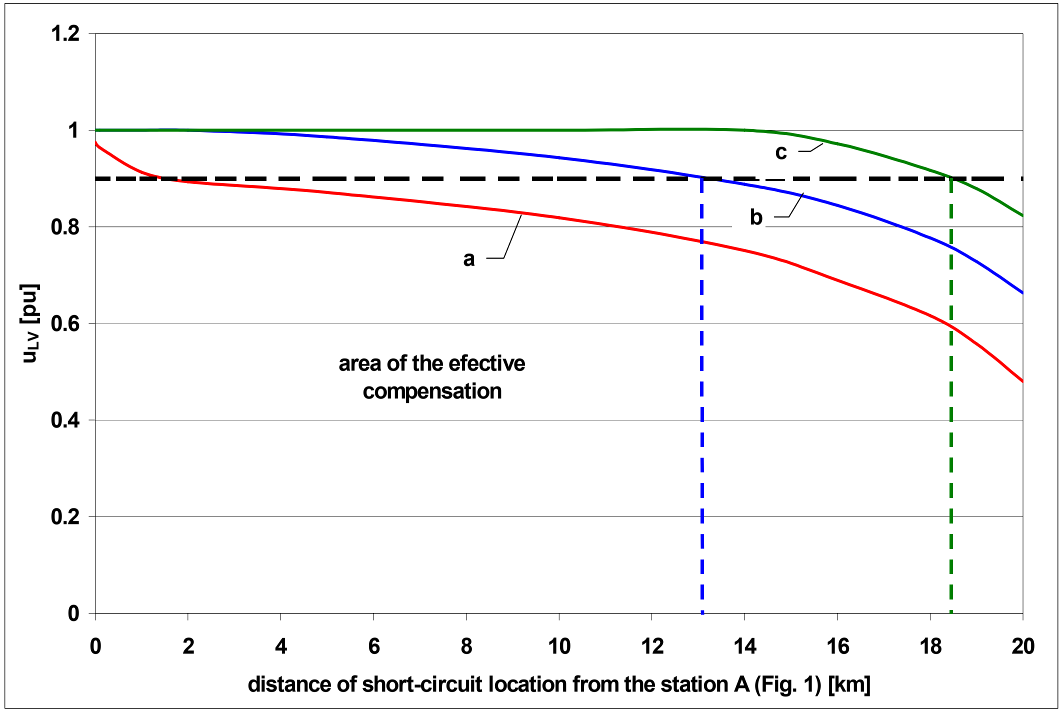
a) with no compensation for both transformers;

b) with compensation and a supply transformer of 400 kVA;

c) with compensation and a supply transformer of 160 kVA

The compensation effect depends on the short circuit power of a distribution transformer - a small transformer power will result in a weak connection between networks, whereas a large transformer power will result in a stiffer network connection.

Voltage dips reduction by DES



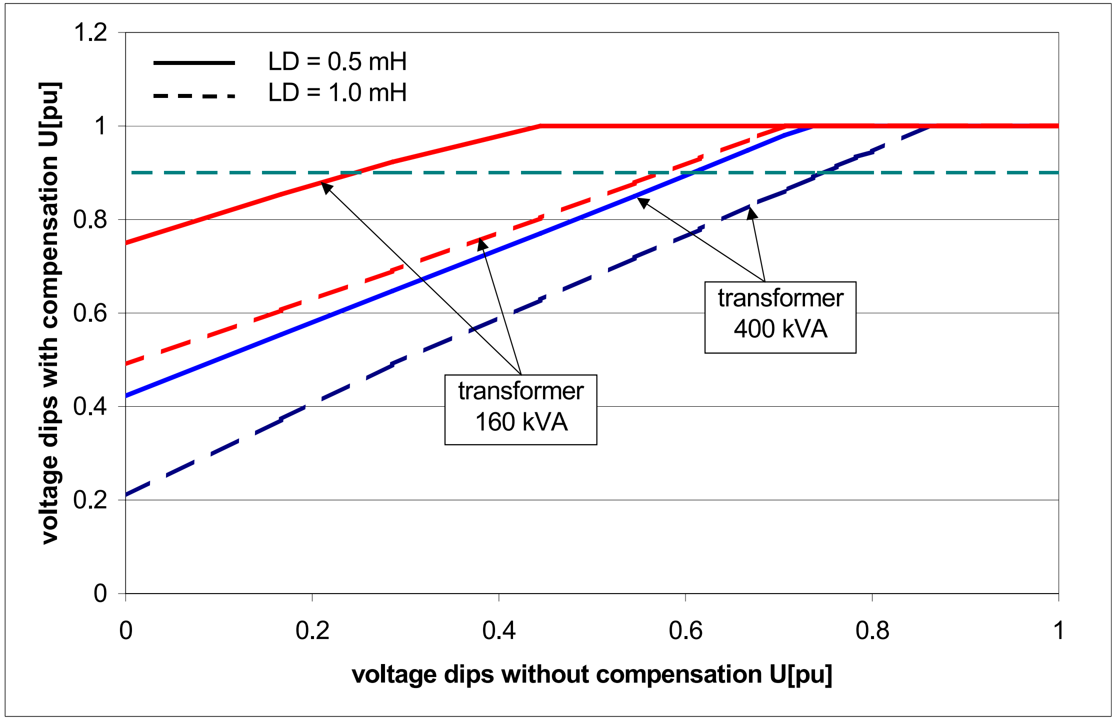
Single-phase voltage dip compensation with DG inverter (L_D = 1,0 mH):

a) with no compensation for both transformers;

b) with compensation and a supply transformer of 400 kVA;

c) with compensation and a supply transformer of 160 kVA

Voltage dips reduction by DES



Inverter compensation for voltage dips in the test network

Conclusions

- The impact of DG on the supplying network is not unambiguous. On one side DESs may be the sources of disturbances which deteriorate network operation conditions but on the other side the presence of sources close to the loads offers many opportunities to improve the power quality and reliability of supply.
- The impact of DES on voltage quality at the PCC depends strongly on the specific local situation. The higher value of short-circuit power at the PCC (the lower value of the network impedance) the smaller effect of disturbances.
- The assessment of DG impact requires analysis of the network operation in many aspects. Such an analysis can not be done without suitable knowledge about the network but is required from an investor when he applies for connection requirements.

Conclusions

- The possibility of ancillary services that DESs offer to the DNO is the promising feature of grids with DG. The philosophy of DESs connection may be changed from „not harm” to „not harm and help”.
- Obvious applications could be:
  - Distribution networks – local voltage control and PQ improving
  - Transmission network – voltage and frequency control – contribution to the system security.
- The questions are:
  - How does inverter rating and the type of energy source to which it is connected influence its controllability for accomplishing different functions?
  - What type of ancillary services would be rational and effective for a particular inverter?
  - Who will be the operator: the utility or the DES owner?

Bibliography

1. Act of 10 April 1997: *Polish Energy Law*. Law Gazette (Dziennik Ustaw), 1997, No 54, Item 348 (with late changes)
2. Bollen M. H-J., Yang Y., Hassan F.: Integration of Distributed Generation in the Power System – A Power Quality Approach, 13th International Conference on Harmonics and Quality of Power, Wollongong, Australia 28.09-1.10. 2008
3. EN 61400-21:2002. Wind turbine generator systems. Part 21: Measurement and assessment of power quality characteristics of grid connected wind turbines
4. Kacejko P.: Distributed generation in electrical power system, Published by the Technical University of Lublin, 2004
5. Mieński R., Pawełek R., Wasiak I., Gburczyk P., Foote C., Burt G., Espie P., 2004. „Voltage dip compensation in LV networks using distributed generation. *IEEE 11th International Conference on Harmonics and Quality of Power*, September 12-15, Lake Placid, USA
6. PN-EN 50160, 2002. *Voltage Characteristics of Electricity Supplied by Public Distribution Systems*, 1994

Bibliography

7. Wasiak I., Mienski R., Pawelek R., Gburczyk P., Espie P., Burt G.M., 2003. “Improving electrical power quality using distributed generation: Part 2 – case studies”, *7th International Conference on Electrical Power Quality and Utilisation*, September 17-19, Cracow, Poland
8. The Instruction of Transmission System Operation and Maintenance (IRiESP), PSE-Operator S.A.
9. The Instruction of Distribution Networks Operation and Maintenace (IRiESD), Lodz Energy Company, 2006
10. The Decree of the Ministry of Economy dated 4.05.2007, concerning detailed rules of the functioning of the electrical power system, Law Gazette (Dziennik Ustaw), 2007, No 93, Item 623