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The German experience with integrating photovoltaic systems into the low-voltage grids

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ABSTRACT

The integration of rooftop photovoltaic systems in the low-voltage distribution grids has become a major international trend, helped by the sinking prices for photovoltaics. One of the key questions revolves around the technical challenges brought about by the grid integration of these decentralized systems. This paper therefore analyzes the substantial practical experiences of ten representative German distribution system operators, who play a leading role in this field. Our findings show that grid expansion measures are primarily undertaken to ensure compliance with the permissible limits for voltage and current. Grid optimization measures represent the most economical initial step and include, for instance, changes in grid structure and wide-area control. Once their potential is maximized, classic grid expansion measures such as laying parallel cables are implemented. In individual cases, the low-voltage grid is reinforced by so-called intelligent operating equipment such as voltage regulators or voltage-regulated local distribution transformers. Moreover, improved grid planning measures lead to a better use of the available low-voltage grid capacity. The practical solutions successfully implemented by German distribution system operators should also prove relevant for other countries that are currently planning the deployment of decentralized renewable energies.

1. Introduction

Germany is among the world leaders in the development and integration of renewable energies, in particular in the area of photovoltaic (PV) systems. By the end of 2015, the installed PV capacity in Germany was at approximately 40 GW [1]. More than half of the expansion until 2015 took place in the country's low-voltage grids, amounting to a total of 22 GW [1]. Most of this capacity takes the form of rooftop systems installed on residential or commercial buildings. In 90% of these rooftop systems, the installed capacity is under 30 kW [1]. Therefore, the expansion of photovoltaics at the low-voltage level is taking place for the most part with small-scale systems, which is a unique characteristic of the German energy transition.

Due to the decline in prices for PV technology, the expansion of rooftop photovoltaics has become a major trend on the international stage as well [2]. Many countries have reacted to this development and, like Germany, have begun to revise their regulatory framework conditions for decentralized energy [3,4]. In this context, a central question revolves around the technical and organizational challenges posed by the integration of decentralized energy into the grid.

The technical challenges related to the integration of distributed energy resources into the low-voltage grid were clearly reported and discussed in Ref. [5]. The factors limiting the expansion of PV include the thermal rating of grid equipment, the permissible voltage range, the fault level rating of grid equipment and issues related to power quality, grid reliability and network protection.

A wide range of solutions were proposed both in scientific articles [6–12] and technical reports [5,13]. To overcome capacity or voltage limitations, the reconfiguration, reinforcement, and expansion of grid equipment are all considered valid solutions [5,6,10]. Further proposed solutions include but are not limited to reactive power provision of PV inverters [9–11,13], active power curtailment of PV inverters [7,9–11], implementation of large-scale battery systems [6,10], implementation of voltage regulated

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distribution transformers [2] [7,9,10], implementation of booster transformers [10], control of demand-side appliances such as electric vehicles [8,9], advanced voltage control at the high/medium voltage substation (wide-area control) [5,10], and advanced grid monitoring [12].

However, so far an analysis is lacking of the individual measures that are or have already been implemented in practice. This is why the focus of our paper is on the experiences of German distribution system operators (DSOs) in the grid integration of photovoltaic systems in low-voltage grids, based on ten representative interviews. We will provide a comprehensive description of the practical measures employed by German DSOs in the expansion of the low-voltage grids, and discuss the relevance of each measure. Additionally, we will explain both how grid planning works with regard to integrating photovoltaic systems and how the operation of the low-voltage grids has changed with the expansion of photovoltaics.

The paper is organized as follows: Section 2 summarizes relevant background information on the interview partners, pertaining in particular to their credentials and their representativeness based on their network characteristics. Section 3 describes the grid structure in Germany, specifically focusing on the role of photovoltaic systems in the low-voltage grid. Section 4 explains the individual measures for the integration of photovoltaic systems into the grid and the circumstances under which they are implemented, as derived from the interview series. Section 5 presents a ranking of the measures and discusses their general applicability.

2. Background on the interview series

In order to collect information about the practical (technical and organizational) measures for integrating PV systems into the German low-voltage grid, we conducted semi-structured [3] interviews with DSOs. The surveyed DSOs agreed to take part in the interviews on condition of anonymity. Accordingly, we cannot state their names, their companies, or any other data potentially identifying them. Therefore, we can only include aggregated data. Out of the 813 German DSOs we selected ten that operate large-scale grids. Large-scale in this case means that, in addition to urban regions, the grids primarily supply rural areas where the expansion of renewables (e.g. biomass, photovoltaics, wind power) is taking place. All selected DSOs are thus among the top 30 in Germany with respect to the installed renewable energy capacity. By selecting large-scale DSOs, we insured that the interview partners have an extensive experience with integrating photovoltaics. Furthermore, large-scale DSOs can implement measures on several distribution grid levels to facilitate the PV integration into the low-voltage grid.

Table 1 shows some relevant characteristics of the ten selected DSOs and compares them to the corresponding values of all German DSOs. The surveyed DSOs operate a circuit length of 676,957 km which represents 38% of Germany's distribution grid. This relatively high share highlights the fact that, despite the large number of DSOs, the majority of the grid is operated by a small number of companies. For instance, the 10 largest DSOs operate more than 60% and the 30 largest DSOs more than 80% of Germany's installed renewable capacity. In our case study, the PV capacity installed in the surveyed grids amounts to 44% of the PV capacity installed in Germany until 2015. The installed capacity for wind power and biomass is slightly higher, as illustrated in Table 1. With respect to the low-voltage grid, the surveyed DSOs operate 37% of the circuit length, which encompasses 37% of all PV capacity installed at this grid level.

We selected DSOs from throughout Germany in order to ensure the necessary diversity of structural framework conditions, as they may influence the integration measures. For example, the share of PV in the renewable energy mix, the share of renewables in the low-voltage grid, or the population density differ significantly among the surveyed DSOs. Thus, the largest share of photovoltaics in the renewable energy mix is 82%. As a result of the high PV penetration, this DSO also has the highest share (56%) of installed distributed renewable capacity in the low-voltage grid compared to the installed capacity of all grid levels. By contrast, our survey also includes DSOs with a PV share as low as 15% and DSOs with a share of renewables in the low-voltage grid as low as 5%. The DSOs with a high share of PV are typically found in southern Germany, whereas the DSOs with a low share of PV are located in northern Germany. The structural data also shows that the population density in the grids of the selected DSOs can vary significantly as well. Some DSOs have up to 40 offtake points per kilometer of low-voltage power line, while others report only 19 offtake points per kilometer.

Table 2 summarizes the credentials of the interview partners. Each surveyed DSO was represented by at least one technical expert, typically the head of grid development. In four cases, additional staff from the regulatory or the accounting department took part in the interviews. In order to respect the DSO decision to remain anonymous for this research project, we will use the letters “a” to “j” to reference their statements and opinions throughout the paper.

3. Role of photovoltaic systems in the German low-voltage grid

3.1. Grid structure in Germany

The German grid has four voltage levels: low voltage, medium voltage, high voltage, and extra high voltage, as presented in Table 3. The low-, medium-, and high-voltage grids constitute the so-called distribution grid, which is under the ownership of 813 DSOs [16]. The reason for so many DSOs is the historically large number of regional grid operators. By contrast, the extra high-voltage grid is operated by only four transmission system operators.

Table 3 also shows the typical nominal voltage for each grid level. Due to technical and historical reasons, other nominal voltage levels such as 10 kV, 15 kV or 30 kV can be chosen for the medium-voltage grid. For the low-voltage grid, however, the nominal voltage is always 400 V. Due to differing load and power generation situations as well as electric resistances in the grid, the voltage varies within one grid level. According to DIN EN 50160, a tolerance range of ± 10% of the nominal voltage is allowed [17]. In the low-voltage grid, for instance, the voltage may consequently range from 360 V to 440 V.

The various grid levels are connected with each other through the transformers of the substations, which transform the voltage between the two respective voltage levels. Between low and medium voltage the voltage ratio is usually fixed (approximately a factor of 50).[4] Due to this fixed ratio, the voltage on the low-voltage side changes with the voltage on the medium-voltage side of the transformer. The substations of the higher voltage grids are always equipped with voltage regulators in order to be able to adjust the

[2] Transformer with on-load tap changer.

[3] See for example Ref. [14] for more information about qualitative interview techniques.

[4] The voltage ratio is the result of the relative voltage difference between medium and low-voltage levels. The nominal voltage at the medium-voltage level (20 kV) is 50 times higher than the nominal voltage at the low-voltage level (0.4 kV).