The 5 % Approach as Building Block of an Energy System dominated by Renewables

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Abstract

We describe an approach for doubling distribution grid capacity for connecting renewable generators based on curtailing a maximum of 5 % of the yearly energy fed in to the grid on a per-generator basis. The paper contains information about the control unit needed for automatic minimum curtailment and the field test that has been set up to validate the approach. Furthermore, topics concerning the operationalization of the 5 % approach using both, operational technology and information technology are discussed.

1. Introduction

Following the current German legislation the distribution grid has to be laid out such that it can absorb the entire electricity generated from renewable energy sources. The usage of distribution grids for electricity in Germany is more and more determined by feed-in distributed energy resources (DER). This leads to situations in which allowable transformer loads or cable loads are exceeded or in which voltage thresholds are violated. Grid operators are only allowed to temporarily throttle renewable generators (grid curtailment) if there are no other options to prevent harm to the power grid infrastructure. Furthermore, they are forced to execute grid construction after grid curtailment actions have taken place, which additionally provides security for investments into renewables as subsidies are connected to the amount of feed in.

Assessment of load and system design both follow a worst case approach resulting in the system being dimensioned towards a maximum load. In the case of grids dominated by decentralised power feed-in, this maximum load is given by the cumulated installed generation capacity combined with minimal electricity consumption. Frequency and duration of such load situations is not taken into account in the worst case approach. This typically results in a low number of hours of full grid capacity utilisation, since utilisation is determined by the feed-in characteristics of connected generators. Figure 1 depicts the annual load duration curve of a photovoltaic generator. It is obvious that the generator only reaches its maximum output for a few hours per year. Accordingly, the fraction of electricity generated in the upper power region with respect to the annual energy quantity (area below the curve) is very small.

Thus, distribution grid dimensioning in Germany is currently adjusted to feed-in situations only occurring a couple of hours per year. As a consequence enormous investments in grid construction are required. Therefore, the following questions concerning system layout of today's distribution grid structures arise:

- Is it macroeconomically reasonable to plan distribution grids based on rare maximum loads?
- By which percentage can grid connection capacity be augmented when the distribution grid does not have to account for rare maximum loads?
- What is the overall macroeconomic balance when substituting grid expansion by grid capacity extension by means of fine-grained curtailment?

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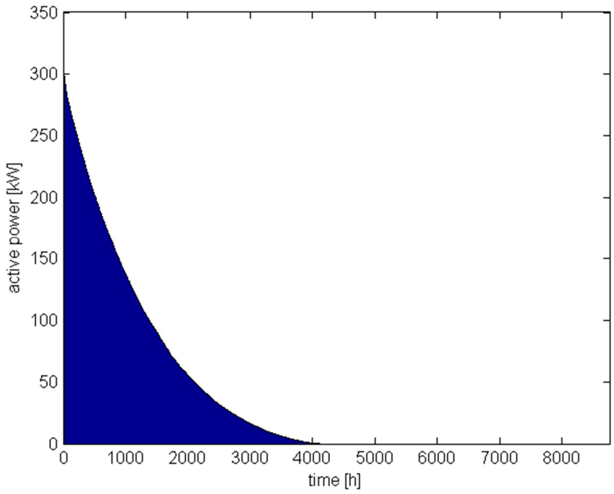

Figure 1: Illustration of a simulated annual load duration curve of a photovoltaic generator

2. The 5 % Approach

The main hypothesis of the 5 % approach is that load flow dependent throttling of a low percentage (i.e., less than 5 %) of yearly power feed-in carried out in maximum load situations leads to a drastic increase of grid connection capacity. The approach's key characteristic is the load flow dependent throttling of generators, since voltage stabilisation and equipment usage result from summed up load both from consumption and feed-in. This substantially discriminates the 5 % approach from an overall throttling of generators since both frequency and duration of throttling are minimised by load flow dependent control of generators.

In the sense of smart grids we look at an intelligent system for generation management consisting of the following main components:

- metrological coverage of all voltage- and load critical components of the distribution grid.
- possibility for continuous control of reactive power output of all generators based on ICT
- online load flow calculation based upon a grid state identification to continuously monitor all relevant system parameters
- continuous identification of sensitivity of monitored system variables towards generator feed-in in order to identify optimal target values (minimum throttling)
- temporary and well-dosed throttling of relevant generators in case of impending threshold violations of equipment currents or node voltages

2.1. Assessment of the Approach's Potential by Simulation

To assess the potential that can be achieved by the approach described above, simulation experiments were carried out on basis of a model corresponding to a rural type grid as controlled by the distribution system operator EWE NETZ. The model characteristics were as follows:

- Steady-state power flow calculation based on a yearly time series (15 minute resolution)
- Consumption loads modelled based on a load-model devised by RWTH Aachen [1]
- Definition of feed-in (e.g., photovoltaics, wind) based upon measured yearly time series

Based on the medium-voltage grid model, different simulation scenarios were evaluated, using a scenario with 100 % feed-in as reference. To determine 100 % feed-in, all generation capacities were iteratively increased until minimal allowed voltage stability and maximum allowed transformer utilization were reached. In the subsequent comparison scenarios, feed-in was further increased stepwise. Using an optimization algorithm feed-in in course of a simulation year was reduced whenever system parameters exceeded tolerance limits. Installed generation capacity was stepwise increased from 100 % to 325 %.

Figure 2 shows the results from simulating the different scenarios. The diagrams show grid connection capacity for feed-in depending on the percentage of curtailed generation. Each scenario was calculated both for a wind intensive year and for a year with low winds in order to take into account different wind years.

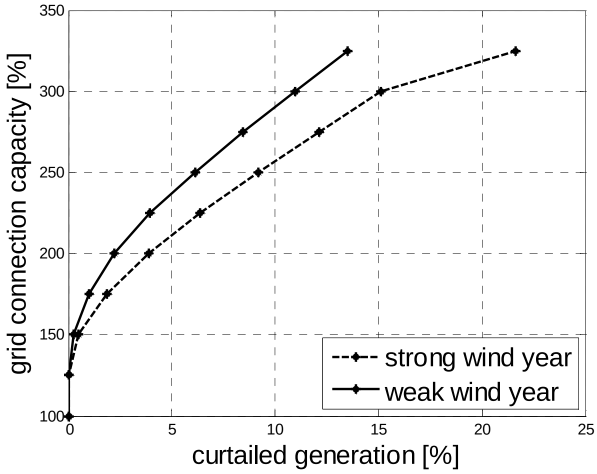

Figure 2: Dependency between curtailed energy and grid connection capacity during one year

The simulation results strongly support the hypothesis. Curtailing the yearly energy feed-in by 5 % would allow to double grid connection capacity in rural type distribution grids.

3. Validating the 5 % Approach

Before implementing the 5 % approach, the promising simulation results have to be validated under real conditions. To this end, a field test is carried out to validate the relationship between reduced feed-in and grid connection capacity. The field test is characterized by a power flow dependent scheduling of renewable generators.

In order to validate the 5 % approach for general distribution grids, a system study is carried out. Therein, critical parameters are identified by means of a sensitivity analysis and it is studied by which amount distribution grid connection capacity can be increased using intelligent management of power generation.

Note, that regulatory aspects of the 5 % approach are not part of the field test. However, in the German context, it is obvious that implementing the 5 % approach must not lead to financial disadvantages for plant operators. A possible preliminary approach would be paying the fed-in energy with factor 1.05 compared to the current price for electricity from renewables fixed in current laws. Whenever there is at least one control action for a given generator within an accounting period, all fed-in energy will be paid for. If there is no control action in the accounting period, only 95 % of the fed-in energy will be paid for (95 % * 1.05 = 100 %). Following this strategy, no difference in funding will be imposed by implementing the 5 % approach.

3.1. Field Test

Figure 3 depicts the selected field test area being representative for medium voltage grids operated by EWE NETZ. The selection occurred such that connected low voltage grids do not substantially contribute to the overall power feed-in. Thereby, it can be avoided to include feed-in from generators installed on the low-voltage level into the 5 % control.

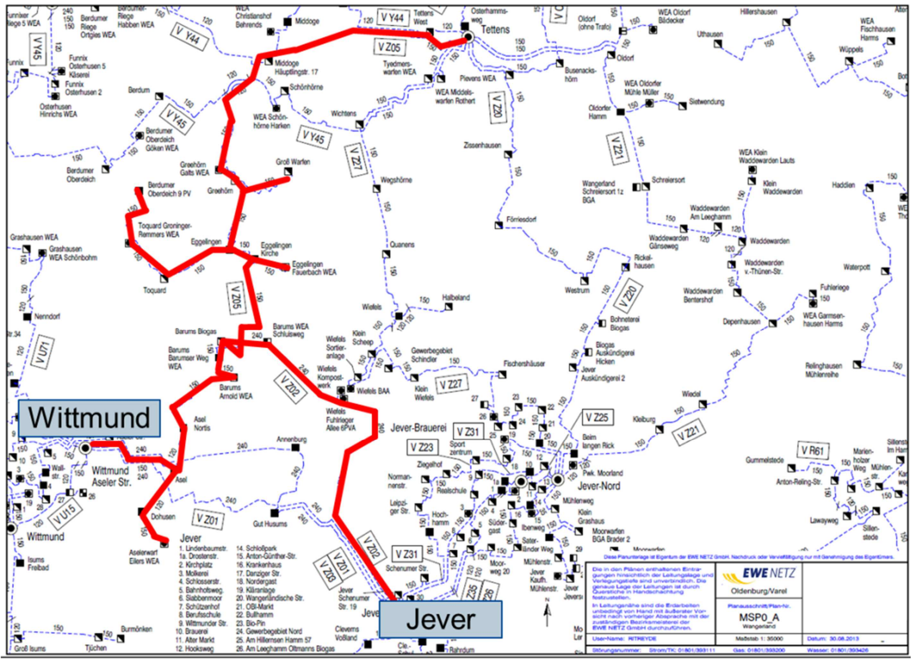

Figure 3: Field test area

In order to guarantee that equipment usage (electrical current) and voltage stability only depend upon measured and controllable feed-in, the switch from switching station Tettens has to be opened resulting in connection to the high voltage grid only via Jever substation.

The selected grid area contains 11 generators corresponding to a maximum feed-in of 10 MW. These generators are controlled during the field test. In order to avoid control activities external to the field test, generators are operated with a constant reactive power ratio. The following values are measured (once per minute) in order to provide information to a controller performing the task of regulating feed-in from power generators:

- Currents from lines, substation and switching station
- Voltages from substation, switching station and grid connection points of power generators.
- Power and primary voltage from all low-voltage-transformer substations
- Reactive power, active power and voltage of distributed generators

Furthermore, for purpose of validation, wind and radiation measurements are constantly taken.

Figure 4 shows the general system configuration for the field test.

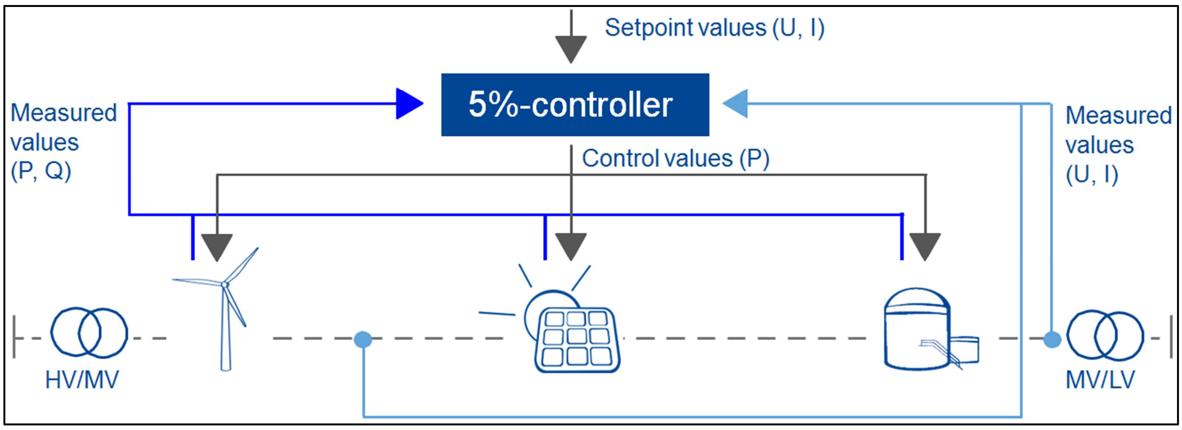

Figure 4: System configuration of the 5 % controller in the field test

The quantities relevant for assessing the increase of grid connection capacity are the admissible voltage ranges according to EN 50160 [2] and the allowable currents for grid equipment. Since doubling of power generation capacity is not possible during the field test, evaluation will be based on the following assumptions:

- Calculation of virtual operational thresholds (grid voltage thresholds and maximum allowable equipment currents) based upon 50% of the actually installed generation capacity
- Operation of the field test grid with 100% of the actually installed generation capacity and control of generators such that the virtual operational thresholds are observed

In order to validate the 5 % approach, the energy curtailed must not exceed 5 % of possible generation taking into account the weather conditions (wind, radiation). To gather statistically adequate evidence, the field test has to run for at least an entire calendar year. Only after this period the ratio between curtailed energy and available energy can be properly calculated.

3.2. Field test requirements towards an implementation of a 5 % control unit

Measurements take place separately and in a given frequency. Both, the necessary frequency and the timespan between threshold violation detection and the issuance of control values will be evaluated during the field test. Generator feed-in reduction shall occur in steps of 10% of generator capacity. As soon as the control unit determines that feed-in reduction can be (partially) taken back without thresholds being violated, feed-in reduction shall (partially) be taken back.

The control strategy shall take into account:

- safety margins for set point values after threshold violation
- Delayed approach of nominal values to real values in order to avoid short-time electrical overloading of grid equipment due to exorbitant inertia of the whole control
- Grading of nominal value in order to avoid oscillation

Since the quality of control has a significant influence on the successful implementation of the 5 % approach, a control quality (deviation from set point values in per cent) for voltages and for currents must be guaranteed. Quality of control will be evaluated throughout the field test.

4. Control Unit Design

The control unit supporting the 5 % approach is based upon a product called BTC | Grid Agent. It operates in a continuous loop consisting of three steps:

1) Read measurements and set points
2) Calculate control values for generators using power flow calculation and taking into account technical limitations
3) Send control values to generators

Thus the controller uses a model-based method, a grid model being used for power flow calculations. The main advantage of this method over PID controllers (see [3]) that are not model-based is the reduced number of control actions needed to correct threshold violations due to the higher possible accuracy. This results in faster control process alignment, especially in face of low quality communication links. Generally model-based-approaches enhance stability of control due to the higher amount of knowledge of the system under control.

During the field test, the controller has to evaluate measurements from about 20 measurement points and has to issue about 10 control values in each cycle. The frequency of control cycles necessary for ensuring the needed control quality will be evaluated during the field test. Having been evaluated in scenarios for controlling reactive power settings of heterogeneous wind farms, the control unit can perform multiple control cycles per second. However, this performance will most likely not be reached during the field test for validating the 5 % approach, because the increased size of grid models needed.

Note that, besides control values being sent to generators, event information is sent to distribution management systems or other supervising systems. Also, parameters e.g. for transforming set point values can be modified during run time. They are held in the parameter and curves storage.

Another property to be mentioned is that the grid agent takes into account whether generators react to the control values issued. If they do not react, they are incorporated into control for a period of time that can be specified.

The grid agent's architecture is depicted in Figure 5. The agent has three main types of modules that are executed in each control cycle: Set point modules calculate set point values from set point information (electrical quantities and precision information) and ongoing measurements. Control modules calculate control values from set points and measured values. There are several variants of control modules. One variant splits control values to power control values for single generators using power flow calculation. Another variant limits power change rates to acceptable values for generators depending on their operation conditions. Finally, monitoring modules serve the purpose of restricting set point values, e.g. stub currents, to the technical specifications of electrical equipment and generators.

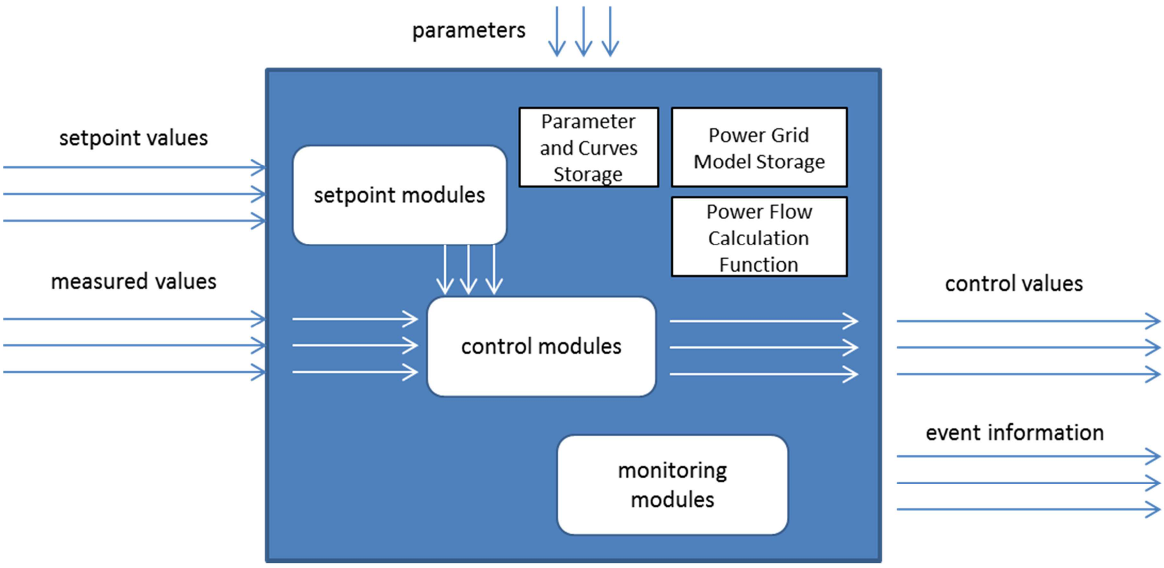

Figure 5: Conceptual architecture of the Grid Agent

The control unit software has been designed with universal extendable APIs so that it can be adapted to different execution environments (e.g. embedded PCs, matlab, SCADA systems, the simulation framework MOSAIK [4]) by adapters. A couple of those have already been developed.

The power flow calculation function is used by the control modules and relies upon the power grid model stored in the power grid model storage.

5. Convergence between IT and OT and the 5 % Approach

Systems in the energy sector can be distinguished into OT (operational technology) and IT (information technology) [5]. Operational technology is focused on monitoring, supervision, control, and automation; for instance SCADA systems, automatic control units and sensors are considered as OT-systems. Typical non-functional requirements of OT are high availability, 24/7 operation, and redundancy. IT systems provide functions for business, market, documentation, and management that are usually not directly connected to the physical energy system equipment. IT systems are mainly used during office times and typically require less availability than OT systems, and do not typically run on embedded systems. Examples for IT systems are billing systems, GIS (geographic information systems), asset management systems, customer care systems, or energy trading systems. A core element of smart grid architectures (see e.g. [6]) is to connect IT and OT systems, sometimes called IT/OT-Convergence. Most systems that are discussed in the following are systems of the grid operator.

The 5 % approach can be assigned to the OT-domain. We consider it an OT-component because it is a non-market mechanism to continuously operate the grid and to deal with exceptional feed-in situations. While the field test focus is on the electrical principles (i.e., pure OT), several scenarios for IT/OT integration relevant to business and regulatory integration can be identified:

- **Billing:** Billing systems and Meter Data Management Systems (MDMS), both systems of the IT-domain, are involved in the 5 % approach, to implement the financial compensation for the loss of feed-in subsidies. Advanced Metering Infrastructure (AMI) would be suitable to provide billable measurement data about the feed-in (measurements provided by the DER control might be not billable, as it is not measured.
- **Topology:** The 5 % approach requires an up-to-date model of the grid topology (i.e., the model fits to the physical reality in terms of connection and switch positions), as the control units implementing the 5 % approach need to know which and how DER relate to a bottleneck. Typically, a GIS (geographical information system) is the primary software system for static grid topology (graph of nodes such as transformers and edges for electrical connections). Dynamic topology additionally includes current switch positions and is typically held in a DMS (distribution management system). For any topology model based control, it has to be ensured that GIS and DMS are integrated to provide an up-to-date and high-quality dynamic data model. The technical integration of topology models should rely on standards (e.g., from the IEC CIM family [7]) in order to reduce medium- and long-term integration costs, and to avoid a vendor lock-in [8].
- **Providing information to DER operators:** Operators or owners of DER should be informed about current, future and past grid curtailment actions. This can be a regulatory requirement. The information allows them to schedule maintenance to times when the DER is not allowed to feed-in. The Customer Information Systems (CIS), Customer Relationship Management (CRM) and Customer Portals are (potential) systems of the IT-domain that need to be informed about actions that are made by the OT-component implementing the 5 % approach.
- **DER master data:** The non-topological master data of DER, such as address information, installed capacity, and communication parameters, are typically managed by Enterprise Resource Planning or Asset Management systems. As with the topology data model, it is an IT/OT-integration challenge that the data from the IT-systems is up-to-date and of sufficient quality.

A general challenge of these IT/OT integrations is the quality of data (topology data, DER master data) from the IT-systems. The quality level is not always that required for use in critical automatic control systems. Additionally, each connection used for IT/OT integration could be used for an attack against the critical control systems in the OT-domain. Completely separating OT (such as SCADA) from IT would provide security, but “no network connection between IT and OT” is not a realistic option for SCADA systems [9]. Therefore, sophisticated security architectures are required for IT/OT integration. Standardized communication (e.g., using the IEC CIM standard family [7]) can support the security of integration as the exchanged data could be decoded and scanned by a security system that supports the standard.

Besides the IT/OT integration challenges, IT/IT data exchange between owners of different market roles may have to be provided for completely implementing the 5% approach as well. For instance, the correct amount of the billed energy may have to be reported to transmission system operators and further reported to official authorities.

6. Conclusion and Further Work

It is the purpose of the described field test to validate the 5 % approach. The next step will be to align the regulatory framework and the 5 % approach and to create solutions allowing distribution grid operators to implement it efficiently, taking into account aspects of integrating OT and IT.

Reliability and maintainability are very important factors for distribution system operation. Their interdependency as well as their dependency upon the degree of centralisation of OT and IT and also their influence on costs are important topics that still have to be looked upon in the context of smart grids.

There are a number of other purposes for control in distribution grids. An interesting topic, still to be researched is the coexistence of control strategies with different aims and for different grid domains. The cooperation or coordination between control units can either be mediated by distribution management systems or take place directly between controllers.

A possible extension to the 5 % approach could be to combine it with approaches with near-future predictions, such as load predictions and feed-in predictions to enable curtailment actions coordinated with energy market action instead of reactive actions. However, it is a real challenge to predict the local feed-in and load for distribution grids, and it needs to be studied whether the potential benefit compensates the risks and costs for dealing with prediction errors.

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