INTELLIGENT DISTRIBUTION GRIDS IN RESPECT OF A GROWING SHARE OF DISTRIBUTED GENERATION

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ABSTRACT

For the integration of a high amount of distributed generation fundamental changes in electricity network operation are required. For avoiding expensive extension of grid capacity an intelligent electricity infrastructure is needed. That means to design and operate electrical distribution grids with intelligent approaches as for example some processes in biological organisms. Ideas for how to operate intelligent grids from the scientific point of view and a discussion from the grid operator's point of view are presented within the following paper.

WHY INTELLIGENT ELECTRICITY GRIDS?

Although the term 'intelligent network', which origins from the area of telecommunication systems, is more and more often used in the context of electricity grids (see e.g. [1], [2]), there is no common definition for the properties of intelligent electricity grids. To separate the term from its telecommunications counterpart, we will use the term 'intelligent grid'. In a technical context, the term *intelligent* refers to properties such as autonomy, context-awareness (i.e. to sense and react on environmental states and events), to the capability to learn, make use of gathered knowledge (data) and the ability to solve problems. Admittedly, an *intelligent grid* will not factually behave intelligently, but its components will feature functionalities that emulate intelligent behaviour.

Electricity grid investments are done for very long-term time horizons. Thus, new components have to be designed in such a way that future technical demands, which are not completely predictable today, can be fulfilled. For avoiding expensive extension of grid capacity an intelligent electricity infrastructure is needed.

Many large network systems tend to develop, as they grow, towards huge hierarchical structures with relatively simple and approved technologies on the lower levels. This can be observed in biological organisms, but as well in technical systems as e.g. telecommunication systems or the Internet. Therefore a new approach for intelligent grid solutions - permitting a growing share of DG – is to design electrical distribution grids similarly to known models of processes in biological organisms. From the technical point of view organisms consist of several control systems, starting from decentralised independent ones to central organised ones, by using components like e.g. receptors, sensors, messenger systems, interfaces, data transfer or handling mechanisms. The identification of these solutions developed within several evolutionary phases delivers ideas for modelling electricity grid and communication network components and systems.

CURRENT SITUATION IN AUSTRIA

Innovative distribution network operators (DNOs) are already taking part in research and demonstration projects. Those operators intend to learn how to deal with the change towards a more and more decentralized electricity system. Three Austrian DNOs are currently performing such a research and demonstration project – called "DG DemoNet – Concept"[1]. The main goals of this project are:

to select parts of networks in Austria for practical realisation of demonstration networks with a high penetration of DG and

to analyse within these low and/or medium voltage network parts, the possibilities for implementing different model systems (Step model "DG Integration") and project the technical, organisational and economical realisation.

The first result of this project is a status report, where the current situation of DG in distribution networks is analysed and presented.

The share of DG in the networks of the three DNOs is shown in Table 1. In two cases the installed capacity of distributed generation is close to the maximum load in the network. The dominating primary energy carriers are hydro power and photovoltaic (with a high number of units but small installed power). Excluding the 110 kV level, the development potential of DG in 30 kV networks and below is still limited.

The DG units are not homogeneously distributed in the networks (see Figure 1). The ratio of DG capacity and loads in different branches (see Figure 2) is not the same as shown in Table I for the whole network.

[1]The project DG DemoNet-Concept is supported in the Framework of the "Energy systems of the future" programme – an initiative of the Federal Ministry for Transport, Innovation and Technology (BMVIT).

Table I: Share of generation in distribution grids

	DNO1 (NL 4-7)	DNO1 (NL 3–7)	DNO2 (NL 3-7)	DNO3 (NL 4-7)
GWh_{gen}/GWh_{dem}	0.11	0.41	0.54	0.11
$MW_{inst}/MW_{gridmin}$	0.72	2.37	2.76	0.58
$MW_{inst}/MW_{gridmax}$	0.22	0.90	0.94	0.17

NL *network level (level 3 is equivalent to 110 kV, level 7 to 0.4 kV)*

GWh_{gen}/GWh_{dem} *ratio of energy delivered by DG and energy demand in the network (annually)*

$MW_{inst}/MW_{gridmin}$ *ratio of installed DG capacity and minimum load in the network*

$MW_{inst}/MW_{gridmax}$ *ratio of installed DG capacity and maximum load in the network*

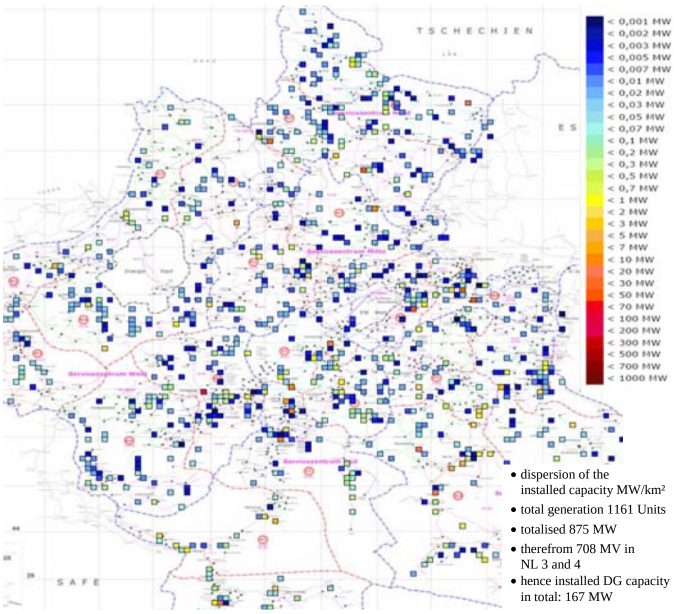

Figure 1: Dispersion of the installed DG power per m², Energie AG OÖ Netz GmbH

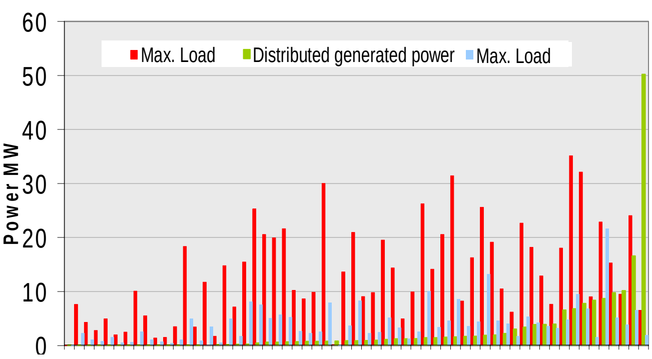

Figure 2: Max. load and installed DG capacity in substations (30 kV radial networks), EnergieAG OÖ Netz GmbH

Only in a few 30 kV radial networks the maximum load can be supplied by distributed generation. In the substations some of the branches are dominated by loads and some branches are special generation branches (e.g. connection of a chain of power station or several large units).

The experiences of the DNOs show that, if in the distribution networks the dispersion of DG units is almost like the dispersion of the loads, a DG share (different DG types) of approximate 60% (installed power of DG) of the maximum load in the network seems to be possible without voltage problems, estimated over all. This value will decrease if the units are concentrated at unique nodes, especially in case of peripheral nodes.

The key barrier for generation in distribution network is the voltage rise effect due to the power injection (see [3]). If it is not possible to connect the desired power, currently there are two approaches used. The first one is to find a point of common coupling with a higher short circuit power or to reinforce the network. The second possibility is to reduce the feed in power when voltage is exceeding the upper limits.

Demand side management (DSM) and remote control of DG units is in general not yet used in respect to voltage level and there are only few measurement data in the peripheral distribution network available. Because of limited share of DG neither the DSM nor measurement data and remote control of DG were required before.

For a high DG share a change towards an intelligent network operation is necessary. Within the following chapter, possibilities for an intelligent approach for active voltage control in distribution networks from the scientific point of few are presented.

THEORETICAL INNOVATIVE SOLUTIONS FOR AN INTELLIGENT DISTRIBUTION GRID

According to Chapter 1, an intelligent approach for integration of a rising share of DG would start, where necessary, with local solutions for each generation unit or sensible network areas. Furthermore, with growing share of DG, an intelligent approach would request a step by step implementation of local measuring and controlling units as well as communication channels and coordinating central systems. In the framework of the *DG-DemoNet Concept* Project, a set of such innovative approaches for voltage control has been developed. These tools actively use network assets (e.g. On-Load Tap changers, OLTC), distributed generators and even loads to perform voltage control (see [4] for theoretical considerations about voltage control). These tools have been theoretically developed and then implemented into a simulation environment for validation and improvement. For this purpose, the simulation software DIgSILENT PowerFactory® has been used and adapted to allow performing realistic simulations. Investigations have been made on an exemplary MV network provided by a

DNO. This network comprises about 200 nodes and represents a total demand of 9 MW.
In order to limit the complexity, the LV networks have been modelled through aggregated loads with load flows corresponding to the actual load and generation structure. For loads and small generators, the corresponding synthetic profiles (15-min values for a whole year, [5]) have been used, while for large generators measurement data were available. On the basis of the developed tools, various steps have been defined according to the implementation complexity, thus defining a *step model*. These steps correspond to approaches for the operation of the distribution network which allow integrating an increasing amount of distributed generation. The proposed five steps are shown in Table II and described below.

Table II: Step Model "DG Integration" - Voltage control tools used for each step of the model

Operation approach	OLTC	DG	Loads	Decoupl. assets
Current practise	Fix set-point	-	-	-
Local voltage control	Fix set-point	✓	✓	✓
"Decoupling solution"	Fix set-point	-	-	✓
Distributed voltage control	Variable set-point	-	-	✓
Coordinated voltage control	Variable set-point	✓	✓	✓

Current practise

This first step corresponds to the current approach, i.e. passive operation of the distribution network mainly based on the On-Load Tap Changer, OLTC. In case of voltage limit violation due to the connection of distributed generation, the network must be reinforced, also to avoid an automatic disconnection of the DG units because of overvoltage.

Local voltage control

In this approach, the OLTC is further controlled traditionally (fix set-point), but some selected generators and/or loads perform local voltage control with reactive and active power management. Due to higher R/X ratios in distribution networks compared to the transmission networks, the use of reactive power management for voltage control may not be always sufficient. If required, active power must be curtailed (regulatory and economical frameworks will be considered in the next steps of the projects). The selection of the generators which perform voltage control must be done on the basis of detailed analysis through offline studies.

"Decoupling solution"

This approach considers the use of additional assets (e.g. voltage regulators) to "decouple" the voltage in parts of the network for which the voltage situation is different. This solution has been considered at the initial stage of the study, from a theoretical point of view. Like the other solutions, it will be economically assessed.

Distributed voltage control

In this step, the OLTC is controlled according to real-time voltage measurements at *critical nodes* of the network. In case the voltage exceeds the operational limits at one of the monitored nodes, the OLTC performs a tap changing. The *critical nodes* have to be selected on the basis of offline studies in order to ensure that compliance with the voltage limits at these nodes imply compliance in the whole network. Of course, the effectiveness of this control is limited by the network characteristic (e.g. different load flow characteristic of MV branches). This solution supposes a communication infrastructure with limited requirements between selected nodes and the OLTC controller.

Coordinated voltage control

This step represents the most complex control (coordinated use of local voltage control distributed voltage control). A control unit controls the OLTC and the generators and/or loads participating to local control on the basis of the measurements received for the critical nodes. The use of coordinated local control allows solving the conflict appearing in the previous approach (OLTC not able to maintain the voltage within the limits in the whole network). Like in the previous steps, the critical nodes and the controlled generators have to be suitably selected (selection criteria are currently developed). For this control, the requirements on the communication infrastructure are higher. Table III summarises the most important advantages and drawbacks from the technical point of view.

Table III: Step Model "DG Integration" – Important advantages / drawbacks – technical point of view

Operation approach	Advantages	Drawbacks
Current practise	▪ Approved standard solution	▪ limited DG amount
Local control	▪ easy to implement, ▪ P & Q control usually available on most DGs ▪ extendable/scalable	▪ complex selection of controlled DGs ▪ not coordinated
"Decoupling solution"	▪ isolate a problematic area	▪ partly inflexible, difficult to scale
Distributed control	▪ simple ▪ extendable/scalable	▪ communication infrastructure needed ▪ effectiveness depending on the network structure
Coordinated control	▪ coordinated ▪ high effectiveness ▪ effective use of all the resources ▪ extendable/scalable	▪ complexity ▪ high engineering efforts (selection of critical nodes and controlled DGs)

OPERATIONAL ASPECTS OF PRESENTED INNOVATIVE SOLUTIONS

The experience of everyday life of network operators results in the following four issues which have to be regarded from operator's point of view:

- Alternative supply conditions e.g. in case of renovation
- Technical and economic sustainability of grid-structure
- Availability and reliability of complex IT and communication systems
- Black start capacity, islanding mode conditions and re-synchronization

The more decentralized and distributed generation units are implemented into distribution grids, the stronger the dependency on installed distributed generation capacity will be. That means that the generation even in case of alternative supply conditions (parts of the distribution network are unavailable) will be needed but upper limit of voltage must not be exceeded although this case is not in the scope of EN 50160 ([6]). By including such alternative supply conditions lower levels of the step model are leading to restrictions in respect to voltage limits for the case of normal supply. On the other hand upper levels require more specialized and complex solutions. However costs and its effectiveness have to be regarded.

The grid is "living" – The development of generation units depends on resources, tax breaks, governmental aid and investment incentives. The development of the loads is corresponding to economy, population and life style. Designers of the distribution grid structure have to base their planning on predictable future requirements for decades. To ensure the sustainability of upper level steps of the model the system basically has to be open for changes. As measurement transformers and OLTCs are long term used components, the optimal choice of the node for installation has to be defined regarding future developments. Within the extension process of a grid optimal nodes for controlling and measuring will change, a step by step adaptation therefore might be inefficient. The "Coordinated control" step might require a high level of engineering for each significant extension of the grid.

Traditionally, long term use, availability and reliability are in the focus of electrical network operators. These basic properties of the systems and its components ensure good power quality and the given high availability and reliability of electrical power supply. Years of experience show that complex IT and communication systems can meet these criteria only if they are of highest quality. But even those systems require permanent maintenance. Using such systems for implementation of the "coordinated control" step would mean high cost for installation as well as for operation. Therefore a cost effective solution which works redundant and can be installed and operated easily is needed.

If the local ratio of DG exceeds 100% of the highest load, an island mode operation might be part of the concept for supply guarantee if the given mix of plants is sufficiently able to be coordinated in load adaptation processes. But if the capacity of the grid is not anymore sufficient for supplying a region, the capabilities of island mode and black start are absolutely necessary. Otherwise, possibilities of load reduction have to be implemented. For stable island mode operation and black start, the technical equipment as well as the engineering effort in planning and operating is rather sophisticated and of course expensive. In case of black out of transmission grid, the resynchronization process of several islands with distributed generation still has to be discussed in detail.

CONCLUSIONS AND OUTLOOK

Investigations showed that innovative solutions can significantly contribute to active network control in distribution networks with high shares of distributed generation. The developed step model provides solutions for integrating large shares of distributed generation with increasing complexity. Based on the experience of the DNOs participating in the project, the developed set of tools still has to be investigated and tested. The most critical issues are the operation in case of alternative supply conditions, the possibility to adapt the control to the network evolution, the reliability problems related to information and communication technology equipment and the black start or operation in islanding conditions.
Once all these technical questions are answered, the economical and organisational aspects will be analysed. Based on a technical, economical and organisational assessment, active voltage control will be implemented in selected parts of the networks of the three DNOs.

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