Energy Reports 6 (2020) 336–342

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Research paper

Innovative measures for integrating renewable energy in the German medium-voltage grids

Benjamin Bayer, Adela Marian *

Institute for Advanced Sustainability Studies, Berliner Str. 130, 14467 Potsdam, Germany

ARTICLE INFO

Article history:
Received 4 June 2019
Received in revised form 8 October 2019
Accepted 31 December 2019
Available online xxxx

Keywords:
Distribution grid
Grid integration
Renewable energy
Hosting capacity
Medium voltage grid

ABSTRACT

Grid integration remains one of the key challenges related to the worldwide expansion of distributed renewable energy systems. This paper presents innovative measures for increasing the hosting capacity of distribution grids with a focus on the medium-voltage grid, based on representative interviews with leading large-scale distribution system operators (DSOs) from Germany. For grid optimization, DSOs have implemented dynamic voltage control in substations, adapted the grid structure for renewables, applied the "N minus zero" rule for planning grid operation and used the capability of renewable energy systems to provide reactive power. For grid expansion, DSOs have installed voltage regulators, voltage-regulated distribution transformers, substations used exclusively for renewables, and express feeders that connect substations with the generation centers. This practical experience should also prove relevant for other countries currently planning the expansion of distributed renewable energy systems.

1. Introduction

Germany is a frontrunner in the expansion and integration of renewable energy systems. Since the introduction of feed-in tariffs in 1990, the installed capacity of photovoltaics, wind energy, and biomass has increased significantly, reaching 92 GW at the end of 2015 (International Renewable Energy Agency, 2017). A main characteristic of this growth is its decentralized character. A total capacity of 85 GW is connected to the distribution grid. More than half of it, 44 GW, is installed in the medium-voltage (MV) grid (50 Hertz et al., 2016). Another 24 GW are connected to the low-voltage (LV) grid, and 17 GW to the high-voltage (HV) grid.

The expansion of distributed energy systems has also become an international megatrend as a result of the falling prices of renewable energy systems, especially biomass, photovoltaics and wind energy (REN21, 2017). Several countries have responded to these developments and adapted their regulatory frameworks for these technologies. The energy systems of those countries could experience a similar development as in Germany, and their distribution system operators (DSOs) will look for innovative solutions to increase the hosting capacity in order to integrate a growing number of renewable energy systems into the grid.

A growing amount of literature discusses state-of-the-art integration measures for increasing the hosting capacity of the distribution grid. Some articles and books give a broad overview of the potential technical measures (Mateo et al., 2017; Vandenbergh et al., 2013; Etherden and Bollen, 2011). Others describe and discuss specific solutions, such as reactive power supply from distributed generators (Braun, 2008; Kraiczy et al., 2017; Collins and Ward, 2015), active power curtailment of distributed generators (Collins and Ward, 2015; Kraiczy et al., 2017; Etherden and Bollen, 2011), grid-supporting electricity storage system (Resch et al., 2017; Díaz-González et al., 2012), voltage-regulated distribution transformers (Forum grid technology of the VDE, 2016), and grid-supporting demand response (Spiliotis et al., 2016). The deployment of voltage regulators for single power lines and dynamic voltage control at HV/MV substations (wide-area control) are also mentioned in the literature (Vandenbergh et al., 2013; Mateo et al., 2017; Papathanassiou et al., 2014). But few articles describe the integration measures implemented by DSOs in the field (Papathanassiou et al., 2014; Bianco et al., 2015). A comprehensive overview on the practical measures implemented by German DSOs is lacking so far. Such an overview should, however, be of great interest for academia and practitioners, as German DSOs are leading in the field of integrating distributed renewable energy systems.

This article is part of a project analyzing the practical experience of German DSOs with the integration of distributed renewable energy systems into the electricity grids, based on representative interviews with large-scale grid operators in Germany (Bayer and Marian, 2016; Bayer and Matschoss, 2016a; Bayer et al., 2016a; Bayer and Matschoss, 2016b; Bayer et al.,

* Corresponding author.
E-mail address: adela.marian@iass-potsdam.de (A. Marian).

https://doi.org/10.1016/j.egyr.2019.12.028

2016b; Bayer and Matschoss, 2016c,d; Bayer et al., 2016c; Bayer and Matschoss, 2016e; Marian and Thomas, 2016). Our previous work has tapped into this practical 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 (Bayer et al., 2018). This work was complemented by an analysis of the regulatory aspects of financing grid expansion and operation driven by the increased integration of renewable energy (Matschoss et al., 2019). The present article will focus on innovative measures that have proven to be cost-efficient for increasing the hosting capacity for renewables in the MV grid. The concrete integration challenges at MV level deserve special attention because the grid characteristics and deployment of renewable energy systems differ compared to the LV grid, and therefore may require different approaches and solutions.

The paper is organized as follows: Section 2 outlines the German context, focusing on the expansion of renewables and the characteristics of the MV grid. Section 3 describes pioneering optimization and expansion measures that have proven their practical feasibility in the MV grid. Section 4 analyzes the measures and discusses their general applicability.

2. Background on renewable integration and the medium-voltage grid in Germany

2.1. Development and grid distribution of renewables

The installed capacity of renewable energy sources is rapidly growing in Germany, as presented in Fig. 1. In terms of installed capacity, photovoltaics and wind energy are the fastest growing renewable energy technologies. The massive deployment of wind energy started in the nineties; a total installed capacity of one GW was reached in 1994. The development of photovoltaics took off 10 years later, with annual capacity additions in excess of 7 GW during the boom years of 2010 to 2012. At the end of 2015, the installed capacity of wind energy (onshore and offshore) and photovoltaics reached about 45 GW and 40 GW, respectively. Of the 45 GW of wind energy, 42 GW are installed onshore (Deutsche Windguard, 2016).

A unique characteristic of Germany is the decentralized character of the renewable energy deployment. Most biomass, photovoltaic and wind energy systems are connected to the distribution grid, which encompasses the LV, MV, and HV grids. As shown in Fig. 2, the MV grid in particular holds significant renewable capacity. The MV grid and HV/MV substations host 14 GW of photovoltaics, 24 GW of wind energy and 6 GW of biomass totaling 44 GW. This decentralized character is also due to the Renewable Energy Act, which enables the installation of small wind farms and photovoltaic systems. For example, more than half of the German onshore wind parks have less than six turbines (BMWi, 2015). Also, most of the photovoltaic capacity installed in the MV grid consists of rooftop and ground-mounted systems with a capacity of less than 1 MW (50 Hertz et al., 2016).

2.2. Requirements for grid integration

DSOs ensure the safe and reliable operation of the grid (Electricity and Gas Supply Act, 2016). They are also required by law to connect renewable energy systems to the grid and guarantee priority dispatch (Renewable Energy Sources Act, 2000, 2017). When project developers request a connection for a new system, grid operators perform a grid compatibility check to determine which grid connection point can be reached most cost-effectively. In this calculation, the DSO considers both the grid connection costs from the renewable energy system to the grid connection point and the potential costs of expanding the existing grid.

The grid compatibility check essentially verifies compliance with ampacity and voltage requirements, as these determine the respective grid area's hosting capacity. The power flow must not exceed the ampacity rating of the equipment to prevent damage to it. This concerns especially the distribution transformers (Bayer and Marian, 2016; Bayer and Matschoss, 2016a; Bayer et al., 2016a; Bayer and Matschoss, 2016b; Bayer et al., 2016b; Bayer and Matschoss, 2016c,d; Bayer et al., 2016c; Bayer and Matschoss, 2016e; Marian and Thomas, 2016), since power lines are typically not affected by ampacity rating restrictions. Another central requirement is voltage stability (e.g. 20 kV ±10%) in daily operation as defined in the European norm DIN EN 50160 (CENELEC, 2011). The grid compatibility check includes two extreme scenarios: maximum possible generation with lowest possible demand and lowest possible generation with highest possible demand.

The German guidelines for grid planning set additional rules to simplify the grid planning procedures in order to guarantee compliance with the ±10% voltage requirement for both LV and MV in daily operation. The recommendations on how to allocate the ±10% voltage bandwidth for the maximum generation scenario and the maximum demand scenario are schematically represented in Fig. 3. For the maximum generation scenario, which is relevant for the expansion of renewable energy systems, the guidelines recommend a maximum voltage increase of up to 3% in the LV grid (Forum grid technology of the VDE, 2011) and of up to 2% in the MV grid (BDEW, 2008). The grid infrastructure is planned and implemented accordingly. As these are only recommendations, DSOs can implement customized grid planning rules to make better use of the ±10% voltage bandwidth for their specific conditions. Furthermore, the recommended allocation of the voltage bandwidth becomes obsolete when voltage-regulated distribution transformers are installed; they allow voltage deviations to be reset to the desired level. Thus, DSOs have a higher voltage bandwidth in the LV grid and, when widely used, also a higher voltage bandwidth in the MV grid.

Another planning and operation principle concerns grid reliability in single-contingency scenarios, such as the failure of one substation or one power line. These events are also known as "N minus one" scenarios. For MV and higher levels, the grid must be designed to guarantee security of supply in such single-contingency events. As established by law (Renewable Energy Sources Act, 2017), this principle does not apply for renewable energy systems in order to reduce the costs for grid expansion. Instead of designing the MV grid to be able to maintain the normal operation of renewable energy systems during single-contingency events, DSOs can implement operational procedures to curtail power from renewable energy systems in such cases.

3. Integrating renewables in the medium-voltage grid

3.1. Background on the interview series

To collect data on innovative measures for integrating renewable energy systems in the MV grid, we conducted semi-structured expert interviews (Crow and Edwards, 2013) with representative DSOs from Germany. This approach is particularly suitable, as it is topic-centered, flexible in structure and based on interactional exchange. In this fashion, relevant information that is not yet available in the scientific literature is brought into focus (Rapley, 2005; Meuser and Nagel, 2009; Trinczek, 2009). First, the interviewees were asked to explain in detail the measures that had been implemented so far to integrate renewable energy systems in the MV grid. Additional inquiries were aimed at specific aspects of the measures and their applicability. Finally, the interviewed DSOs were asked to assess further measures that are known from the literature but were not mentioned at the beginning.

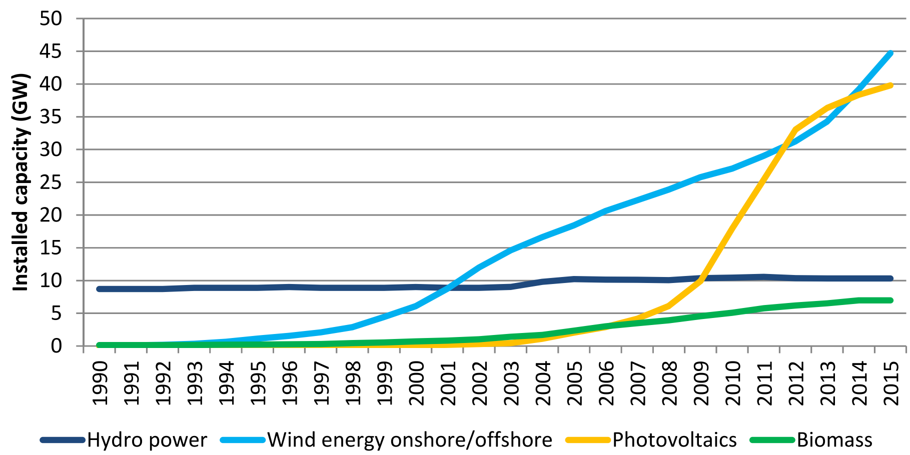

Fig. 1. Evolution of installed renewable capacity in Germany, based on data in (International Renewable Energy Agency, 2017).

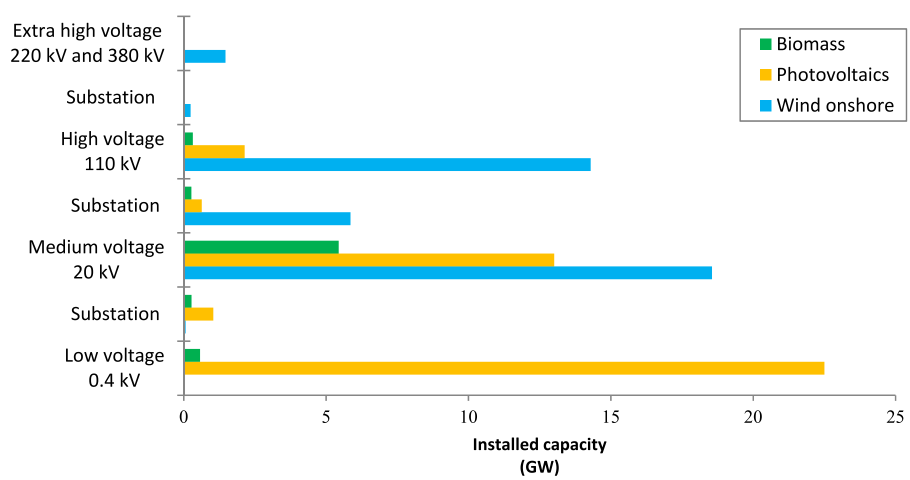

Fig. 2. Installed capacity for biomass, photovoltaics and wind energy per voltage level, calculated for the year 2015 from data in (50 Hertz et al., 2016).

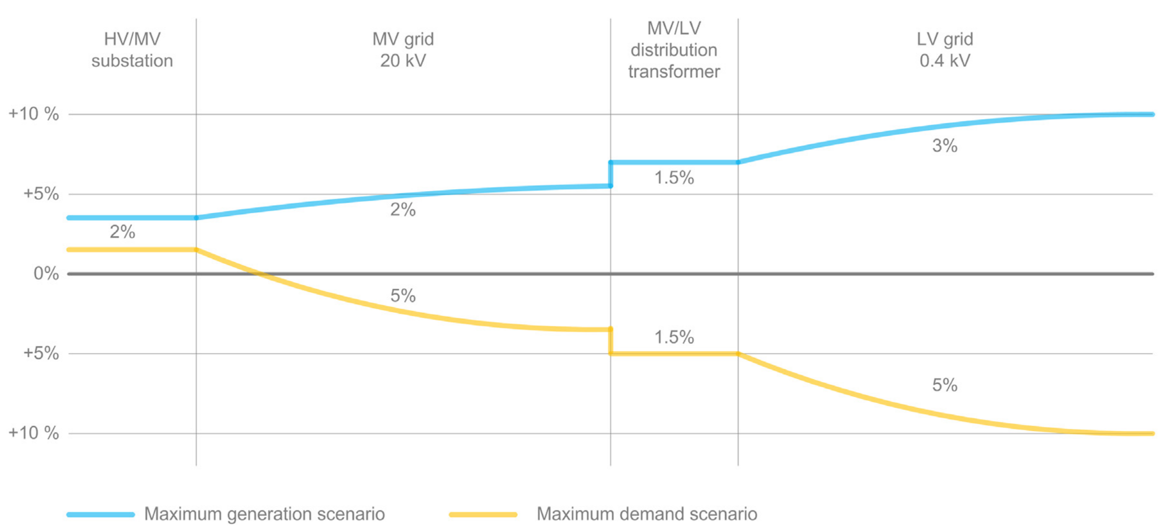

Fig. 3. Recommended allocation of voltage bandwidth, based on (Forum grid technology of the VDE, 2016).

We selected ten large-scale DSOs (Bayer and Marian, 2016; Bayer and Matschoss, 2016a; Bayer et al., 2016a; Bayer and Matschoss, 2016b; Bayer et al., 2016b; Bayer and Matschoss, 2016c,d; Bayer et al., 2016c; Bayer and Matschoss, 2016e; Marian and Thomas, 2016) within Germany's top 30 in terms of installed renewable energy capacity (Bayer et al., 2018). They operate a total circuit length of 676,957 km, which amounts to 38% of Germany's distribution grid. Their installed capacity of biomass, photovoltaic and wind energy represents 44%, 47% and 58% of the country's total installed capacity (Bayer et al., 2018). The interviewed DSOs operate in different parts of Germany, from north to south, and the structural parameters for their grids vary accordingly. For example, the share of wind energy in their respective renewable energy mixes ranges from just 5% at one end of the scale to 80% at the other. The share of photovoltaics varies from 18% to 82%, and of biomass from 4% to 25%.

At least one technical expert represented each DSO (Bayer and Marian, 2016; Bayer and Matschoss, 2016a; Bayer et al., 2016a; Bayer and Matschoss, 2016b; Bayer et al., 2016b; Bayer and Matschoss, 2016c,d; Bayer et al., 2016c; Bayer and Matschoss, 2016e; Marian and Thomas, 2016). In some cases, additional staff members from other departments attended the interviews. As the surveyed DSOs decided to remain anonymous for this research project, we only state the respective job positions of the interview partners in the References.

Based on the interview series, the following subsections present the innovative measures for increasing hosting capacity. These innovative measures were introduced to keep grid expansion to the necessary minimum, that is to say, to avoid building new power lines. Thus, for the optimization of the MV grids, DSOs have implemented dynamic voltage control at HV/MV substations, adapted the grid structure to reduce grid impedance and improve the distribution of renewables in the grid, applied the "N minus zero" rule along with advanced procedures for fault detection and correction, and used the capability of renewable energy systems to provide reactive power for voltage control (see Section 3.2). The DSOs have also implemented pioneering grid expansion measures. They installed voltage regulators, voltage-regulated distribution transformers, HV/MV substations exclusively for renewable energy systems, and express feeders that connect HV/MV substations with generation centers (see Section 3.3).

3.2. Innovative grid optimization

3.2.1. Dynamic voltage control at HV/MV substations

Transformers at HV/MV substations are equipped with a voltage regulator to adapt the voltage ratio between the HV and MV grid. Previously, DSOs used the voltage regulator only to offset voltage fluctuations on the HV side and maintain the voltage of the MV side at a constant level of, for example, 20.6 kV.

Due to the increasing capacity of renewable energy systems at the MV level, five DSOs mentioned that they have updated electronics and software of the voltage regulator to adjust the voltage on the MV side depending on the feed-in of renewables and the load flow at the substation (Bayer and Marian, 2016; Bayer and Matschoss, 2016b,c,d; Marian and Thomas, 2016). The principal aim is to reduce the voltage on the MV side of the transformer in times of high feed-in. For example, one DSO stated that the voltage may be set as low as 19.6 kV in times of high renewable generation (Bayer and Matschoss, 2016c). Likewise, a larger voltage band can be used for the MV or LV voltage level than is depicted in Fig. 3.

The DSOs also highlighted the constraints of this concept. For example, nearby industrial consumers connected at the MV level might be detrimentally affected by voltage variations (Bayer and Matschoss, 2016c), which limits the applicability of dynamic control. Furthermore, the possible voltage reduction also depends on the geographic distribution of renewable energy systems in the respective MV grid area (Bayer and Matschoss, 2016d). Nevertheless, the implementation of dynamic voltage control is regarded as one of the most economic measures for increasing the hosting capacity (Bayer and Matschoss, 2016c,d).

3.2.2. Adapted grid structure

The DSOs highlighted changes in optimization targets for structuring the grid to account for the expansion of distributed energy systems. The grid used to be optimized to reduce grid losses, facilitate fault detection and correction, and provide easier physical access to switching stations. The increasing share of integrated renewables and the resulting need for grid expansion led to an additional objective: avoiding the construction of new power lines or substations. This new goal of minimizing the grid expansion comes into conflict with the aforementioned optimization goals.

Measures may need to be taken to reduce grid impedance, leading to a greater hosting capacity for renewable energy systems. One example implemented in practice is the closed-loop operation of MV ring grids (Bayer and Marian, 2016; Bayer and Matschoss, 2016d), whereby open ring grids with a radial structure are turned into closed rings. This way, previously independent power lines that were supplied by the same local distribution transformer become connected at the switching station, building a closed loop. This measure, however, complicates fault detection and recovery, and is controversial among grid operators as a consequence.

Further measures are aimed at distributing the renewable energy system more evenly between power lines and HV/MV substations to better utilize the available grid capacity. To this end, several DSOs also adapted the grid structure, for instance by building new switching stations on an MV power line (Bayer and Matschoss, 2016b; Bayer et al., 2016b; Bayer and Matschoss, 2016d).

3.2.3. Applying the "N minus zero" rule

The DSOs also pointed out the potential of the "N minus zero" rule to increase the hosting capacity (Bayer and Marian, 2016; Bayer and Matschoss, 2016a). Unlike the "N minus one" scenario, where the grid has backup capacity to sustain the failure of one grid element, in the "N minus zero" scenario, grid operators take advantage of the available backup capacity. Additional renewable energy systems are then connected to the grid and generate electricity during normal operation, but can be disconnected if necessary. For example, some HV/MV substations are equipped with a second transformer that serves as backup capacity during contingency events or maintenance breaks, thus fulfilling the "N minus one" criterion. By the "N minus zero" rule, DSOs can take advantage of this transformer to host more renewable energy systems in the respective MV grid area during normal operation. During maintenance work or contingency, the DSOs need to curtail the output of these additional renewable energy systems to safeguard grid operations. This measure increases the usable grid capacity but also renders grid operation more complex. DSOs must implement the corresponding operation guidelines and protection procedures so that the respective renewable energy systems are curtailed when needed.

3.2.4. Reactive power control

DSOs also use the reactive power capabilities of renewable energy systems to ensure voltage quality. As described in Section 2.2, the provision of active power leads to a voltage increase along the power lines. The additional provision of reactive power can counteract this voltage increase, thereby raising the hosting capacity of the respective grid areas. In the MV grid, renewable energy systems are typically required to provide reactive power according to a fixed characteristic curve. On this curve, the feed-in reactive power either depends on the current active power feed-in or the voltage at the connection point (Bayer and Marian, 2016; Bayer and Matschoss, 2016a; Bayer et al., 2016a; Bayer and Matschoss, 2016b,c,d; Bayer et al., 2016c; Bayer and Matschoss, 2016e; Marian and Thomas, 2016). More advanced techniques, in which reactive power provision is controlled automatically by the DSO's supervisory control systems, are currently only used at the HV level of two DSOs (Bayer et al., 2016a,c). One DSO also highlighted that reactive power control can also be employed to even out the reactive power balance in the MV grid, which normally is provided by generation systems connected at HV level and above (Bayer and Matschoss, 2016c). For example, wind energy systems directly connected to an HV/MV substation can be used to provide reactive power compensation, since they do not face the same voltage constraints as more remote wind generators.

3.3. Innovative grid expansion

3.3.1. Voltage regulators

To mitigate voltage issues while avoiding conventional grid expansion through the installation of new power lines, four DSOs installed voltage regulators (booster transformers) in MV lines (Bayer and Matschoss, 2016b; Bayer et al., 2016b; Bayer and Matschoss, 2016e; Marian and Thomas, 2016). This technology makes it possible to adjust the voltage at a specific point in the MV line where it is installed. Its mode of operation is comparable to the voltage control at the HV/MV substation with the restriction that just the voltage of a specific power line segment is regulated. Two DSOs highlighted that this technology is still being tested in pilot projects (Bayer et al., 2016b; Bayer and Matschoss, 2016e). The other two DSOs have already passed the pilot phase and installed a small amount (two-digit number) in specific cases where voltage regulators turned out to be the least expensive alternative (Bayer and Matschoss, 2016b; Marian and Thomas, 2016). In their experience, the high cost of the equipment still hinders a more frequent use.

3.3.2. Voltage-regulated distribution transformers

In recent years, all except one of the DSOs interviewed have installed voltage-regulated distributions transformers in their grids (Bayer and Marian, 2016; Bayer and Matschoss, 2016a; Bayer et al., 2016a; Bayer and Matschoss, 2016b; Bayer et al., 2016b; Bayer and Matschoss, 2016c,d; Bayer et al., 2016c; Bayer and Matschoss, 2016e; Marian and Thomas, 2016). The typical operational purpose has been to control the voltage in LV grids with a high concentration of photovoltaic systems (Bayer et al., 2018). There are, however, also application concepts for the MV grid (see e.g. Forum grid technology of the VDE, 2016; BMWi, 2015). These concepts aim at using the full $\pm 10\%$ voltage bandwidth (see Fig. 3) in the MV grid, as the voltage deviations can be offset thereafter by the voltage-regulated distribution transformers. The application of this concept is, however, rare so far. Just two DSOs substituted more than 100 traditional transformers with voltage-regulated distribution transformers.[1] These two DSOs explicitly mentioned that the implementation of voltage-regulated distribution transformers was also partly driven by the voltage problems in the MV grid. The other DSOs installed voltage-regulated distribution transformers even less frequently, as they only tend to be cost-efficient in specific cases or are still being tested in pilot projects.

3.3.3. Exclusive substations for renewables

All of the DSOs interviewed said that MV/HV substations had to be expanded or newly built due to the increased reverse flows that exceed the transformer's capacity rating (Bayer and Marian, 2016; Bayer and Matschoss, 2016a; Bayer et al., 2016a; Bayer and Matschoss, 2016b; Bayer et al., 2016b; Bayer and Matschoss, 2016c,d; Bayer et al., 2016c; Bayer and Matschoss, 2016e; Marian and Thomas, 2016). A special case is the construction of substations exclusively used for the connection of renewable energy systems. In this case, the DSOs can take advantage of the "N minus zero" principle and avoid installing backup capacity. In single-contingency events and during maintenance work at the substation, the renewable energy systems are simply disconnected from the grid. Also, the protection mechanisms in case of technical faults are less complex and expensive to implement. Several DSOs said that substations exclusively built for renewable energy systems were the most cost-effective option in specific cases (Bayer and Matschoss, 2016a; Bayer et al., 2016a; Bayer and Matschoss, 2016b; Bayer et al., 2016b,c; Marian and Thomas, 2016). Two DSOs even have built more than 100 of these substations (Bayer et al., 2016a,c). According to two DSOs, this mechanism for grid integration might become economically interesting if the installed capacity of renewable energy systems exceeds 10 MW at a specific grid connection point (Bayer and Matschoss, 2016d; Bayer et al., 2016c).

3.3.4. MV grid with express feeders

Though the MV grids have been expanded to increase the hosting capacity, the basic grid structure, e.g. ring grids, typically has been maintained. Nonetheless, three DSOs mentioned the implementation of "express feeders". These are power lines with large cross-sections spanning between 500 and 800 mm^2 that directly connect the HV/MV substation with the generation centers of the respective MV grid area (Bayer and Marian, 2016; Bayer and Matschoss, 2016a; Bayer et al., 2016b). One DSO mentioned that the typical length of such a connection is around 3 km; another DSO mentioned that such a power line may be up to 15 km long (Bayer and Marian, 2016; Bayer and Matschoss, 2016a). Due to the line's large cross-section, the voltage drop on this power line is very low and can be regarded as an extension of the substation's busbar. As a consequence, the voltage drop on the power line can be significantly reduced, and the hosting capacity of the MV grid is increased. This mechanism has proven to be cost-effective in areas with voltage problems due to a high deployment of renewable energy systems.

4. Summary and discussion

The experience of the German DSOs showed that several innovative measures have proven their practical feasibility for increasing the renewable hosting capacity in the medium-voltage grid, as summarized in Table 1. In the area of grid optimization, four innovative measures are used to tackle voltage or ampacity constraints. These optimization measures include dynamic voltage control at the HV/MV substations, reactive power provision by renewable energy systems, and reducing the grid impedance by means of ring grids in closed-loop operation. Further optimization potential arises from applying the "N minus zero" rule as a planning approach and curtailing renewable energy systems when the MV grid is not in normal operation. According to their planning principle, the DSOs first used these measures to improve the hosting capacity. It is important to highlight that all optimization measures lead to more complexity in daily operation. For example, DSOs that take advantage of the "N minus zero" principle for renewables utilize the full capacity of the grid. However, the grid then has fewer reserves for potential contingencies and requires targeted interventions during contingencies or maintenance work.

Due to the continuous expansion of renewable energy systems and the limited potential of grid optimization measures, the DSOs implemented additional measures for grid expansion. Among the state-of-the-art measures is the installation of intelligent grid equipment such as voltage regulators for single MV lines

[1] We do not cite the two interview partners to guarantee their anonymity.

Table 1
Measures for MV grid integration.
Source: Own compilation based on Bayer and Marian (2016), Bayer and Matschoss (2016a), Bayer et al. (2016a), Bayer and Matschoss (2016b), Bayer et al. (2016b), Bayer and Matschoss (2016c,d), Bayer et al. (2016c), Bayer and Matschoss (2016e), Marian and Thomas (2016).

Measures	Voltage constraints	Ampacity constraints	Brief assessment
Innovative grid optimization			
Dynamic voltage control	×		Initial measures for increasing hosting capacity
Adapted grid structure	×		
Applying the "N minus zero" rule		×	
Reactive power control	×		
Innovative grid expansion			
Voltage regulators	×		Deployment frequency is still low and limited to specific cases
Voltage-regulated distribution transformers	×		
Exclusive substations for renewables	×	×	Deployed in areas with very high number of renewables
Express feeders	×		

and voltage-regulated distribution transformers. Despite having successfully passed field tests and being proven assets for grid integration, their present deployment is still limited to specific cases, since conventional grid expansion measures are usually more cost-effective. Here it is worth mentioning that the current incentive scheme regulating the revenues of German DSOs poses a financial disadvantage for these innovative measures, as they tend to have higher operating costs than conventional grid expansion (Matschoss et al., 2019). However, this is rather a subordinate reason for the low deployment.

In the area of grid expansion, the DSOs mentioned two further measures. These entail exclusive HV/MV substations for renewable energy systems that do not need to fulfill the "N minus one" criteria, and the installation of express feeders in the MV grid to connect the generation centers with the HV/MV substations. These two measures have proven to be the most cost-effective in areas of the MV grid with a very high share of renewable energy systems.

The existing literature on the measures for increasing the hosting capacity describes additional pioneering measures as an alternative to conventional grid expansion, such as: the active curtailment of renewable energy systems during peak generation periods (Collins and Ward, 2015), the installation of grid-supporting electricity storage systems (Resch et al., 2017) and grid-supporting demand response (Spiliotis et al., 2016). These measures have not yet been adopted by German DSOs though. Some articles cite regulatory obstacles as a reason (Mateo et al., 2017; Resch et al., 2017). In the case of electricity storage systems, the DSOs acknowledged the obstacles but highlighted that the cost of storage systems is the primary reason for not implementing them (Bayer and Matschoss, 2016d; Bayer et al., 2016c). This situation might, however, change as these technologies are further developed. In the case of active curtailment of renewable energy systems, the German regulators passed a law in 2016 allowing curtailment of renewable energy systems to avoid or reduce grid expansion. According to the DSOs, this measure will be first implemented in the HV grid, but it is possible that it will be implemented in the MV grid thereafter (Bayer and Matschoss, 2016d).

This analysis also shows that there are several similarities and overlaps with measures for increasing the hosting capacity in the LV grid as presented in Bayer et al. (2018). For instance, measures like reactive power control, optimized grid structure, and voltage regulators exist in different forms for both voltage levels. Moreover, measures such as dynamic voltage control and voltage regulated distribution transformers help guarantee voltage compliance both in the LV and MV grid. Furthermore, it is noteworthy that the deployment frequency of grid elements like voltage regulators is low for both LV and MV grids and that pioneering measures like grid-supporting electricity storage systems and grid-supporting demand response have not yet reached practical relevance for either grid level.

5. Conclusions

German DSOs have gathered substantial experience in the field of integrating distributed renewable energy systems in the medium-voltage grid. To gain information about innovative measures that have proven to be cost-efficient, we conducted and evaluated interviews with leading large-scale DSOs from throughout Germany.

The German experience shows that the grid offers several initial optimization techniques such as dynamic voltage control at the HV/MV substations, in order to increase the hosting capacity. Consequently, as no grid expansion is required, the integration costs at the very beginning are limited and do not constitute a significant financial burden. On the other hand, the complexity of grid management increases in daily operation.

Once the potential of grid optimization is exhausted, various pioneering measures such as express feeders have proven to be cost-efficient when high numbers of renewable energy systems are installed in confined areas. Further options, for instance voltage-regulated distribution transformers, were successfully tested within pilot projects, but deployment is still rare. Alternative measures discussed in literature like grid-supporting electricity storage systems have not yet been implemented due to their present cost–benefit ratio.

These findings should also prove relevant for a growing number of countries planning to expand renewable energy generation with distributed systems, as DSOs worldwide are looking for proven solutions to increase the hosting capacity while keeping the additional grid assets and costs to a minimum.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We are very grateful to Patrick Matschoss for organizing the interviews with the distribution system operators. We are also greatly indebted to the participating distribution system operators for their time during the interviews and for their valuable comments afterwards. We thank Harald Bock, Christian Goldbach, Olaf Görlitz, Osman Kurt, Ulrich vom Felde and the other 21 interview partners who chose to remain anonymous.

This work was financed by the German Federal Ministry of Education and Research (BMBF) and the Brandenburg State Ministry of Science, Research and Culture (MWFK), Germany, who fund the Institute for Advanced Sustainability Studies.

References

50 Hertz Transmission, Amprion, TenneT TSO, TransnetBW, 2016. Master data of the German renewable energy plants, used for the annual financial statement 2015 [Original German title: EEG-Anlagenstammdaten Gesamtdeutschland zur Jahresabrechnung 2015]. https://www.netztransparenz.de/de/file/Anlagenstammdaten_2015_final.zip (accessed 29 September 2016).

Bayer, B., Marian, A., 2016. Interview with the head of grid development of a German large-scale distribution system operator.

Bayer, B., Marian, A., Matschoss, P., 2016b. Interview with the head of grid development, the head of regulatory affairs and the head of sales of a German large-scale distribution system operator.

Bayer, B., Marian, A., Matschoss, P., Thomas, H., 2016c. Interview with the chief technology director of a German large-scale distribution system operator.

Bayer, B., Matschoss, P., 2016a. Interview with the head of the grid development and a staff member in the controlling department of a German large-scale distribution system operator.

Bayer, B., Matschoss, P., 2016b. Interview with the head of grid planning of a German large-scale distribution system operator.

Bayer, B., Matschoss, P., 2016c. Interview with the head of grid development, the head of asset management and the head of regulatory affairs of a German large-scale distribution system operator.

Bayer, B., Matschoss, P., 2016d. Interview with the head of grid development and a staff member in the grid development department of a German large-scale distribution system operator.

Bayer, B., Matschoss, P., 2016e. Interview with a staff member in the grid technology department of a German large-scale distribution system operator.

Bayer, B., Matschoss, P., Thomas, H., 2016a. Interview with the head of grid development and the head of regulatory affairs of a German large-scale distribution system operator.

Bayer, B., Matschoss, P., Thomas, H., Marian, A., 2018. The German experience with integrating photovoltaic systems into the low-voltage grids. Renew. Energy 119, 129–141. http://dx.doi.org/10.1016/j.renene.2017.11.045.

German Association of Energy and Water Industries (BDEW), 2008. Power generation systems in the medium-voltage grid. Guideline for connecting and operating power generation systems in the medium-voltage grid. [Original German title: Erzeugungsanlagen am Mittelspannungsnetz. Richtlinie für Anschluss und Parallelbetrieb von Erzeugungsanlagen am Mittelspannungsnetz].

Bianco, G., Noce, C., Sapienza, G., 2015. Enel distribuzione projects for renewable energy sources integration in distribution grid. Electr. Power Syst. Res. 120, 118–127. http://dx.doi.org/10.1016/j.epsr.2014.07.014.

German Federal Ministry for Economic Affairs and Energy (BMWi), 2015. Market report on onshore wind energy [Original German title: Marktanalyse Windenergie an Land].

Braun, M., 2008. Reactive power supply by distributed generators. In: 2008 IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, Pittsburgh, PA, USA, http://dx.doi.org/10.1109/PES.2008.4596266.

European Committee for Electrotechnical Standardization (CENELEC), 2011. DIN EN 50160: Voltage characteristics of electricity supplied by public distribution networks.

Collins, L., Ward, J.K., 2015. Real and reactive power control of distributed PV inverters for overvoltage prevention and increased renewable generation hosting capacity. Renew. Energy 81, 464–471. http://dx.doi.org/10.1016/j.renene.2015.03.012.

Crow, G., Edwards, R., 2013. What is Qualitative Interviewing? Bloomsbury Publishing, London.

Deutsche Windguard, 2016. Status of onshore wind energy expansion in Germany - Additional evaluations and data for 2015 [Original German title: Status des Windenergieausbaus an Land in Deutschland - Zusätzliche Auswertungen und Daten für das Jahr 2015].

Díaz-González, F., Sumper, A., Gomis-Bellmunt, O., Villafáfila-Robles, R., 2012. A review of energy storage technologies for wind power applications. Renew. Sustain. Energy Rev. 16, 2154–2171. http://dx.doi.org/10.1016/j.rser.2012.01.029.

Electricity and Gas Supply Act, 2016. [Original German title: Gesetz über die Elektrizitäts- und Gasversorgung (Energiewirtschaftsgesetz - EnWG)].

Etherden, N., Bollen, M.H.J., 2011. Increasing the hosting capacity of distribution networks by curtailment of renewable energy resources. In: Proceedings of the IEEE Trondheim PowerTech. Trondheim, Norway, http://dx.doi.org/10.1109/PTC.2011.6019292, 19–23 June 2011.

Forum grid technology of the VDE, 2011. VDE-AR-N 4105: Power Generation Systems Connected to the Low-Voltage Distribution Network. VDE Verlag, Berlin.

Forum grid technology of the VDE, 2016. Voltage-regulated distribution transformer - Grid planning and operation [Original german title: Regelbarer Ortsnetztransformator (rONT) - Einsatz in Netzplanung und Netzbetrieb].

International Renewable Energy Agency (IRENA), 2017. Renewable energy capacity statistics 2017.

Kraiczy, M., Al Fakhri, L., Stetz, T., Braun, M., 2017. Do it locally: Local Voltage Support by Distributed Generation – IEA-PVPS t14-08:2017. Available at http://www.iea-pvps.org/index.php?id=424.

Marian, A., Thomas, H., 2016. Interview with the chief technology director of a German large-scale distribution system operator.

Mateo, C., Frías, P., Cossent, R., Sonvilla, P., Barth, B., 2017. Overcoming the barriers that hamper a large-scale integration of solar photovoltaic power generation in European distribution grids. Sol. Energy 153, 574–583. http://dx.doi.org/10.1016/j.solener.2017.06.008.

Matschoss, P., Bayer, B., Thomas, H., Marian, A., 2019. The German incentive regulation and its practical impact on the grid integration of renewable energy systems. Renew. Energy 134, 727–738. http://dx.doi.org/10.1016/j.renene.2018.10.103.

Meuser, M., Nagel, U., 2009. Experts and changes in knowledge production. In: Bogner, A., Littig, B., Menz, W. (Eds.), Interviewing Experts. Palgrave Macmillan, UK, London, pp. 17–43.

Papathanassiou, S., et al., 2014. Capacity of distribution feeders for hosting DER: Report of the CIGRÉ Working Group C6.24. Available at https://www.cigreaustralia.org.au/assets/ITL-SEPT-2014/3.1-Capacity-of-Distribution-Feeders-for-hosting-Distributed-Energy-Resources-DER-abstract.pdf.

Rapley, T., 2005. Interviews. In: Seale, C., Gobo, G., Gubrium, J.F. (Eds.), Qualitative Research Practice. SAGE, London, pp. 15–34.

REN21, 2017. Renewables 2017 - Global Status Report, REN21 Secretariat, Paris, 2017. Available at https://www.ren21.net/wp-content/uploads/2019/05/GSR2017_Full-Report_English.pdf.

Renewable Energy Sources Act (EEG) 2000: Act revising the legislation on renewable energy sources in the electricity sector of 29.03.2000. [Original German title: Gesetz für den Vorrang erneuerbarer Energien (Erneuerbare-Energien-Gesetz – EEG)].

Renewable Energy Sources Act (EEG) 2017: Act revising the legislation on renewable energy sources in the electricity sector of 22.12.2016. [Original German title: Gesetz zur Einführung von Ausschreibungen für Strom aus erneuerbaren Energien und zu weiteren Änderungen des Rechts der erneuerbaren Energien].

Resch, M., Bühler, J., Klausen, M., Sumper, A., 2017. Impact of operation strategies of large scale battery systems on distribution grid planning in Germany. Renew. Sustain. Energy Rev. 74, 1042–1063. http://dx.doi.org/10.1016/j.rser.2017.02.075.

Spiliotis, K., Ramos Gutierrez, A.I., Belmans, R., 2016. Demand flexibility versus physical network expansions in distribution grids. Appl. Energy 182, 613–624. http://dx.doi.org/10.1016/j.apenergy.2016.08.145.

Trinczek, R., 2009. How to interview managers? Methodical and methodological aspects of interviews as a qualitative method in empirical social research. In: Bogner, A., Littig, B., Menz, W. (Eds.), Interviewing Experts. Palgrave Macmillan, UK, London, pp. 203–217.

Vandenbergh, M., Craciun, D., Helmbrecht, V., Hermes, R., Lama, R., Sonvilla, P.M., Rekinger, M., Concas, G., 2013. Prioritisation of technical solutions available for the integration of PV into the distribution grid. Available at https://ec.europa.eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/pv_grid_prioritization_of_technical_solutions_available_for_the_integration_of_pv_into_the_distribution_grid_june_2013.pdf.