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Review

Limitations for the feed-in power of residential photovoltaic systems in Germany – An overview of the regulatory framework

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ABSTRACT

The number of residential photovoltaic systems has increased worldwide. Typically, these systems are installed at the low-voltage level in the electric distribution grids. However, the hosting capacity of the grids is limited by technical constraints and regulations. This publication reviews the national laws and standards limiting the hosting capacity for PV in low voltage grids in Germany. The usual grid planning approach leading to the technical constraints is briefly introduced to help readers from other disciplines understand the challenges in grid integration. The most important German laws, namely the renewable energy law, the energy industry law, and the law on the metering point operation are discussed. Furthermore, national rules and standards used by German distribution system operators are described and motivated by the legal framework. New technologies can increase the PV hosting capacity of the distribution system. The results of studies on grid reinforcement, reactive feed-in power, voltage regulated distribution transformer, active feed-in management, and battery storage are reviewed mainly focusing on Germany.

1. Introduction

The number of residential photovoltaic (PV) systems is increasing worldwide (IRENA, 2015). The successful implementation of different subsidy approaches, such as feed-in tariffs, production tax credits, and net-metering in Germany and many other countries (Rodrigues et al., 2016) has led to a growing number of small PV systems with less than 30 kW. As of 2016 more than 1.5 million PV systems with an overall rated power of more than 41 GW has been connected to the electric grid and over 96% has been installed at the low-voltage level in Germany (DGS, 2015).

There are several definitions of the term "residential PV" in the literature. According to Goodrich et al. (2012) and Rickerson (2014), PV systems with a rated power up to 10 kW are denoted as residential PV. The International Renewable Energy Agency (IRENA) uses the definition "residential PV systems typically do not exceed 20 kW and are usually roof-mounted" (IRENA, 2012). Historically, the challenges to distribution system operators (DSOs) in Germany were caused by the high number of small PV systems as well as the larger systems far away from the load in rural areas. Both types are connected to the low voltage grid but may be handled differently by German laws. Those differences are e.g., different feed-in tariffs, taxes and surcharges as well as technical requirements. The renewable energy law (see Section 4.2) and the thresholds to distinguish between residential, commercial and utility-scale systems changed several times during the last few years. In this work, we take the perspective of the DSOs and loosely define residential PV systems as those connected to the low-voltage grid.

Grid stability and power quality at the low-voltage level is guaranteed by the DSO. Nowadays, the interconnections between the high and medium-voltage grid are monitored widely in real time and remotely controllable actuators exist to control them. On the other hand, at the interconnections between the medium and the low-voltage grid, meters only monitor the current with slave points. At transformer stations these current meters typically only show the most recent and the maximum apparent power since the last readout. Typically, the readout is only performed manually once a year in Germany. Therefore the state of the distribution system is largely unobservable.

Local PV generation changes the load patterns and can exceed the consumption by several times. The feed-in power of the PV systems was not considered in the planning of the distribution grids. This local feed-in power affects the voltage within the grid and the operation of the DSO assets, e.g., transformers, lines and switches. These effects have to be taken into account in both the planning as well as a safe and efficient operation of the electric grid. This is within the sphere of responsibility of the DSOs.

In Germany, several laws, regulations, rules and recommendations influence the hosting capacity of the distribution grid. Several articles have reported on PV integration issues. An international overview on the limits of distribution feeders for hosting decentralized generators is given by Papathanassiou et al. (2014) but is limited to technical issues.

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Nomenclature

Abbreviations

BDEW	German Association of Energy and Water Industries
CIGRE	Council on Large Electric Systems
DSO	Distribution System Operator
EEG	Renewable Energy Law
EnWG	Law on the Energy Industry
IRENA	International Renewable Energy Agency
MR	Maschinenfabrik Reinhausen GmbH
MsbG	Law on the Metering Point Operation
NAV	Low Voltage Connection Regulation
PCC	Point of Common Coupling
PV	Photovoltaic
SLP	Standard Load Profile
STC	Standard Test Conditions
SWU	Stadtwerke Ulm/Neu-Ulm Netze GmbH, a DSO
TAB	Technical Interconnection Requirements
VDE	Association for Electrical, Electronic & Information Technologies (German equivalent of IEEE)
VKW	Vorarlberger Energienetze GmbH, a DSO
VRDT	Voltage Regulated Distribution Transformer

The regulation and grid infrastructure of Germany, Spain, and California is compared by Corfee et al. (2011) but does not consider recent regulatory developments in Germany, such as the law on the metering point operation (see Section 4.3 MsbG, 2016) and the law on development of the electricity market (Strommarktgesetz, 2016). In 2009 to 2012, the German DSOs were overwhelmed by the high annual installation rates of up to 7.5 GW. Nowadays, DSOs have more experience in the integration of residential PV systems into their grids and the application of current standards as e.g., VDE-AR-N 4105 (2011).

Several working groups of the Council on Large Electric Systems (CIGRE) also investigated different aspects of the grid integration of PV systems. Papathanassiou et al. (2014) studied the capacity of distribution feeders and gave a brief summary of rules, methodologies and guidelines applied by DSOs worldwide. The effects of decentralized generators on the protection systems and the challenges of unintentional islanding is described in Myrda et al. (2015). However, both are mainly focused on the medium-voltage level and standards. In the report of Smith et al. (2016), the power quality aspects of photovoltaic installations were examined, specifically addressing harmonics and high-frequency distortions, rapid and slow voltage changes as well as the unbalance due to single-phase installations. Papathanassiou et al. (2014),Myrda et al. (2015) and Smith et al. (2016) neither take into account the national laws nor discuss the low-voltage level.

The objective of this review paper is to introduce non-German audiences and readers unfamiliar with the subject matter to the experiences with PV system integration in Germany from the point of view of the DSO and in the context of the national laws and standards. A brief overview of the national grid planning approaches and technologies to increase the PV hosting capacity is given to provide a basis for further literature research to readers interested in the grid integration of PV systems in low voltage grids. This review focuses on electricity and ignores the coupling of different energy domains, e.g., heat and gas. This work analyzes the different laws, regulations, and standards governing the operation of residential PV systems and their connection to the public electric grid at the low-voltage level. Furthermore, different technologies to increase the PV hosting capacity and meet the requirements of the regulations are highlighted. Techniques like demand response and load management are not considered.

An overview on the roles of the European and German electricity market, respectively, is given in European Network of Transmission System Operators for Electricity (2015) and Crastan (2012) and is beyond the scope of this publication.

This work is organized as follows: Section 2 introduces engineering fundamentals of the electric distribution grid and PV systems, and especially the grid planning approaches. Section 3 discusses the effects of the PV feed-in power on the electric distribution grid. The tasks and responsibilities of DSOs by law are described in Section 4. The technical constraints based on standards are described in Section 5. A short overview of different new technologies in smart grid research and development to increase the PV hosting capacity of the distribution systems is described in Section 6. Section 7 concludes the work.

2. Fundamentals of electric grid planning

This section gives a brief overview of the electric distribution grid in undisturbed situations. A disturbance can be caused by an act of nature beyond control, a system failure or human error but is not in the scope of this work. For example, the grid disturbances that impacted the continental European transmission grid on 4 November 2006 was such an event (European Network of Transmission System Operators for Electricity, 2007).

The fundamental equations are the same for each DSO in the world but the practical application may differ from country to country. The reasons for the differences are climate and geography, supply mix and customer behavior, as well as common devices in households, e.g., air conditioning or electric heating. One example for common devices differences is the production of hot water for showers. In Germany, hot water is mainly produced by the home heating system which is fired by gas or oil; water heating therefore does not affect the electric system. But in Brazil there are mainly direct electric heaters, integrated in the shower heads. These electric heaters account for 60% of the peak load in the evening (Kratzenberg and Beyer, 2012). Such country-specific differences must be considered when adopting and interpreting the results from Germany to other countries and applications.

In the last few decades, the DSOs mainly considered the demand of their customers while planning their distribution grids. Grid planning centers on the requirement of a safe and efficient power supply provided by a public grid infrastructure. The main limits are the compliance with voltage levels and the operation of the grid assets. Typical grid planning issues include expansion of the grid to areas of new construction, grid optimisation, and grid reinforcement necessitated by increase in demand or utilisation. In Germany, recent developments in grid planning for the hosting capacity of low-voltage grids assume a constant minimal consumption instead of a no-load assumption. This will avoid expensive over-sizing of the grid for average operating conditions (Wiest and Finkel, 2012). Different German DSOs define a peak utilisation of at least 80% of the nominal values of the assets as trigger for further investigation. In the case of a repeated exceedances, the DSOs will take medium-term action via asset management or grid planning in order to avoid future shortages.

However, an installed generation capacity of around 30% of the annual consumption may cause so-called reverse power flows during the day and a voltage increase in the distribution grid (Ruf et al., 2012a; Cohen and Callaway, 2016; Wirth, 2015). Reverse power flows occur if the PV feed-in power exceeds the power consumption and power is fed back from the distribution system to the upstream electric grid. Reverse power flows are causing the DSOs to reconsider the traditional approach of dividing the voltage band into subsections for the different voltage levels (see Section 6.1).

2.1. Estimation of maximum power

To ensure reliable electricity supply under peak demand, the DSOs