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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).

Table 1
Circuit length and installed capacity for the surveyed DSOs at the end of 2015, calculated from Refs. [1,15], and data provided by the DSOs. The corresponding information for the entire German grid is also included for comparison.

		Germany	Surveyed DSOs	Percentage share
All voltage levels				
1	Circuit length	1,780,856 km	676,957 km	38%
2	Biomass capacity	7 GW	3 GW	47%
3	Wind power capacity	41 GW	24 GW	58%
4	PV capacity	39 GW	17 GW	44%
Low-voltage grid				
5	Circuit length	1,173,065 km	434,721 km	37%
6	PV capacity	23 GW	8 GW	37%

Table 2
Details of the interviewed DSOs, such as number of participants and their positions in the company.

DSO identifier	Interview partners and their functions	Interview date
a	Head of grid development	August 9, 2016
b	Head of grid development and staff member in the controlling department	September 14, 2016
c	Head of grid development and head of regulatory affairs	July 13, 2016
d	Head of grid planning	June 2, 2016
e	Head of grid development, head of regulatory affairs and head of sales	August 18, 2016
f	Head of grid development, head of asset management and head of regulatory affairs	June 15, 2016
g	Head of grid development and staff member in the grid development department	June 13, 2016
h	Chief technology director	June 1, 2016
i	Staff member in the grid technology department	June 14, 2016
j	Chief technology director	June 16, 2016

Table 3
Grid structure in Germany according to voltage level, based on Refs. [15,18]. The nominal voltages, grid lengths, as well as characteristics of the substation transformers are also included.

<table>
<tr><th>Grid category</th><th>Voltage level</th><th>Circuit length</th><th>Typical nominal voltage</th><th>Voltage regulation by substation</th></tr>
<tr><td rowspan="6">Distribution grid
(813 operators)</td><td rowspan="2">Low voltage</td><td rowspan="2">1,173,065 km</td><td rowspan="2">400 V</td><td></td></tr>
<tr><td rowspan="2">Typically fixed voltage ratio</td></tr>
<tr><td rowspan="2">Medium voltage</td><td rowspan="2">511,164 km</td><td rowspan="2">20 kV</td></tr>
<tr><td rowspan="2">Automated voltage control</td></tr>
<tr><td rowspan="2">High voltage</td><td rowspan="2">96,658 km</td><td rowspan="2">110 kV</td></tr>
<tr><td rowspan="2">Automated voltage control</td></tr>
<tr><td rowspan="2">Transmission grid
(4 operators)</td><td rowspan="2">Extra high voltage</td><td rowspan="2">35,970 km</td><td rowspan="2">220 kV, 380 kV</td></tr>
<tr><td></td></tr>
</table>

ratio between the two voltage levels. This allows, for instance, the voltage on the medium-voltage side to remain approximately constant, despite fluctuations on the high-voltage side due to energy feed-in from wind power.

3.2. Low-voltage grid structure

The low-voltage distribution system in Germany provides grid access points for households, small businesses and small farms. In addition, distributed power generation systems are connected to this voltage level as well. As described in the following sections, these are mainly photovoltaic systems, but can also include small wind turbines and small biomass plants.

In rural areas, the low-voltage grids are predominantly supplied by a single local distribution transformer. In these areas, the low-voltage grids have a radial structure [b,d,g], in which several power lines are connected to the local distribution transformer without being connected to each other (see Fig. 1). For more densely populated rural areas, the grid may be set up as a ring grid or, alternately, two local distribution transformers can be used to supply a single power line [f,j]. By contrast, the grids in urban areas are more likely to be interconnected (i.e. as a ring grid).

The low-voltage grid typically supplies an area with a radius of about 500 m [b,e], using mostly underground cables as opposed to overhead lines [a–j]. Among the DSOs surveyed, the proportion of underground cabling was at least 60% [a–j]. Some operators even have 99% of their lines as underground distribution lines. The relatively high percentage of overhead lines of 40% is mainly found in rural regions and is due in large part to historical reasons [f,g].

3.3. Legal framework conditions for the expansion of photovoltaics

The first broad-based test of photovoltaic deployment in Germany took place in the year 1991 with the Federal Government's “1000 Roofs Solar Power Program” [19]. The breakthrough for photovoltaics was achieved with the “100,000 Roofs Solar Power Program” in 1999 and the introduction of the Renewable Energy Sources Act (EEG) in 2000. The interplay of these two programs –

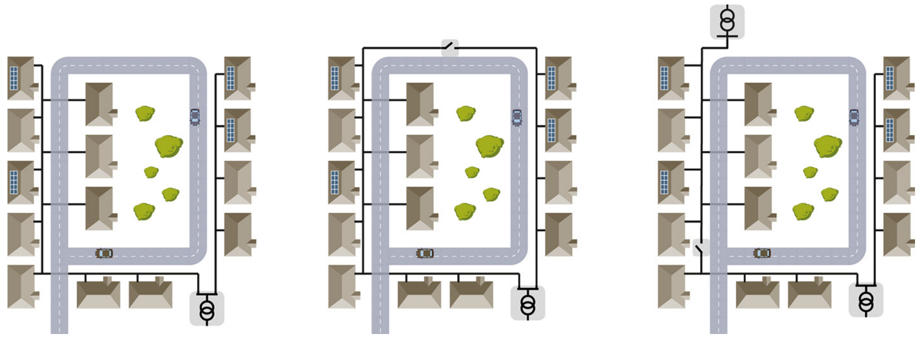

Fig. 1. Schematic representation of a radial grid (left), ring grid (middle) and grid with second local distribution transformer (right).

investments, low-interest loans and a fixed remuneration rate, or feed-in tariff, of over 50 eurocents/kWh – enabled a cost-effective operation of photovoltaic systems [19]. With the reform of the EEG in 2004, the feed-in tariff was again increased in order to compensate for the discontinuation of the "100,000 Roofs Program" [19]. Since then, the profitable operation of photovoltaics is possible based on the EEG feed-in tariff.

Apart from large ground-mounted systems, the German feed-in tariff enables a wide range of rooftop installations through a multi-tiered remuneration system. The EEG 2004 included a three-tier structure with different remuneration levels for installations up to 30 kWp, in the range 30–100 kWp and larger than 100 kWp. The structure has slightly changed during the EEG reforms, though the multi-tier arrangement for supporting small-scale systems has remained in place. [5]

In addition to the feed-in tariff, the EEG also regulates the grid connection. DSOs are required by law to connect renewable energy systems as quickly as possible to the most economical grid access point. DSOs are also obliged – if necessary – to expand network capacities in order to integrate renewables [20,21].

For rooftop PV systems up to 30 kW, the building connection point is considered the most economical grid access point; for systems larger than 30 kW, the distribution system operator must determine which grid access point is most economical [20,21]. The grid access point is therefore the point where the connection and expansion of network capacities brings about the lowest possible overall costs. This might be the building connection point, for example, or the nearest local distribution transformer. The costs for the connection of the photovoltaic system to the grid access point are carried by the system operator [20,21]. The costs for the expansion of network capacity, if necessary, are carried by the DSO [20,21].

3.4. Development and characteristics of photovoltaic expansion in Germany

As can be seen in Fig. 2, solar power is one of the fastest growing renewable energy technologies in Germany. Since the EEG reform in 2004, the installed photovoltaic capacity has grown from 1 GW to 40 GW by 2016. During this period, there was approximately 3 GW of average annual PV growth. In the boom years of 2009–2012, growth even exceeded 7 GW for three consecutive years.

A later reform of the EEG in 2012, which significantly reduced the feed-in tariff, led to a decline in the expansion of photovoltaic systems in subsequent years. 2015, for example, saw the installation of only 1.5 GW of PV capacity, the lowest level of expansion since 2007. For the future, the German government plans an annual gross capacity deployment of 2.5 GW [21].

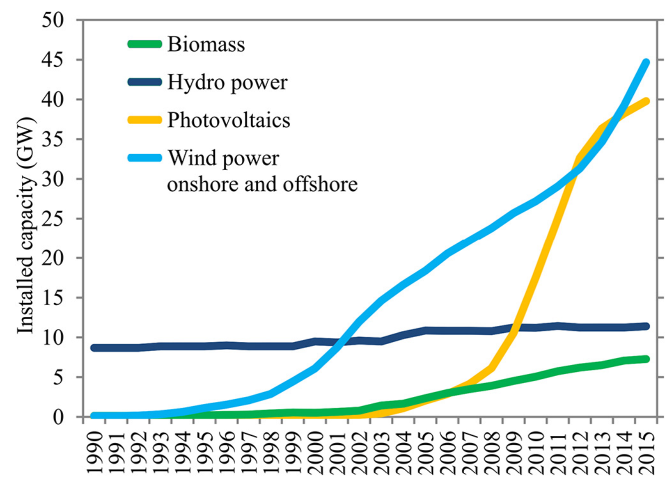

Fig. 2. Development of installed capacity of renewable energies in Germany, based on data in Refs. [22,23].

Apart from photovoltaics, wind energy (onshore and offshore) is also a fast-growing renewable technology with 45 GW installed at the end of 2015. Biomass energy is the third contributor to renewable power in Germany with 7 GW installed by 2016. By contrast, as shown in Fig. 2, the installed capacity of hydropower has remained practically constant in the last two decades.

As mentioned earlier, one of the particular characteristics of photovoltaic systems is that expansion takes place for the most part through the integration of small-scale systems in the low-voltage grids. This is largely a result of the design of the EEG and due to the technological characteristics of photovoltaics. Small PV systems are almost as efficient as utility-scale PV systems. As Fig. 3 shows, a total of 23 GW of PV capacity had been installed in the low-voltage grids by the end of 2015. This corresponds to 57% of the installed photovoltaic capacity. The expansion in the medium and high-voltage grids is significantly lower, with 13 GW and 2 GW respectively. No other (renewable) generation technology achieves a comparably high level of installed capacity in the low-voltage grids. For instance, the installed capacity of wind power and biomass systems in the low-voltage grids amounts to only 97 MW and 843 MW respectively [1]. As indicated in Fig. 3, wind energy systems are primarily installed in the medium-voltage and high-voltage grids, whereas the majority of biomass energy is integrated into the medium-voltage grids.

[5] For example the EEG reform in 2014 introduced the tiers up to 10 kWp, 10–30 kWp, 30–100 kWp, 100–1000 kWp and larger than 1000 kWp.

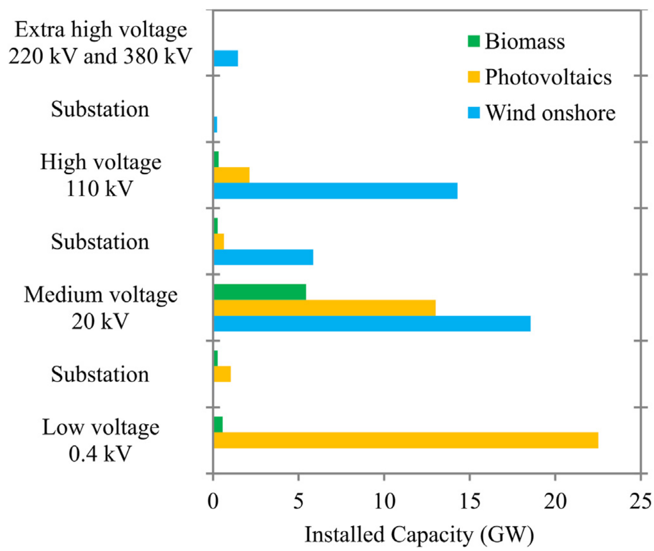

Fig. 3. Installed capacity for biomass, photovoltaics and wind energy per grid level, calculated from data in Ref. [1].

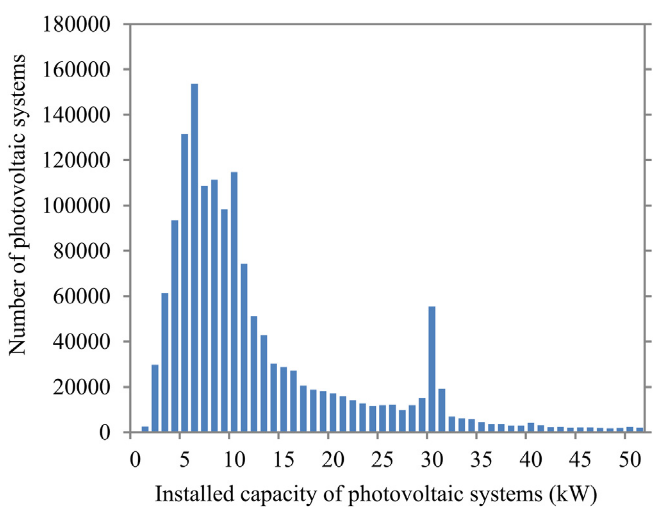

Fig. 4. Number of photovoltaic systems in the low-voltage grid according to their size up to 50 kW, calculated from data in Ref. [1].

Typically, the photovoltaic systems in the low-voltage grids have an installed capacity of only a few kilowatts. It is possible, however, for individual units to have an installed capacity of over 100 kW. Fig. 4 depicts the precise size distribution for systems of up to 50 kW; larger systems in the low-voltage grids are relatively rare. The figure shows that over 90% of photovoltaic systems in the low-voltage grids have a capacity of under 30 kW; the most common size for installed systems is in fact only 6 kW. The peak at 30 kW is a result of the regulatory framework: For systems of up to 30 kW, the grid access point is the building connection point. Consequently, grid connection is always possible at a minimal cost for the owner of the PV system.

The surveyed DSOs pointed out that the expansion of photovoltaic systems in the low-voltage grids (but also in general) is taking place primarily in rural regions [e, f]. The background to this development is that the majority of photovoltaic systems are installed on the rooftops of one to two-family owner-occupied homes.

4. Measures for the integration of photovoltaic systems in the low-voltage grid

4.1. Reasons for grid expansion

DSOs are responsible for a safe and reliable operation of the low-voltage grids. Within the scope of the grid compatibility check, the technical assessment is made as to whether a photovoltaic system can be connected to the low-voltage grid without impermissibly exceeding the limits for voltage or current-carrying capacity. This principle of grid compatibility also applies when integrating other renewable energy systems such as wind and biomass.

Due to the significant expansion of photovoltaic systems in the low-voltage grids, all surveyed grid operators already had to implement measures in their respective grid areas in order to guarantee the integration of photovoltaic systems.

As primary reasons for the grid expansion, the surveyed grid operators indicated both the compliance with the voltage range and the compliance with the limits for the current-carrying capacity of the operating equipment. Particularly in grid areas in southern Germany, the overload of operating equipment was cited as the main reason for grid expansion [f–h]. Typically the local distribution transformer is replaced. For DSOs in northern Germany, on the other hand, maintaining the voltage range was the most frequent reason cited for grid expansion [a,d,j]. Another DSO indicated that these problems occur with approximately the same frequency [e].

DSOs identified various potential reasons for these regional differences. On the one hand, the installed capacity per household in southern Germany is significantly higher than in the north. Higher feed-in capacity makes it more likely that operating equipment (e.g. transformers) is overloaded through reverse flow [a]. Differences in settlement structures were also cited as an additional reason for the regional differences [a,i]. Two of the surveyed DSOs stated that because the housing structures in northern Germany are more spread out, voltage problems are more likely to occur due to the longer low-voltage lines [a,i]. One DSO also suggested that the high number of renewable energy systems in the northern German medium-voltage grid could increase the voltage problems in the low-voltage grid [g]; if the permissible voltage range is already exhausted at the medium-voltage level, the leeway in the low-voltage grid is correspondingly smaller.

4.2. Overview of measures

When the grid compatibility check indicates that the low-voltage grid in question can no longer accommodate the requested photovoltaic system, the grid operator can take various measures to ensure that the permissible voltage and current limits are adhered to in the future as well. Table 4 provides an overview of the most common measures implemented in the German grids so far.

Measures 1.1 to 1.4 are typically associated with classic grid expansion. Measures 2.1 and 2.2 are so-called intelligent operating devices, developed only a few years ago for use in the low-voltage grids. Under certain circumstances, they present an economical alternative to classic grid expansion measures. By using measures 3.1 to 3.4, the hosting capacity of the grids can be increased without the grid having to be expanded; in many cases this is the most economical initial measure. In addition, grid monitoring has been strengthened, feed-in management implemented and grid planning revised in order to ensure safe grid operation (see measures 4.1 to 4.3).

In the case of thermal capacity problems (current exceeds permissible limit), distribution system operators can make use of five measures, depending on the overloaded piece of equipment

Table 4
Measures for the integration of photovoltaic systems into the low-voltage grid.

	Measures	To maintain voltage range	To avoid thermal overload of transformers	To avoid thermal overload of power lines
1	**Classic grid expansion**			
1.1	Replacing local distribution transformers	X	X	
1.2	Segmenting local grid	X	X	X
1.3	Laying parallel cables	X		X
1.4	Increasing conductor cross-section	X		X
2	**Intelligent equipment**			
2.1	Voltage regulator	X		
2.2	Voltage-regulated distribution transformers	X		
3	**Grid optimization**			
3.1	Individual tap changing of distribution transformers	X		
3.2	Wide-area control	X		
3.3	Reactive power feed-in	X		
3.4	Changing grid topology	X	X	X
4	**Grid operation and planning**			
4.1	Grid monitoring			
4.2	Feed-in management			
4.3	Improved grid planning			

(power line or transformer). If a local distribution transformer is overloaded, it can be replaced, the local grid can be segmented, or the grid topology may be changed. If, on the other hand, the power line is overloaded, it can be replaced, a parallel cable can be laid, the local grid can also be segmented, or the grid topology may be changed.

Several further measures are being implemented in the case of voltage problems, in addition to the classic grid expansion. For example, in some instances of voltage faults, operators can choose between laying parallel cables, adding a voltage-regulated local distribution transformer or adding a voltage regulator (booster transformer). Moreover, changing the grid topology or an optimized reactive power supply might also help to solve voltage issues.

The integration measures can be further classified into dynamic and static. Dynamic measures increase the hosting capacity by automatically regulating specific properties of the grid, such as the voltage ratio between grid levels or the feed-in of reactive power. The dynamic measures include implementation of voltage regulators and voltage regulated distribution transformers, wide-area control and reactive power feed-in. By contrast, static measures increase the hosting capacity by making permanent changes to the grid. In addition to all classic grid expansion measures, the static measures include individual tap changing of distribution transformers and changing the grid topology.

4.3. Classic grid expansion measures

4.3.1. Replacing the local distribution transformer

Local distribution transformers couple the medium-voltage and low-voltage grids and typically have an output ranging from 100 to 630 kVA [c,f]. These transformers were originally designed exclusively for consumer grids; however, the development and integration of renewable energy sources gave rise to situations where PV generation significantly exceeds demand. This can lead to reverse flow into the medium-voltage grid in individual regions, and the local distribution transformers have to be set up for maximum reverse flow instead of maximum demand.

All surveyed DSOs indicated that in some low-voltage grids, the local distribution transformers had to be upgraded to accommodate the strong growth of PV [a–j]. Three DSOs explicitly stated that the local distribution transformer was typically the first point of congestion for a low-voltage grid [e,f,i]. Other operators with a relatively small amount of PV generation indicated that a transformer replacement was necessary only in a few rare instances [a]. One of the interview partners also pointed out that a bigger transformer with a higher short-circuit capacity also has a positive effect on voltage control, as the voltage drop is reduced at the transformer [f].

4.3.2. Segmenting the local grid

A very high deployment of photovoltaic capacity can also exceed the capacity of a single local distribution transformer to handle the reverse flow from the low-voltage grid.

One possible solution is to create a new low-voltage grid by segmenting the existing local grid and supplying the separated

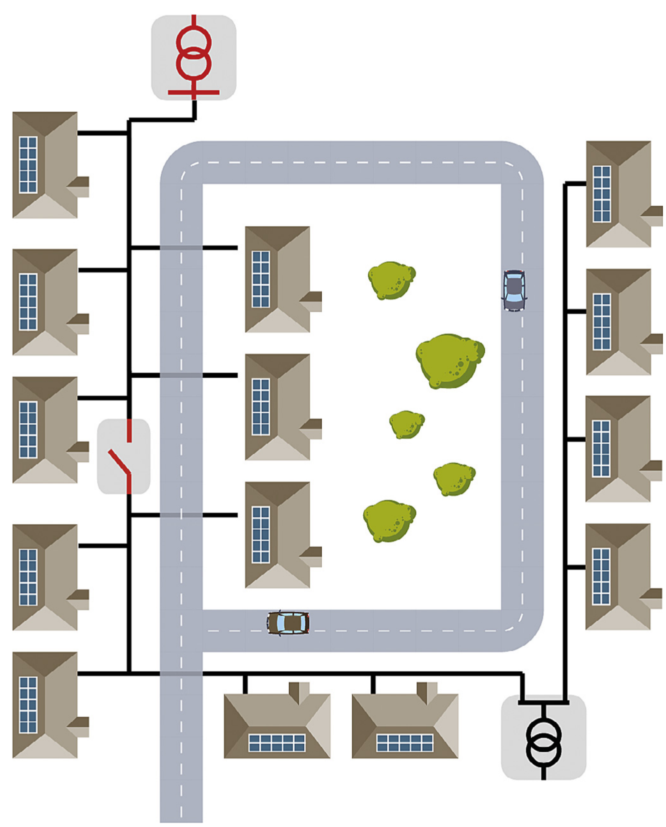

Fig. 5. Schematic representation of a local grid with additional local distribution transformer.

subsection by an additional local distribution transformer. In Fig. 5 the additional transformer and the switching station, which separates the power line in two segments, are highlighted in color. Apart from overload issues in the transformer, this measure can also be applied to maintain the recommended voltage range or when the ampacity limit of the cables is reached.

This measure was mentioned in particular by grid operators in southern Germany [f–h] and was only occasionally implemented by DSOs in northern Germany [a,e,h], since it is necessary only in the case of very high PV generation rates. In addition, this is a relatively complex measure that also affects the medium-voltage grid [f,g]. To exemplify the complexity involved: One DSO mentioned that a low-voltage grid planner can plan and complete only five local distribution transformer substations per year [g].

4.3.3. Laying parallel cables

The laying of parallel power lines is a common option for cases where the cross-section of a cable is no longer sufficient due to voltage or current issues. This measure is depicted in Fig. 6. The parallel cable runs from the local distribution transformer to a cable distribution box where it connects to the respective low-voltage grid. The larger cross-section decreases the grid impedance, thus reducing the voltage drop in the power lines.

Apart from the DSO with the lowest number of photovoltaic units, all operators have made use of parallel cables [a–j]. Those surveyed DSOs with a comparatively small number of photovoltaic systems used the parallel cables to solve voltage issues [a,d]. In these cases, the cables did not even come close to their current-carrying capacity. One grid operator reported that voltage-regulated local distribution transformers are used whenever possible in such instances to prevent two or more parallel cables [a]. This would have the disadvantage of including cables with different residual lifespans, leading to more frequent excavation work for maintenance or replacement.

Furthermore, DSOs with a high level of PV integration into the low-voltage grids indicated that the insufficient ampacity of some existing cables is also a reason for adding parallel cables [e,g]. This could be particularly relevant for older cables that still have a smaller cross-section than today's standard.

4.3.4. Increasing the conductor cross-section

The replacement of existing low-voltage lines by ones with a larger cross-section is another measure that can reduce the voltage drop in the lines and increase the current-carrying capacity.

Only one DSO stated that cables had been replaced before the end of their lifespan to accommodate PV integration into the grid [f]. In case of age-induced substitutions, two DSOs indicated that they utilize larger conductor cross-sections than in the past, although the typical new cross-sections differ from operator to operator [c,e]. One DSO stated that a cross-section of 150 mm^2 is used almost exclusively and that laying parallel cables is preferred over increasing the cable diameter [c]. Two other operators noted that a cross-section of 150 mm^2 is partly not sufficient to accommodate PV integration, and that cross-sections of 240 mm^2 are therefore being used [a,c]. One DSO also uses cross-sections of 300 mm^2 in specific cases [c].

One DSO also pointed out that there is currently very little willingness to switch from overhead lines to cables in the low-voltage grids [f], as homeowners would have to change their electrical connection point for this purpose. This would be both time-consuming and expensive, and represents a barrier to the further undergrounding of distribution lines.

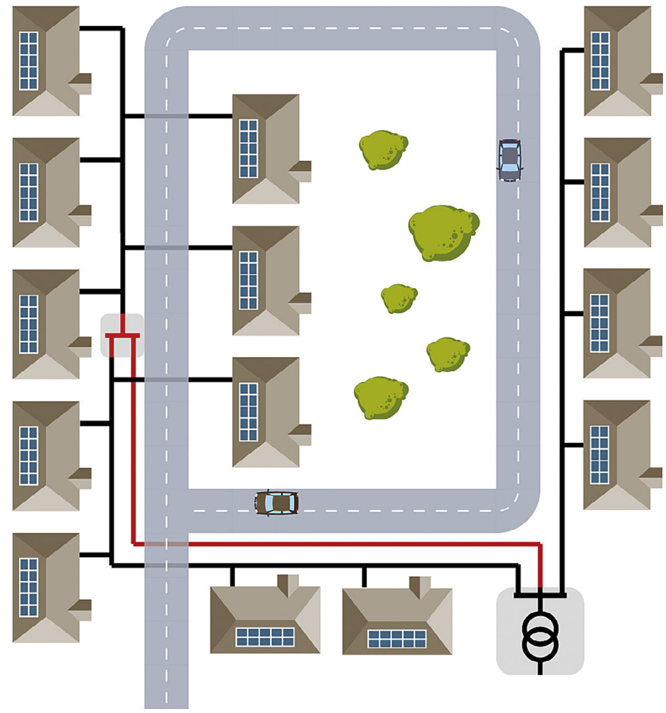

Fig. 6. Schematic representation of a parallel power line (highlighted in color). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.4. Use of intelligent operating equipment

4.4.1. Voltage regulator

A so-called voltage regulator (or booster transformer) can be used in the low-voltage line in order to raise or lower the voltage level. In physical terms, this voltage regulator is a transformer that automatically regulates the voltage ratio depending on the voltage in the low-voltage line. Compared to the voltage-regulated local distribution transformer, the voltage of a single line can be adjusted without simultaneously affecting the voltage of the other low-voltage lines (see Fig. 7).

Four DSOs indicated that they have been testing voltage regulators from different manufacturers within the scope of pilot projects [f–h]. Two of the DSOs explicitly stated that voltage regulators could be used in the near future as standard operating equipment [g,i]. Especially for low-voltage grids with long power lines, voltage regulators could present an economically and technologically beneficial alternative to classic grid expansion measures [g].

4.4.2. Voltage-regulated local distribution transformers

As explained in Section 4.3, local distribution transformers couple the medium-voltage grid (20 kV) and the low-voltage grid (400 V). Standard local distribution transformers have fixed voltage ratios, and the steps can be set manually in a limited range. If the voltage ratio remains constant, the voltage in the low-voltage grid increases as the voltage in the medium-voltage grid increases (see Fig. 8).

By contrast, voltage-regulated transformers can adjust the voltage ratio automatically and without interrupting the power supply. By gradually increasing the voltage ratio, for instance, the voltage on the low-voltage side of the transformer can remain nearly constant at 400 V even when the voltage in the medium-voltage grid increases. The step-by-step increase of the voltage ratio due to increasing voltage in the medium-voltage grid is shown

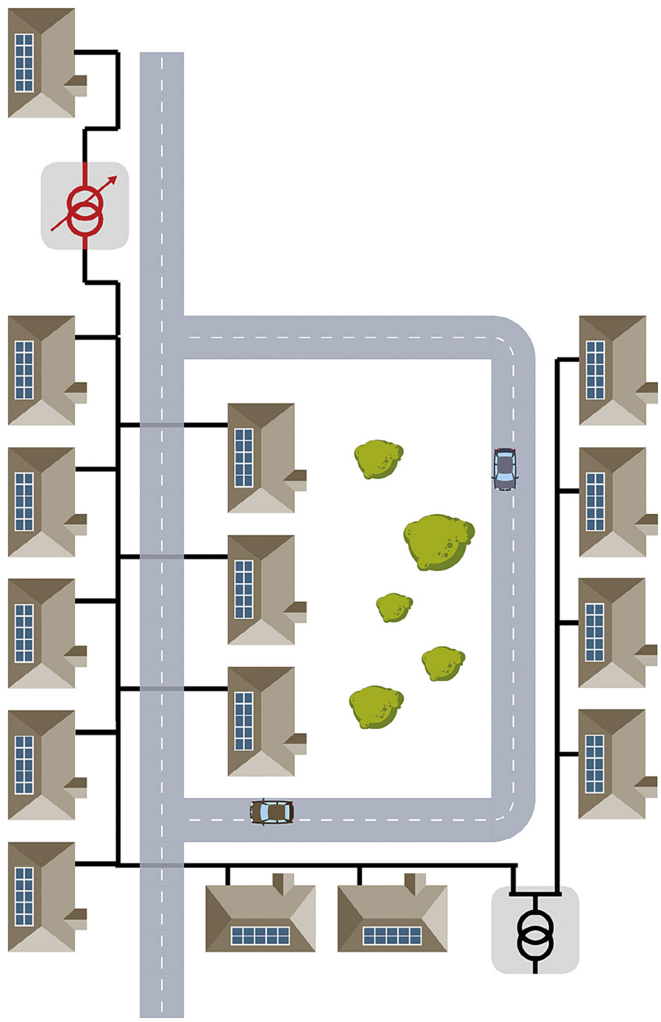

Fig. 7. Schematic representation of a voltage regulator for single low-voltage lines (highlighted in color). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

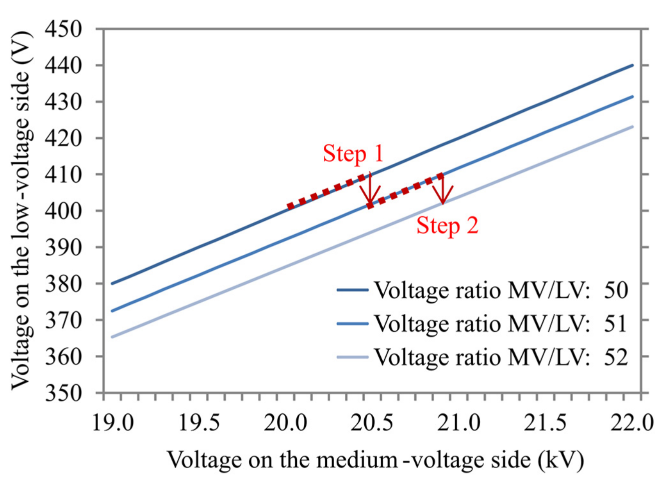

Fig. 8. Schematic representation of the adjustable voltage ratio between the medium-voltage and the low-voltage sides of a voltage-regulated transformer.

as an example in Fig. 8.

The integration of PV systems into the low-voltage grid also leads to a voltage increase with increasing distance to the local distribution transformer. For photovoltaic systems located at the end of long power lines, there is a risk of the maximum nominal voltage of 440 V (400 V + 10%) being exceeded at the end of the line. By means of controlling the voltage ratio, the voltage on the low-voltage side of the transformer can be set to the desired level so that there is a sufficient voltage buffer for the feed-in from photovoltaic systems.

Nine of ten DSOs operate voltage-regulated local distribution transformers [a–j]. However, these transformers are typically used in few individual cases or in the context of pilot projects [c,d,f–j]. Only two of the surveyed DSOs indicated that they already have installed more than 100 voltage-regulated local distribution transformers.[6] In terms of percentage, this translates into a maximum of 1–2% of all local distribution transformers in use in the respective grid areas. These two DSOs stated that for certain cases the voltage-regulated local distribution transformer is the most economical option.

The differing number of devices in use reflects the varying assessment of voltage-regulated local distribution transformers. One reason cited for the low usage numbers is the fact that in certain grid areas capacity issues represent the most common problem. As a result, voltage-regulated local distribution transformers are not a solution for these cases [g]. In addition, two other DSOs stated that voltage-regulated local distribution transformers are often only an intermediate solution for the voltage problems that exist at a given time [c,f]. They pointed out that capacity issues will eventually arise due to the continuously growing PV capacity, so that classic grid expansion is thought to be the more effective alternative approach in the long term.

With a view to the future, only one DSO indicated that he had developed a comprehensive rollout concept incorporating the continuing development of local grid structures.[7] From a long-term perspective, this grid operator is expecting great advantages through the decoupling of the medium- and low-voltage grids.

4.5. Grid optimization

4.5.1. Individual tap changing of distribution transformers

As explained above, the voltage ratio of normal (non-controllable) local distribution transformers can be adjusted manually. By decreasing the voltage on the low-voltage side of the transformer, a larger range becomes available up to the higher voltage limit. This additional range may be used for further photovoltaic systems in the low-voltage grid. However, the voltage range down to the lower voltage limit will shrink correspondingly. Consequently, the voltage on the low-voltage side of the transformer cannot be set too low, since the voltage limits must also be respected in the event of high demand and low PV generation.

In the interviews, four DSOs stated that they have individually adjusted the voltage ratio as a result of PV integration into the low-voltage grids in order to avoid exceeding permissible voltage limits at the end of the lines [b,d,g,i]. One DSO also added that the voltage ratio is seasonally adjusted [d]: In the summer the voltage ratio is increased due to the high level of photovoltaic feed-in, while in winter the voltage ratio is reduced due to the high load from electrical heaters. Another grid operator stated that individual tap changing of the local distribution transformers, in conjunction with wide-area control, is technically sufficient and economically more efficient that the use of voltage-regulated local distribution transformers [g].

[6] We do not cite the two interview partners to guarantee their anonymity.
[7] We do not cite the interview partner to guarantee the anonymity.

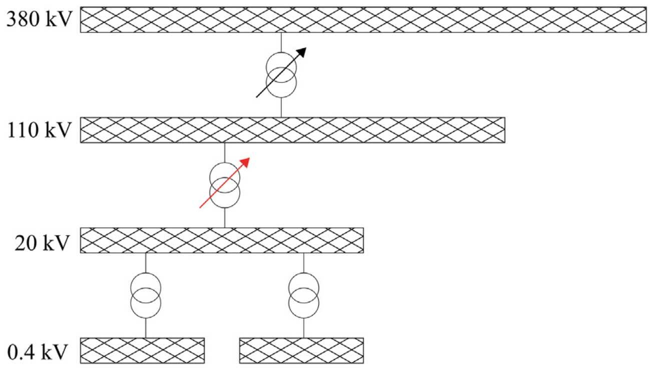

Fig. 9. Schematic representation of wide-area control between the high- and medium-voltage levels.

4.5.2. Wide-area control

Grid operators use the control option between the high- and medium-voltage levels to adjust the voltage level for the complete supply area of a transformer substation, including low-voltage grids (see Fig. 9). In the past, the voltage on the medium-voltage side of the substation was regulated to a fixed value (e.g. 20.6 kV). Within the scope of wide-area control, the voltage in the transformers can be set dynamically depending on the load situation (e.g. in the range 20.4 kV–20.8 kV) [f].

Six DSOs mentioned explicitly that they control the voltage at the high-to medium-voltage transformer substation to support the PV integration in the low voltage grid [e–g,j]. The two DSOs with the greatest share of PV integration stated that they actively adjust the voltage depending on the level and direction of the power flow. In this way, they respond to photovoltaic feed-in in the low-voltage grid, so that the medium-voltage level is reduced as much as possible during periods of high PV generation. One DSO indicated that he temporarily reduced voltage to 19.8 kV [g], while another DSO reduces the voltage to a minimum of 20.4 kV [f]. One of the operators also pointed out that in grid areas with a high load due to a significant share of industrial power, voltage cannot be significantly reduced [f]. According to statements by the interview partners, wide-area control can be implemented relatively cost-effectively [f,g]. Thus, in the case of older substations, solely the transformer regulator (i.e. electronic component) must be replaced, while for newer substations only a software update is required.

4.5.3. Reactive power feed-in through photovoltaic inverters

Inverters capable of reactive power [8] can contribute to maintaining the voltage range in the low-voltage grids. In particular for long low-voltage power lines, the permissible voltage limits can be exceeded at the feed-in point. If the inverters simultaneously supply reactive power, however, the voltage at the grid access point can be reduced by 1–2% [f].

According to VDE application regulation VDE-AR-N 4105 from 2011, inverters must be capable of providing reactive power [24]. The standard characteristic curve from the VDE application regulation is preset at the factory, although it can be individually set by the grid operator. However, PV inverters almost always use the standard characteristic curve rather than setting individual specifications [f–h]. Using individual characteristic curves is primarily an organizational issue due to the high number of PV systems in the grid [f].

[8] Reactive power is generated when coils or capacitors are installed in the grid. The grid voltage can also be changed by the absorption of reactive power. This effect is used by inverters capable of reactive power.

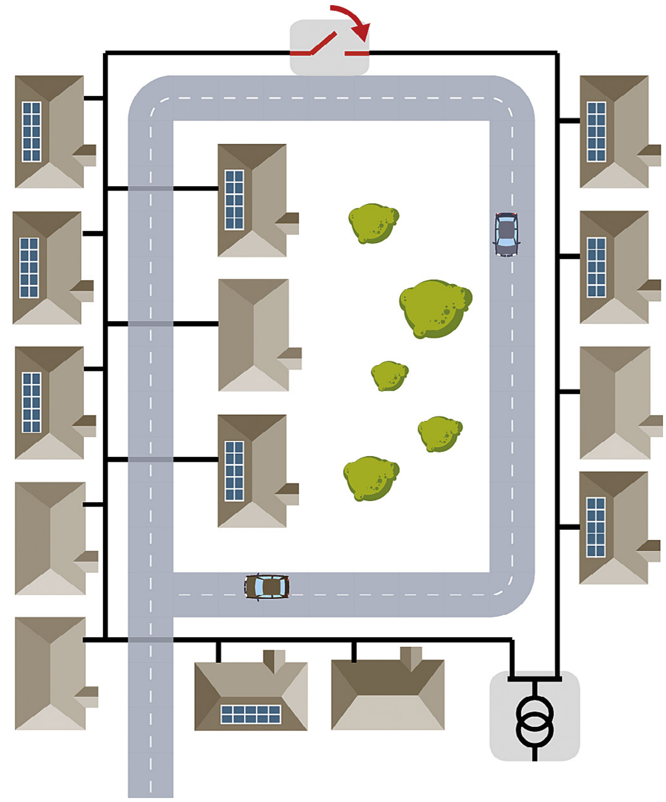

Fig. 10. Schematic representation of a closed ring grid.

Additionally, DSOs continuously modify and expand the grid, resulting in a need for further individual readjustments [f]. Correspondingly, only one DSO indicated that he sets individual characteristic curves in very particular cases [d], although he does not verify whether the setting was performed correctly. This also has to do with the high number of PV systems in the low-voltage grid.

4.5.4. Changing the grid topology

Under certain conditions, a change in grid topology can help to integrate additional PV capacity into the low-voltage grids. This is for example possible in the case of ring grids. These are typically operated as an open ring grid, i.e. the grid structure in operation corresponds to a radial grid. By connecting the two power lines at the switching station, the grid can also be operated as a closed ring (see Fig. 10). This reduces grid resistance, thereby reducing the voltage drop in the grid [j]. As a result, grid expansion because of voltage problems can be temporarily avoided [j]. One of the DSOs also pointed out that, in some instances, grid expansion is necessary in order to merge two power lines into one ring grid [j].

A further optimization measure can be implemented for grid lines that can be supplied by two local substations [f]. If the reverse flow at one local distribution transformer is significantly higher than at the other, a portion of the grid feed-in can be transferred to the second local distribution transformer by activating a pair of switches in the system (see Fig. 11).

The DSOs that considered this option also pointed out that these measures could only be implemented for the specific grid topologies described here [d,f,j]. These are however relatively rare, as most low-voltage grids are designed as radial grids. In addition, one grid operator noted that these measures represent only a temporary solution and that additional measures are necessary to integrate further photovoltaic capacity into the low-voltage grids [f].

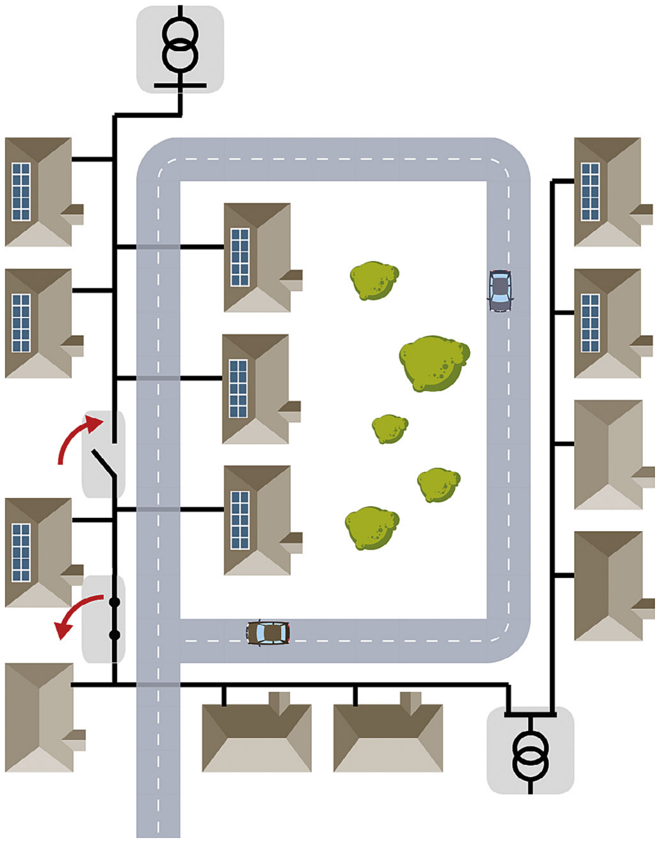

Fig. 11. Schematic representation of a local grid with second local substation.

4.6. Grid operation and planning

4.6.1. Grid monitoring

The DSOs monitor the status of the grids in the control rooms and initiate corrective measures when necessary (e.g. grid switching). The necessary data for monitoring the distribution grids is collected in the high- and medium-voltage grids and transmitted to the control room in real time. Measurement data from a few points are sufficient for the monitoring of the distribution grids. In the medium-voltage grid, for example, current and voltage are measured at the substation's outgoing lines [b,f–h]. In addition, current and voltage are measured at selected grid stations in the medium-voltage grid and transmitted to the control room [a,d,f–h]. The DSOs, however, do not require real-time data from the low-voltage grids to carry out regular operations [a–j].

In the low-voltage grids themselves, only a grid-wide measurement of the maximum current takes place [d,g,i]. This is measured by means of a so-called drag indicator, which only captures the maximum current reached. The readout of the indicator takes place once a year. Up to now, the drag indicator was only able to measure the maximum current, but not the current direction. In the past this was not necessary, since there was no reverse flow from the low-voltage grid to the medium-voltage grid. Now, however,bi-directional drag indicators are utilized.

By contrast, there is no grid-wide measurement of the voltage in the low-voltage grids. The compliance with the voltage range is verified as part of the grid compatibility check by calculations. Nevertheless, event-specific measurements are carried out, for example when electricity customers report irregularities or when calculations indicate that the voltage is approaching the permissible limits [b,g]. So far no DSO has indicated plans to introduce grid-wide measurement points in the low-voltage grids.

4.6.2. Feed-in management

Since the 2012 amendment of the Renewable Energy Sources Act, all photovoltaic systems with a capacity of up to 100 kW must participate in the so-called simplified feed-in management scheme [32]. With this regulation, the legislator established the prerequisites that enable DSOs to throttle the output of photovoltaic systems in the event of grid congestion by using remote-control technology. The obligation to expand the grid in order to integrate renewable energy remains unchanged in the 2012 and 2014 amendments of the Renewable Energy Sources Act. Consequently, this instrument can only be used in case of temporary congestion and technical faults and not as an alternative to grid expansion. Starting with the 2017 amendment of the Renewable Energy Sources Act, the feed-in management can be used under certain conditions as an alternative to grid expansion [23]. This serves in particular to prevent bottlenecks or voltage issues in the high- and medium-voltage grids. In the long run, this mechanism could also be used for the low-voltage grid.

For the simplified feed-in management, ripple control systems are commonly used, which send uni-directional control signals to the photovoltaic systems [c]. Photovoltaic systems with a capacity of up to 30 kW alternately have the option of limiting the active power feed-in to 70% of the installed capacity. The DSOs interviewed stated that the technological prerequisites exist to regulate the photovoltaic systems when necessary [d–g,i]. However, this instrument is not applied in regular grid operations, and photovoltaic systems up to 100 kW are not subject to active curtailment [d–g,i]. Only one DSO cited plans to test this instrument within the framework of a research project [i].

One of the DSOs explained that the planning principles for the low-voltage grids are a safeguard of secure grid operations [e]. These planning principles prevent operating equipment from becoming overloaded in regular grid operations. For example, the grid compatibility check ensures that the feed-in capacity of photovoltaic systems does not exceed the capacity rating of the local distribution transformer. One grid operator also pointed out that it is not possible to verify the implementation of power curtailment due to the unidirectional communication [e].

Some grid operators, however, stated that there have been instances of photovoltaic systems automatically reducing their feed-in capacity due to overvoltage at the feed-in point [f,g]. Yet these automatic curtailments are only a temporary occurrence until grid expansion is completed [g]. In many cases, customers are already made aware of the possibility of such curtailments when the grid compatibility check is carried out [g].

4.6.3. Improved grid planning

Private persons or legal entities who wish to feed energy into the grid are required to apply for a grid connection prior to installation of the photovoltaic system. Within the scope of the grid compatibility check, the DSO checks for compliance with the voltage range in the low-voltage grid and also ensures compliance with the current-carrying capacity of the operating equipment in the grid. As mentioned earlier, for photovoltaic systems bigger than 30 kW, the DSO also determines the grid access point with the lowest overall costs for grid connection and grid expansion. This is not necessary for smaller PV systems, as the grid access point is the building connection point due to statutory requirements.

Two DSOs pointed out that a grid compatibility check is not carried out for all grid connection requests [b,j]. One DSO does not conduct a grid calculation for photovoltaic systems smaller than 10 kW, but instead issues general approval for these systems [j]; for photovoltaic systems larger than 10 kW, however, a grid compatibility check is carried out. This assessment takes into account all the systems in the respective low-voltage grid, so that existing small systems under 10 kW are also tested during this step. Furthermore, no individual grid compatibility checks are carried out in network areas in which only a small number of photovoltaic systems have so far been connected to the low-voltage grids. By contrast, two other DSOs carry out individual grid compatibility checks for all photovoltaic systems, including small-scale systems [d,f].

There are also various ways in which the grid compatibility check is carried out. One DSO conducts a grid flow calculation as standard procedure, using simulation programs such as PSS®SINCAL, DIgSILENT PowerFactory, and subsequently uses this calculation for each low-voltage grid compatibility check [f]. Two other DSOs use simulation programs only in grid areas with a high share of PV integration [a,i]. Still one another DSOs leave the choice of the grid calculation tools to the respective grid planners for the low-voltage grid [g].

The prerequisite for using simulation programs is that the low-voltage grids are digitized. This is the case with all surveyed grid operators who expressed their views on the matter [a,b,e–g]. In some cases the digitization of the physical circuit diagrams only took place during the last three to five years [g]. Before that, it was not possible to know, for example, which circuit the PV systems were connected to, since a manual assessment of the analogue grid maps would have been too time-consuming.

The grid compatibility check includes two extreme scenarios: maximum generation with minimum load, and minimum generation with maximum load. As all other variations fall between these two extreme scenarios, the DSOs can ensure that the values for voltage and current intensity stay within the permissible limits during normal operation. The first scenario is essential for the grid compatibility check of new photovoltaic systems. Therefore the DSOs need to make assumptions regarding the maximum generation and the minimum load in the respective low-voltage grid.

For the maximum generation from photovoltaic systems, some grid operators assume a simultaneity factor of 1 [a,d]. This means that in the grid compatibility check it is assumed that all systems can simultaneously feed in at full capacity. Other grid operators have already reduced this value based on experience. One grid operator, for example, assumes a simultaneity factor of 0.8 [f]. In this context, one grid operator also pointed out that ever more precise planning means that safety buffers in the grid are being gradually removed, so that the grid is being operated ever closer to its technical limits [i].

There are also different approaches for the determination of the minimum load. One option is to evaluate the quarter-hour values from the measurements at the substation [f] and use adjustment factors to calculate the load in the low-voltage grids. Here it is assumed that all the lines of a low-voltage grid have the same load behavior. A further option is to use a bottom-up approach and calculate the minimum load of a low-voltage grid based on the standard load profiles and the number of offtake points in the respective grid area [d].

There are further differences with regard to the planning guidelines. According to the DIN EN 50160 standard voltage value may deviate from the nominal value by 10% [18]. This is a universal rule that applies to all voltage levels including the low-voltage level. Given the fixed voltage ratio between the medium- and low-voltage grids, both voltage levels need to be addressed jointly by this rule.

In addition, the VDE application regulation VDE-AR-N 4105 stipulates that the voltage increase from all photovoltaic systems in the low-voltage grid may not exceed 3% in a load-free scenario [31]. This represents a simplified rule for the voltage allocation between medium and low voltage, which is easier to implement in daily planning procedures. However, the regulation allows a deviation from this value in justified individual cases.

Two DSOs indicated that the 3%-rule represents the valid planning tool in the low-voltage grid [c,e]. On the other hand, three DSOs only take the universal 10%-rule into account for planning the low-voltage grid [a,b,g], because as they see it, the 3%-rule is based only on theoretical considerations and not on the actual voltage situation on the ground; the 3%-rule, they argue, signals a grid expansion requirement at an unnecessarily premature point in time. Another DSO added that the 3%-rule cannot be applied when voltage regulators or voltage-regulated distribution transformers are deployed [e].

The different planning criteria can be explained by differences in grid conditions, arising for example from the varying number of renewable energy systems in the overlying medium-voltage grid, as pointed out by one DSO [f]. If the DSO is able to accurately estimate the voltage fluctuations in the medium-voltage grid, then deviations from the conservative 3% rule are acceptable. The same DSO added that, depending on the specific circumstances, either set of rules can be used to guarantee the compliance with the voltage range through grid-planning measures [f].

5. Discussion of the mitigation measures

The interview results show that the DSOs share a very similar overall assessment of the individual mitigation measures. Consequently, they implement the same set of mitigation measures, whereby the practical relevance and the implementation sequence are much alike. Tables 5 and 6 present a ranking of the mitigation measures for capacity and voltage issues, based on their practical applicability. The tables include the actual measures mentioned by the DSOs and other proposed measures that are found in the technical literature [7–10]. Organizational measures such as advanced planning or monitoring are not listed, as they do not mitigate capacity issues but rather help to better identify the occurrence of these problems. Ideally, the implementation of mitigation measures can be postponed in time by improved planning or monitoring.

5.1. Mitigation measures for capacity issues

As Table 5 shows, the initial measure for capacity issues is typically the replacement of the local distribution transformer. The capacity of the distribution transformer is usually upgraded to a maximum of 630 kVA. If this capacity has been reached, the segmenting of the local grid is the next measure. This option might also be the most economical, if the planning procedures show that one or more of the involved power lines might face voltage problems in the near future due to the continued expansion of PV systems. A change in grid topology is also a potential initial measure that can be implemented even before replacing the local distribution transformer. However, this measure is not very common as the low-voltage grids typically have a radial structure. As a consequence, the power lines cannot be connected differently by reconfiguring the grid switches.

5.2. Mitigation measures for voltage issues

Table 6 shows the ranking of measures that are employed to mitigate voltage issues. The implementation of wide-area control is typically the initial measure to increase the hosting capacity of the medium-voltage grid and associated low-voltage grids. The individual tap changing of distribution transformers has also been mentioned as an initial measure to deal with voltage issues. As a

Table 5
Mitigation measures for capacity issues as resulting from the conducted interviews [a–j].

	Measures for addressing capacity issues	Practical relevance	Brief assessment
(1)	Replacing local distribution transformers	High	Typical initial measure. The transformer capacity can be upgraded up to 630 kVA.
(2)	Segmenting local grid	High	Second measure applied when potential of option (1) is exhausted. Consequently less frequently implemented than (1).
(3)	Changing grid topology	Low	Potential initial measure. Scope of application is very limited.
(4)	Other measures: active power curtailment of PV inverters, implementation of large-scale battery systems, control of demand-side appliances	None	Implementation limited to pilot projects for research purposes.

Table 6
Mitigation measures for voltage issues as resulting from the conducted interviews [a–j].

	Measures for addressing voltage issues	Practical relevance	Brief assessment
(1)	Wide-area control	High	Initial measure that raises hosting capacity of all low-voltage grids connected to the substation.
(2)	Reactive power feed-in	High	Since 2012 PV inverters supply reactive power by using the standard factory setting. No direct control by the DSOs.
(3)	Laying parallel cables	High	Typically implemented for voltage issues, as the effect of (1) and (2) is limited.
(4)	Individual tap changing of distribution transformers	Medium	Initial measure implemented by several DSOs.
(5)	Voltage-regulated distribution transformers	Low	Only economical in specific cases. Only one DSO plans a general rollout.
(6)	Voltage regulator	Low	Only economical in specific cases.
(7)	Segmenting local grid	Low	Potential option but mostly implemented in the context of capacity issues.
(8)	Increasing conductor cross-section	Low	Only applied if cables are about to reach end of lifetime.
(9)	Changing grid topology	Low	Potential initial measure. Scope of application is very limited.
(10)	Replacing local distribution transformers	None	Has a positive effect on the voltage drop, but this measure is not implemented for voltage issues.
(11)	Other measures: active power curtailment of PV inverters, implementation of large-scale battery systems, control of demand-side appliances	None	Implementation limited to pilot projects for research purposes.

following step, the laying of parallel cables is typically the next mitigation measure. Reactive power feed-in by PV inverters also plays a role, especially since it is required by law. However, DSOs do not actively control the reactive power setting during operation.

For the remaining mitigation measures, their applicability and frequency of use seem to be rather low due to a variety of reasons. Nevertheless, in specific cases, voltage-regulated distribution transformers, booster transformers, the segmenting of the local grid or changes in the grid topology might be the most economic options and are consequently implemented.

Other innovative options for mitigating capacity and voltage issues are mentioned in the technical literature (see item (4) in Table 5 or item (11) in Table 6). They entail for example the implementation of large-scale battery systems [6,10], the control of demand-side appliances like electric vehicles [8,9], or the active power curtailment of PV systems [7,9,10]. According to the interviewed DSOs, these options are however not (yet) economically and/or technically viable. On the other hand, some academic papers suggest that the regulatory framework is sometimes preventing the implementation of this type of projects [10]. Several DSOs also mentioned regulatory restrictions that hamper innovative solutions. For instance, the present unbundling requirements hamper the optimized operation of large-scale batteries [g]. Another example is the present regulation of operating expenses [d–g,i,j]. These expenses tend to be higher for intelligent grid equipment than for classic grid expansion measures. This creates a disadvantage for DSOs, since in contrast to capital expenditures, there is no return on investment for operating expenses. However, the DSOs also emphasized that the main reason for not implementing measures like large-scale batteries lies in the economic viability of these solutions [c,d,f,g,i]. In the case of active control of demand-side appliances, the technical potential is also very limited according to the statements of two DSOs [f,g]. Voltage-regulated distribution transformers or booster transformers (items (4) and (5) in Table 6) are also affected by the remuneration of operating expenditures. But here as well, the low implementation rate is rather linked to the technical/economical assessment than to regulatory disincentives.

6. Summary and conclusions

The substantial experience accumulated by German DSOs highlights the practical solutions that exist for the technical challenges posed by the grid integration of distributed energy resources. Our paper taps into this experience by compiling and explaining the measures that have been carried out to facilitate the integration of photovoltaic systems in Germany's low-voltage grids. To arrive at our findings, we conducted and evaluated interviews with representative large-scale DSOs.

The primary reason for grid expansion measures is ensuring compliance with the permissible limits for voltage and current. Capacity issues prevail in southern Germany, whereas voltage issues are more frequent in northern Germany. The reasons can be found in the different settlement structures, the higher share of renewables in the medium-voltage grid of northern Germany, and the higher PV deployment in the low-voltage grid of southern

Germany.

Grid optimization measures (such as changes in grid structure and wide-area control) are in many cases the most economical initial measure. Once their potential was exhausted due to the continued PV growth, however, the DSOs have primarily implemented classic grid expansion measures, for instance by replacing local distribution transformers and/or laying parallel cables.

Thus far, the use of so-called intelligent operating equipment such as voltage-regulated local distribution transformers has been economically viable only in individual cases in order to safeguard voltage quality (e. g. 400 V ± 10%). Only one DSO reported conceptual studies for a widespread rollout of voltage-regulated local distribution transformers. Other advanced solutions that are mentioned in the literature, for instance active control of demand-side appliances or implementation of large-scale battery systems, are not considered as viable technical or economical options.

Improved grid planning procedures lead to better estimates of the impact of distributed PV systems, helping to reduce unnecessary safety buffers and to operate the grid closer to its technical limits. Moreover, an active monitoring of medium-voltage grids is sufficient to gather information regarding the voltage quality in the low-voltage grids. Grid-wide voltage measurements in the low-voltage grids are not necessary.

The German experience shows that the planning and operation of low-voltage grids did not fundamentally change with the growing share of PV. Classic grid expansion measures are typically used and advanced technologies are gradually introduced after having been successfully tested in pilot projects. Our findings should also prove relevant for other countries that are planning the expansion of decentralized renewable energies. These countries can start the integration process of PV systems in the low-voltage grid with classic grid expansion measures while investigating and then slowly introducing new measures that are deemed technically and economically viable.

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