Cellular Power Grids for a 100% Renewable Energy Supply

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ABSTRACT

The decentralized generation and storage offers new opportunities for a reliable structure of the electrical power grid. It is proposed to subdivide the power grid into much smaller cells than in a traditional power grid. Since all of these cells contain distributed generators, they could be able to operate on their own, if necessary. In case of a global black-out, the individual cells could be able to survive. The paper discusses the size of such cells. In the next part, technical issues are discussed. In each cell the balance of power generation and demand must be maintained. Furthermore, a suitable grid control like virtual inertia must be applied to all related inverters. This requires an intelligent control not only of the generators but also of selected loads, which need to be reduced or shut down in case of lack of energy. Solving these issues for an individual cell leads to a bottom-up approach to operate a complete global power grid with fluctuating, decentralized renewable energies.

Keywords: Electrical power grid, grid control, decentralized generation, power inverter, black out

1 INTRODUCTION

It is proven that an energy supply with 100% renewable energies is possible in Germany [1], Europe and the whole world. However, this requires a decentralized, distributed energy generation. It will probably not be sufficient to generate and store the energy only in those regions, where the cheapest generation is possible. Instead, each region needs to contribute on its own to the energy supply by using its potential. Every roof needs a photovoltaic (PV) system and every village its own wind park. Also storage needs to be decentralized, located at the generation sites to reduce the grid load.

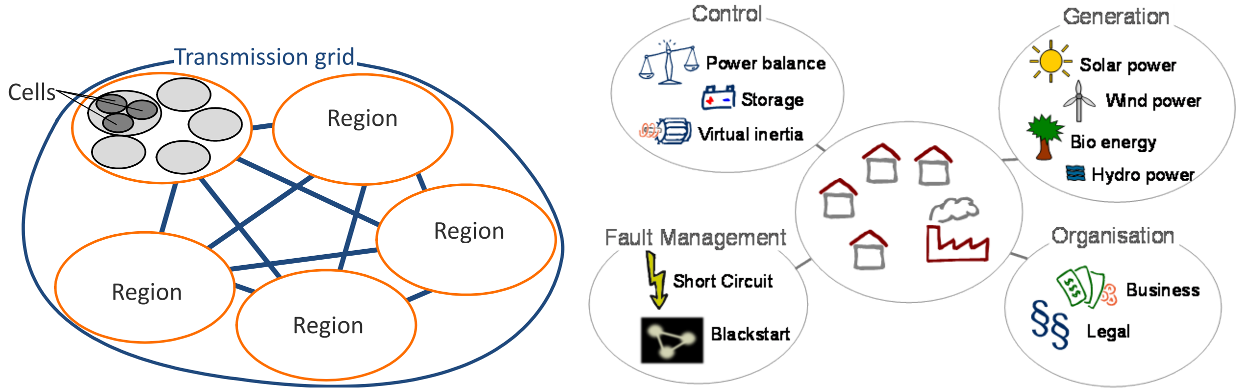

Figure 1: Structure of a cellular grid (left) and tasks for a cell of a cellular grid (right).

Such decentralized generation and storage offers new opportunities for a reliable structure of the electrical power grid. It is proposed to subdivide the power grid into much smaller cells than in a traditional power grid (Figure 1, left). Since all of these cells contain distributed generators, they could be able to operate on their own, if necessary. In case of a global black-out, the individual cells could be able to survive.

There are already some proposals for similar structures. The report of a VDE working group „Active Grids“ [2] rises the idea of such a cellular grid. The initiative “C/sells” [3], part of smartgrids-BW also aims for such a cellular grid structure.

This publication aims to derive the issues related to such an approach and identify further topics of research. Some examples for parts of related aspects are presented. The paper focusses on Germany, but the general conclusions can be taken for any region in the world. Figure 1 (right) illustrates the tasks of such a cell of a cellular grid. The issues can be grouped into four groups: Generation (with Renewable Energies), control, fault management and organisation. Of these four groups, this paper mainly considers generation and control. Before, general issues are discussed.

2 AUTARKY VERSUS AUTONOMY

If the regions are interconnected to each other, a complete *autarky* for each cell is not useful. Autarky means that a cell is able to operate completely independent of external connections. However, it is proposed to select the cell size such that *autonomy* can be achieved. Autonomy is understood as being able to generate the required energy demand within a period of time (e.g. a year). The cells should be able to interchange power, because some regions might have an excess of power, while other may have a power demand at the same time.

A figure of merit to what extend the individual cells must become autarkic is the grade of autarky. It is defined as the ratio of the amount of self-generated power used in a cell to the power demand in this cell, averaged over a period of time (e.g. a year). A grade of autarky of 100% means full autarky.

3 CELL SIZE

A higher grade of autarky obviously reduces the need for infrastructure for power transmission between the cells. On the other hand it increases the need for storage in the cells. A way to reduce the need for storage is to compensate the fluctuating generation by different modalities like wind and solar. Figure 2 shows the grade of autarky which can be achieved with a pure solar or wind supply and with a combination of both [4].

The figure shows it for an investigated community in northern Germany as a function of the ratio between wind and PV generation. The blue curve relates to a grade of autonomy of 100%, while the orange curve relates to an excess generation of 260% (which is the case for the investigated community, see red dot). Both curves don’t include storage. Further details are explained in [4]. It is obvious that a supply with only PV results in a much lower grade of autarky as a supply with wind. A combination increases it by about 8% to 10%. In [4] it is shown that the storage demand reduces nearly by one order of magnitude in this exemplary community with a combined generation with wind and PV compared to a generation with PV only. Concluding, a mix of modalities improves the grade of autarky in a cell. An additional possibility is to use demand side management (DSM). Both requirements lead to conclusions about a reasonable cell size:

A cell size relating to an individual home or street is certainly too small, because then usually only one modality, typically PV, is available. Furthermore, the possibilities for DMS are limited. This would require a much larger storage size. Thus a size which allows a good combination of different power generation modalities and the use of DSM would be reasonable for the cellular grid concept. This would relate to the area of about a community or a similar size. It is a matter of ongoing research to investigate the suitable size of a cell. The aim is to minimize the necessary power exchange between the cells to avoid extensions of the transmission grid.

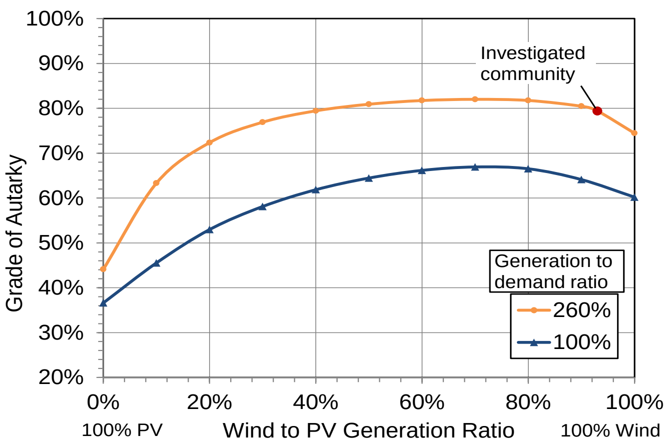

Figure 2: Grade of autarky as a function of the ratio between the annually generated wind energy and PV energy for two different excess ratios [4].

4 AUTARKIC EMERGENCY OPERATION

In cases of severe grid states up to blackout, the individual cells should be able to operate autarkic. The full functionality may not always be guaranteed in such a case, but it would be the goal to provide at least a minimal supply for the most important loads. However, such an operation has several implications.

4.1 Conflict between continuous operation and safety shut down

The actual grid is not designed for such a case. Instead, all distributed generators must shut down in case of a black out [5] because of safety reasons in case of maintenance. As a further problem, connecting the islanded grid after continuous operation to the main grid may be done only with proper synchronisation to avoid damage [6]. As a solution, the generators could be switched off remotely. The control. however, needs to be safe. In Germany, newer PV systems are obliged to have a remote control connected to the grid operator. However, only a fraction of existing PV systems are reliably remote controlled [7]. Another option would be have at least one “master” generator (e.g. a bio-gas generator or a combined heat and power (CHP) system), which is able to “build” the grid. Then, existing infrastructure can easily be integrated. It remains an open question, which are the required minimal properties for such a master generator.

4.2 Balance of power

As a further challenge the balance of power must be able to be maintained in each individual cell. This requires an intelligent control not only of the generators but also of selected loads.

4.2.1 Existing situation

Unfortunately, most distributed generators are not supposed to modulate their feed-in power, but to feed-in always the maximum available power. Larger generators should be remotely controlled by the grid operator, but as mentioned already above, only a fraction can actually be controlled [7]. In addition, there are no loads, which modulate their power demand based on the available power generation. In case of lack of energy the grid operator can only switch on or off parts of the grid. In Germany, legal regulations demand switching off grid areas in a non-discriminating way. It is not allowed to prefer critical infrastructure like hospitals or fire brigades. In Germany this principle is under discussion and related associations demand a change in legislation.

4.2.2 Short term solutions

As short term solution, at least one “master” generator can be established. It must be able to modulate its generation in a wide range and to control the grid frequency. Preferably, it is realized using a synchronous generator or by an inverter, capable of providing similar properties. In case of an excess generation, it can force “slave” generators to switch off or reduce their power generation by emulating an emergency situation by increasing the grid frequency beyond the normal range. In Germany, if the grid frequency exceeds 50.2 Hz, the generator must reduce its feed-in power linearly with increasing grid frequency. Alternatively, it shuts down at an arbitrary frequency between 50.2 Hz and 51.5 Hz, such that the sum of the feed-in power of all generators follows the required curve [5]. The master generator can then set the frequency to the required value in order to balance the power in the grid.

In case of lack of energy, the only available option today is to shut off areas of the grid in the cell. If legally possible, a priority plan should be made to be able to supply most important areas containing critical infrastructure.

4.2.3 Medium and long term solutions

In a long term perspective each of the participating generators should be able to modulate its feed-in power according to the grid state. In order to avoid additional communication, a control based on physical grid variables is proposed. Preferably, feed in power should be controlled by a frequency droop control, similar as today for large generators in power plants.

To achieve a seamless transfer between the “micro-grid” mode and “normal” mode it is preferred to use the same control mode in both cases. During “normal” mode the grid frequency range will probably be much smaller, requiring less power control of each individual generator, while in “micro-grid” mode the frequency range will be broader resulting in a much stronger power modulation.

On the load side, an automatically switching or modulation of loads should be implemented. Here, DSM methods could be applied. The details are still an open question and require further research.

Finally, storages will definitely help maintaining the power balance. Distributed storages, especially those connected to PV systems, are emerging. Attention should be paid to their inverters. They should as soon as possible be able to build and control the grid as distributed “masters”. Since they are still in an early phase of introduction, related standards can still be set.

4.3 Grid control

Most of the renewable energy is fed in by electronic inverters, which do not contribute to grid control (like frequency and voltage control). Especially rotating masses (inertia) of conventional generators are missing. Therefore, a suitable grid control like virtual inertia must be applied to all related inverters. Several research projects have shown such a solution for PV inverters [8] [9]. Enercon offers wind turbines with virtual inertia control, if demanded by the grid operator (private communication). The research project Kombikraftwerk 2 [10] is going to demonstrate a stable grid operation only with renewable generation in Germany, and Younicos AG [11] is going to show a stable grid operation for the island Graciosa only with wind, PV and storage. Own research showed that it should be possible to use the elcap storage, which is available in feed-in inverters to compensate the pulsating ac power, additionally as storage for inertia control [12]. Then, the existing hardware can be used and only the power control needs to be modified.

These examples show that grid control with feed-in only by electronic inverters is feasible. However, an operation in a cellular grid cell has not been demonstrated up to now.

5 EXAMPLES

There are more and more communities and regions in Germany, which aim for a 100 percent Renewable Energy supply of their community or region or have it realized already. The project “100ee region” aims to support those regions by giving consultancy and to interconnect them. The related website gives a good overview of 100% renewable regions in Germany [13].

There are several examples of regions in Germany where at least some of the aspects of a cellular grid are investigated and demonstrated. Some exemplary regions: On the grid connected North-Sea island Pellworm the project “SmartRegion Pellworm” [14] [15] aims to demonstrate a high grade of autarky with a combination of wind, PV and biogas power and with using electrical storage. The project Smart Country [16] [17], led by power provider RWE, relates to a region in Western Germany, Rheinland-Pfalz, in the Eifelkreis Bitburg-Prüm. The region wants to be supplied 100% by Renewable Energies by 2030. The project aims to demonstrate the power balance by using controllable bio gas power. Even further the project IREN2 in Wildpoldsried, Bavaria [18], is demonstrating a real autarkic operation of a micro grid, very similar as proposed in the cellular grid approach. In this project an island grid operable microgrid is in development since July 2014. All necessary components are considered: Controllable low voltage transformers, controllable generators for electrical power and heat (PV systems, bio mass, bio Diesel generators), energy storages (battery, thermal storage), measurement and communication systems, controllable power consumers and in addition components for forcing and testing load steps.

6 TOWARDS 100 PERCENT RENEWABLE ENERGY

Solving these issues for an individual cell will rise questions and give answers, which will appear sooner or later not only in individual cells, but will be relevant for the total power grid.

Therefore, with this bottom-up approach we will learn step by step how to operate a complete global power grid with fluctuating, decentralized renewable energies. Then, despite the fluctuating nature of renewable energies, our power grid will be more reliable and resilient than today.

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