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Time in the Sun

The Challenge of High PV Penetration in the German Electric Grid

ENERGY SUPPLY SYSTEMS ARE FACING significant changes in many countries around the globe. A good example of such a transformation is the German power system, where renewable energy sources (RESs) are now contributing 25% of the power needed to meet electricity demand, compared with 5% only 20 years ago. In particular, photovoltaic (PV) systems have been skyrocketing over the last couple of years. As of September 2012, about 1.2 million PV systems were installed, with a total installed peak capacity of more than 31 GWp. During some hours of 2012, PV already contributed about 40% of the peak power demand. It seems that Germany is well on the way to sourcing a major portion of its energy needs from solar installations. PV must therefore provide a full range of services to system operators so as to replace services provided by conventional bulk power plants.

This article highlights the development of PV in Germany, focusing on the technical and economic consequences for distribution system operation. We highlight the challenges and introduce solutions for smart PV grid integration.

Status of PV in Germany

As mentioned above, as of September 2012 more than 31 GWp of PV capacity was installed in the German energy system. The installed capacity of PV systems is now higher than that of any other RES, as well as that of any conventional power source (see Figure 1). Nevertheless, the cumulative produced energy from PV only accounted for about 6% of



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Germany's overall electricity consumption in the first nine months of 2012.

The strong growth of PV in recent years has resulted from the German feed-in tariff and decreasing prices for PV systems. In particular, small and medium-scale systems of less than 30 kilowatt-peak (kWp) have emerged rapidly during the last few years. As a result, about 70% of the installed PV capacity is connected to the low-voltage (LV) grid, which was not originally designed to host generation (see Figure 2).

As mentioned above, PV generation by itself is able to satisfy about 40% of the overall load during certain sunny and low-load days (see Figure 3). A strong concentration of

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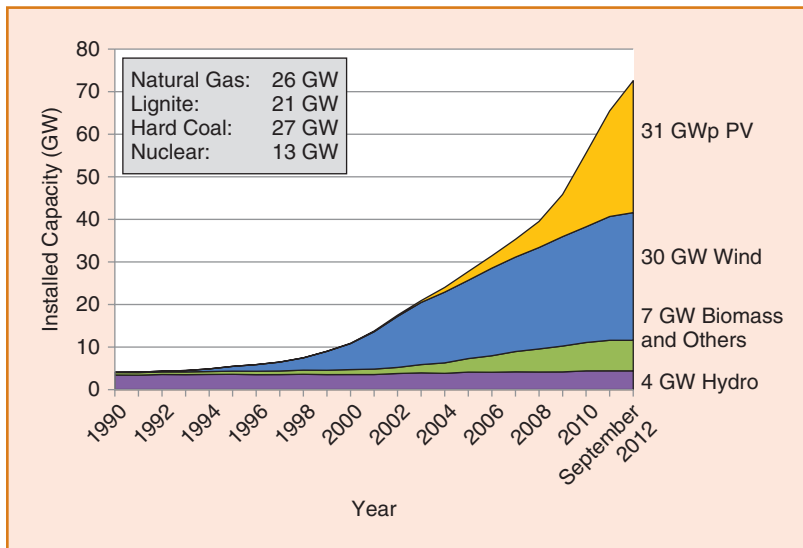


figure 1. Historic development of the installed capacity of RES compared with conventional power sources as of March 2012 (source: German Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety).

PV generation can be found in the sunnier southern region of Germany. Therefore, south German distribution grids typically experience grid-integration challenges related to PV. In some LV grids, the installed PV capacity can even exceed the peak load by a factor of ten.

The impact of high PV penetration rates locally on the distribution system operation is outlined in the following section together with a brief overview on the state of the art in Germany.

Impact of High PV Penetration on the Grid

Three main issues can be identified regarding high PV penetration in distribution grids:

- 1) **Reverse power flows in the distribution system:** In distribution systems where the local PV generation exceeds the local load demand, reverse power flows

occur toward upstream voltage levels. This phenomenon is often accompanied by voltage rises. Consequently, the allowed voltage band of $\pm 10\%$ of the nominal voltage for less than 5% of the ten-minute average root-mean-square values over the course of one week (from power-quality standard EN 50160) is more often violated with PV than without PV.

- 2) **Additional power flows in the transmission system:** Reverse power flows can cause additional power flows from the distribution system to the transmission system.
- 3) **Grid stability (frequency and voltage):** Today, conventional power plants must guarantee the system's stability. Within the European Network of Transmission System

Operators for Electricity (ENTSO-E) control area, the cutoff frequencies for RES still vary; hence, they can cause instabilities in abnormal situations. For further details, see "The 50.2-Hz Risk."

The graphs in Figure 4 show the load flow and voltages for an entire day, as observed in a real LV distribution grid in southern Germany. In this particular distribution system, the PV capacity exceeds the peak load by 900%. As a result, the grid is subject to reverse power flows over the transformer and a rise in voltage.

Actions for Smart PV Grid Integration

In what follows, we highlight possible solutions to the technical issues outlined in the previous section. Note that the technical challenges also have an economic impact on the stakeholders involved.

Supporting Frequency Control

New interconnection requirements—such as the German VDE AR-N 4105 guideline for the low- and medium-voltage grid—are now in place to support a smoother response to frequency deviations of PV systems in case of system overfrequencies. Now, frequencies over 50.2 Hz lead to a smooth power reduction according to a predefined, characteristic curve, until the generation units are disconnected from the grid at a frequency of 51.5 Hz. Figure 5 shows the characteristic curve.

Supporting Voltage Control

95% of the PV capacity is installed in the low- and medium-voltage system;

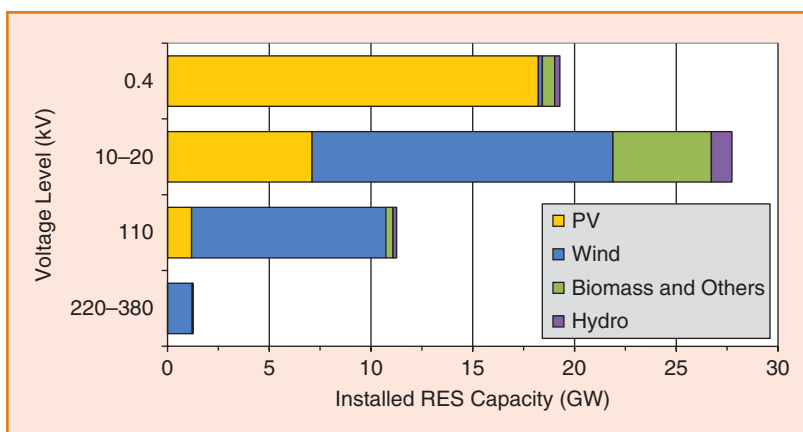


figure 2. Distribution of RES over the typical nominal voltage levels of the German power system (source: energymap.info).

voltage-related issues may therefore occur in distribution grids with high local PV penetration. If the PV capacity cannot be interconnected due to technical reasons, the distribution system operator (DSO) is obliged, according to German law, to conduct necessary grid reinforcement measures immediately. This is done by either replacing transformers in the grid or reinforcing certain lines. By law, the costs for these reinforcement measures must be borne by the DSO itself. Additional load flows are also most commonly resolved via grid reinforcement and/or congestion management. In addition to these conventional means, PV systems installed in Germany must be able to support the local voltage by the provision of reactive power and active power curtailment.

Reducing Congestion

Since 2011, the German feed-in tariff law has required owners of small PV systems (less than 30 kWp) to either limit the active power output of their systems to 70% of the installed PV capacity or install a remote-control interface to receive temporal power reduction signals from the DSO, if necessary. Systems of more than 30 kWp must be controllable remotely. This requirement raises additional questions regarding the security of the communication between generator and system operator and the information and communication technologies (ICT) standards used to enable this feature. These questions have yet to be sufficiently addressed.

From a technical perspective, three types of control approaches can be distinguished: local, decentralized, and central (see Figure 6).

- ✓ Local control strategies do not require communication devices. The distributed energy resource (DER) unit reacts to specific grid situations according to predefined parameters and droop functions, as well as measurements (e.g., of voltage or frequency) at its point of common coupling.
- ✓ Decentralized control strategies are communication-based control strategies that interact with an intermediate level in the grid. For example, LV systems can be clustered into different cells using intelligent,

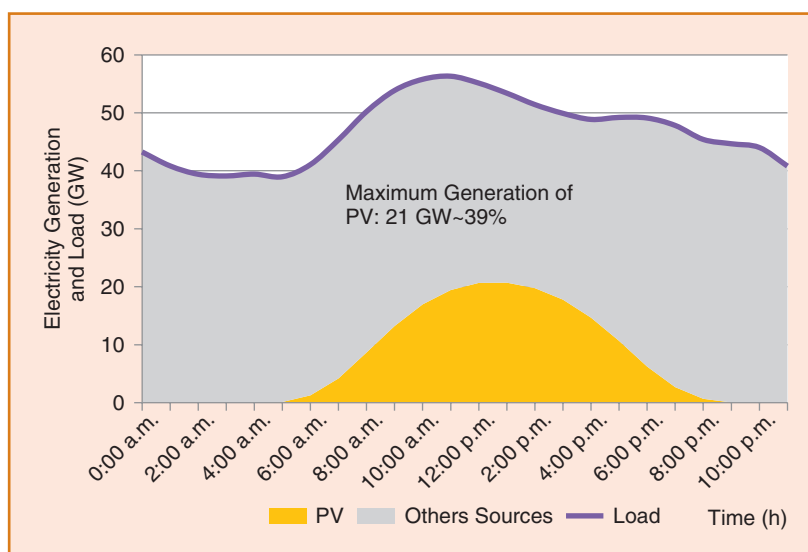


figure 3. Contribution of PV and wind on 26 May 2012 (source: German transmission system operators and European Network of Transmission System Operators for Electricity).

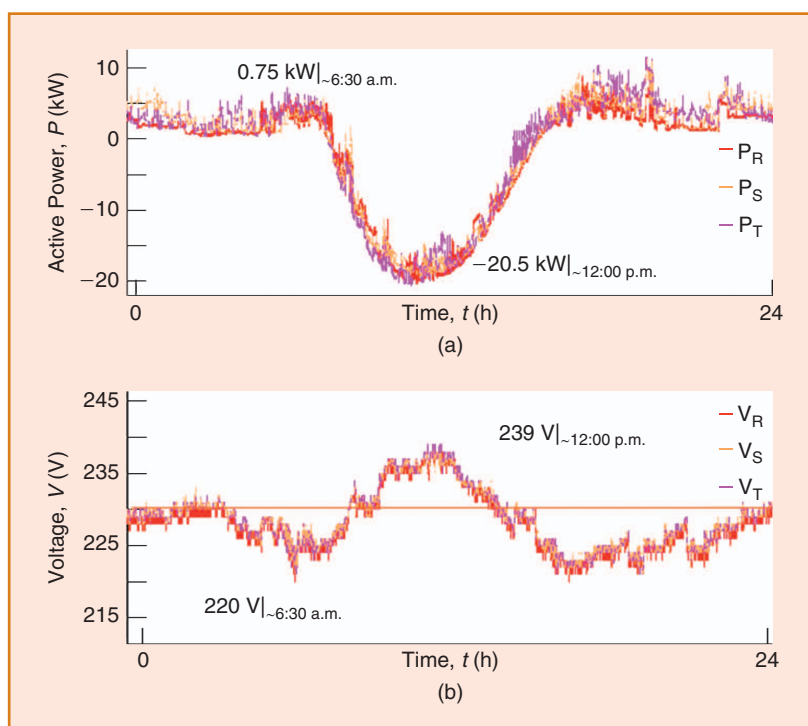


figure 4. Example of (a) load flow and (b) voltage at the transformer in one LV distribution system with high PV penetration over the period of one day (source: University of Stuttgart).

controllable substations. These substations enable autonomous control of the LV grid sections, which can increase reliability and economic efficiency. Furthermore, parameters from the surrounding systems and the higher-voltage levels can be included.

- ✓ Central control strategies describe communication-based control approaches from the distribution

The 50.2-Hz Risk

PV inverters in the European interconnected power system have different fixed cutoff frequencies, as defined by the respective national grid codes. For example, the upper cutoff frequency for PV systems connected to low-voltage grids used to be 50.2 Hz in Germany and 50.3 Hz in Italy and Denmark. During abnormal situations, such fixed threshold values can cause a sudden loss of generation capacity. An example was the unscheduled disconnection of a transmission line in Germany in 2006, which resulted in a separation of the ENTSO-E transmission grid into small regional sections. As a result, significant frequency deviations occurred, as shown in Figure S1, which led to frequency values above 50.2 Hz in areas with surplus generation. In such a scenario, a sudden loss of a high share of the PV generation capacity (due to a threshold-based disconnection) can cause severe under-frequencies and even rolling blackouts. The ENTSO-E-wide primary reserve capacity is only 3 GW, compared to more than 20 GWp of installed PV capacity in the German low-voltage grids. In response to the lack of dynamic power reduction in the case of over frequency, Germany regulators issued a retrofitting of about 315,000 single PV plants at an estimated cost of up to 175 million euros. Further information can be found in “For Further Reading.”

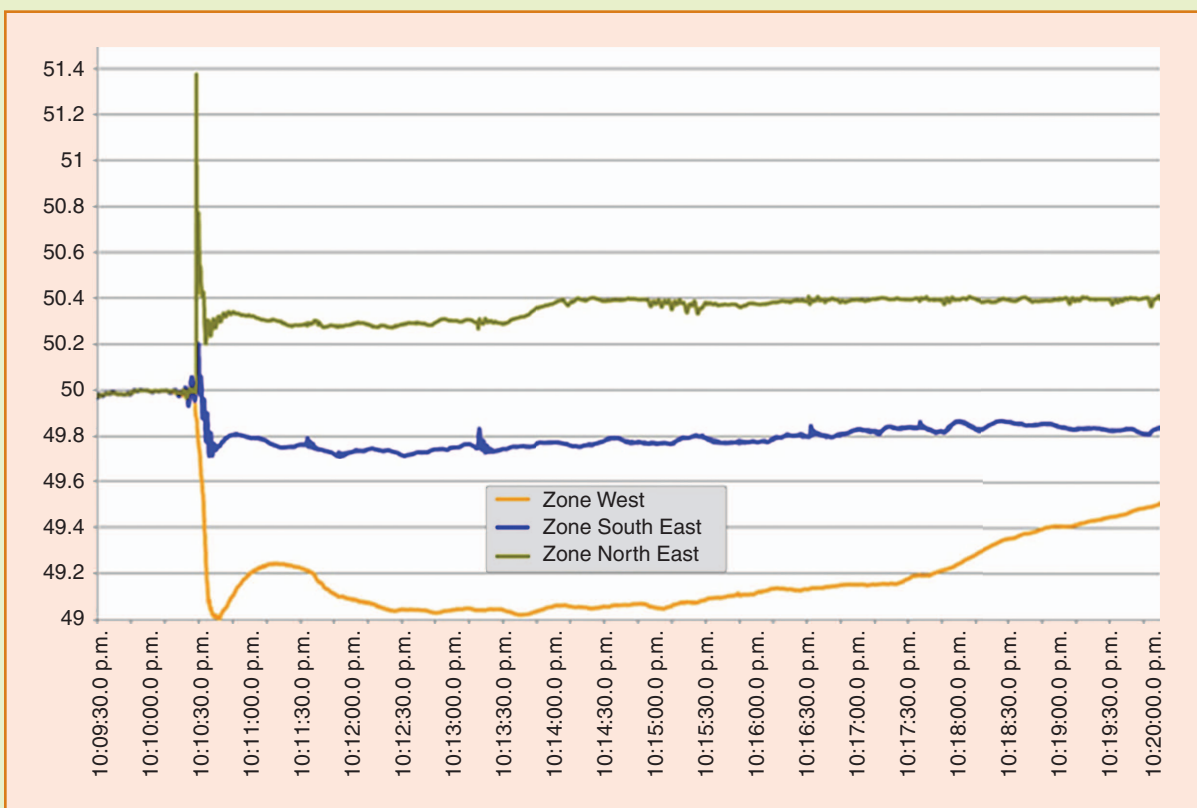


figure S1. Frequency recordings after the split of the ENTSO-E control area in 2006 (source: ENTSO-E, final report on the disturbances of 4 November 2006).

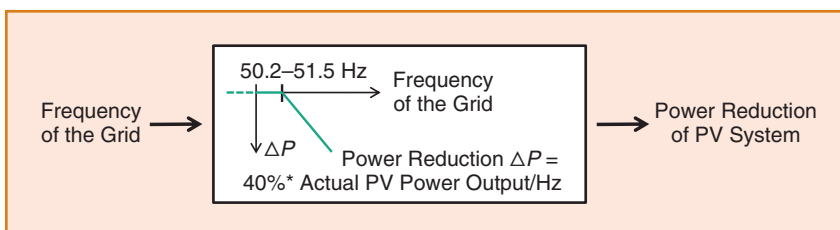


figure 5. Characteristic curve for reducing the power output of PV systems according to frequency deviations.

system control center. For example, a central control strategy is necessary to remotely curtail the active power output of a PV system to resolve congestion issues. Additionally, central control approaches provide the opportunity to optimize grid operation not only locally but also regionally.

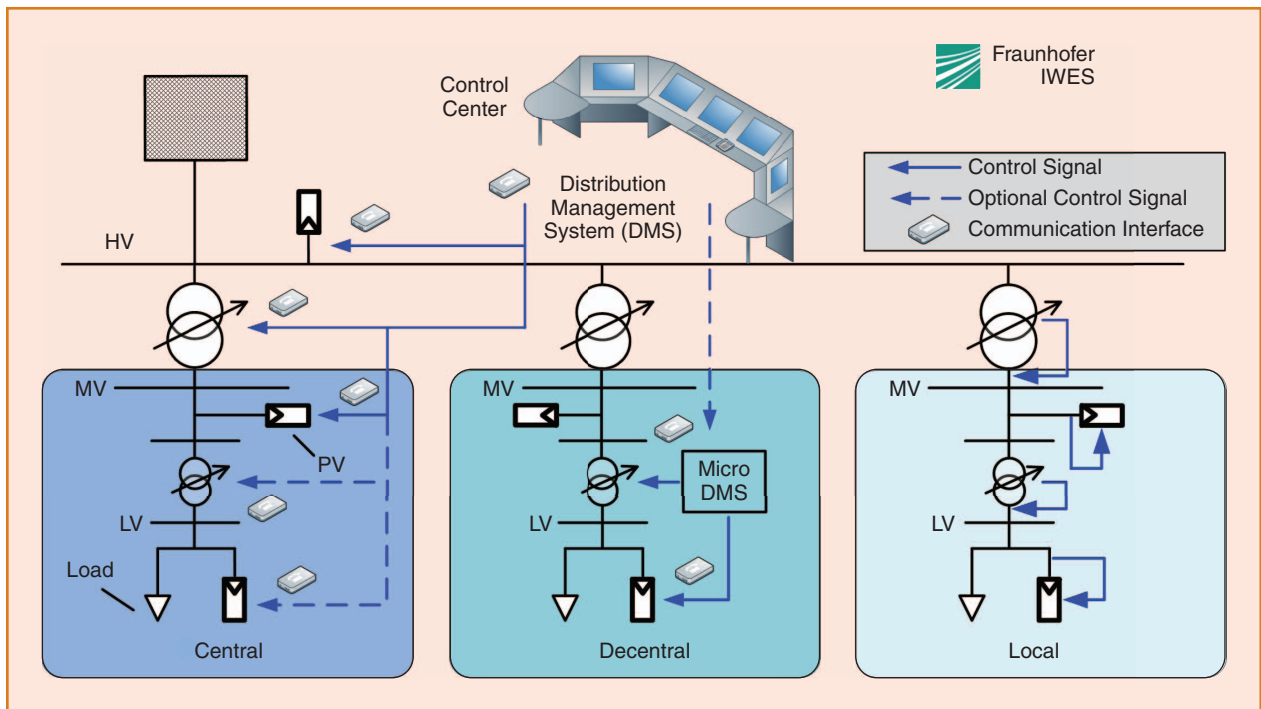


figure 6. Overview of different control approaches (source: Fraunhofer IWES).

Examples of these control strategies, including their economic assessment, are described in detail in the following sections.

Local Voltage-Control Strategies

One major topic of several current research projects, such as the German PV-Integrated project, is to assess—both technically and economically—local control strategies for PV inverters connected to distribution grids. Using their active and reactive power control capabilities, PV inverters themselves can contribute to lowering their impact (in terms of voltage rise) on the grid in times of high solar irradiation. This can, in turn, increase the PV hosting capacity of certain distribution grid sections. Grid-supporting PV inverters are becoming state of the art. They reduce the need for additional grid reinforcement measures, which would be necessary without any form of additional control capabilities. Cost-benefit analyses were conducted for the different voltage-control strategies to determine their economic impact for the PV plant operator, as well as for the DSO at the LV level.

Economical Assessment of Local Voltage-Control Strategies

According to the definition we have given under “Actions for Smart PV Grid Integration,” local control strategies do not require any additional information and communication infrastructure. Therefore, local voltage-control strategies can be easily integrated into the overall grid operation. Once installed and parameterized properly, grid-supporting

inverters can either 1) provide a certain power factor as well as reduce active power output, if local overvoltages are measured (voltage-driven strategies) or 2) simply operate at a certain fixed power factor at any given time (fixed strategies). It is up to the DSO to decide which voltage-control strategy should be implemented. In Germany, most DSOs do not use any of these voltage-control strategies. To address the relatively high economic uncertainty that currently accompanies the decision-making process (in terms of technical benefits versus additional costs), cost-benefit analyses were carried out based on one-year simulations with real low- and medium-voltage grids. In what follows, we present the results of a cost-benefit analysis for a real LV grid.

Figure 7 shows the single-line diagram for the radial LV grid investigated. This particular grid serves a suburban residential area with a total of 122 single households via a 250-kVA transformer. The household loads marked with bold black circles were arbitrarily equipped with 10-kWp PV systems to simulate local congestions and provoke additional grid reinforcement measures to increase the hosting capacity of the grid for further generation capacity.

To reduce the extent of the necessary grid reinforcement measures, local voltage-control strategies were implemented within the inverter models of the PV systems. Table 1 lists the control strategies investigated. Pure local inverter control strategies (A–D), as well as a distribution transformer with on-load tap changer (OLTC), were assessed both technically and economically.

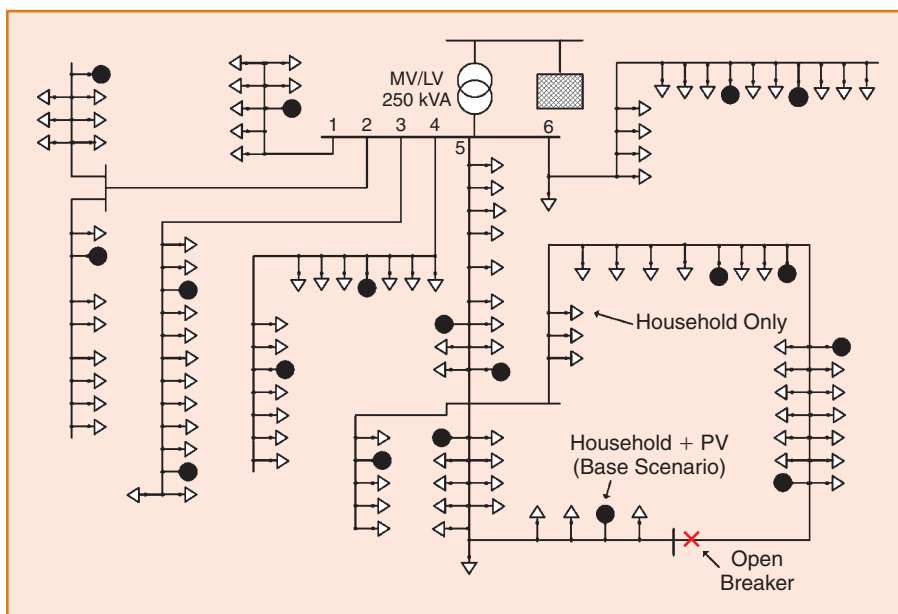


figure 7. LV system with high PV penetration (source: Stetz, Marten, and Braun, 2012).

The cost-benefit analysis was based on one-year root-mean-square simulations with a temporal resolution of one minute using the simulation software PowerFactory from DigSILENT. The introduced grid section, real dc power measurement values (recorded over a one-year period), and high-resolution generic household load data serve as input parameters for the time-domain simulations. Figure 8 summarizes the economic results of the simulations.

As can be seen in Figure 8, the extent of grid reinforcement measures can be significantly reduced by demanding additional voltage-control support by PV inverters, instead of just feeding in pure active power. On one hand, the reduced grid reinforcement results in saved investment costs, which otherwise would have to be borne by the DSO. On the other hand, costs for the PV plant operators may be incurred due

to a reduced temporal active-power feed-in. This so-called opportunity cost can be lowered if self-consumption strategies are also applied. Figure 8 shows that, in particular, strategy B (static reactive-power provision) as well as strategies C and D (automated voltage limitation) can reduce the sum of the cost categories investigated compared with the base scenario (pure active-power feed-in and grid reinforcement). Also, strategy E turned out to be an economically efficient alternative to traditional grid reinforcement measures, depending on the additional costs for the OLTC (here, a cost of €1,000–15,000 is assumed). Further information can be found in the resources listed at the end of this article.

The control approaches mentioned above rely only on local measurement values. In contrast, we can also consider an information exchange between single controllable entities, such as distribution substations and PV inverters, to increase overall system performance. These so-called decentralized control strategies are discussed in the following section.

Decentralized Voltage-Control Strategies

Decentralized approaches can also be used to control an LV grid. These approaches maintain the limits of fundamental parameters required for secure system operation. Such decentralized control can be achieved via the coordination of several active system components—automated and without regulation by the grid control center of the system operator.

table 1. The various control strategies investigated.

Strategy	Description	Regulatory Framework
A	Fixed active-power limitation to 70% of installed PV capacity	Required by the beginning of 2013 by PV systems with an installed capacity of less than 30 kWp and no remote-control capability
B	Reactive-power provision depending on active-power feed-in	Can already be required from DSO, according to German medium- and low-voltage guidelines
C	Automatic voltage limitation: active-power output is reduced so as to maintain a preset voltage threshold value	Not yet officially required
D	Same as strategy C, except reactive power is provided first before active-power output is reduced	Not yet officially required
E	Distribution transformer equipped with OLTC	Not officially required, but first commercialized products are already available on the market

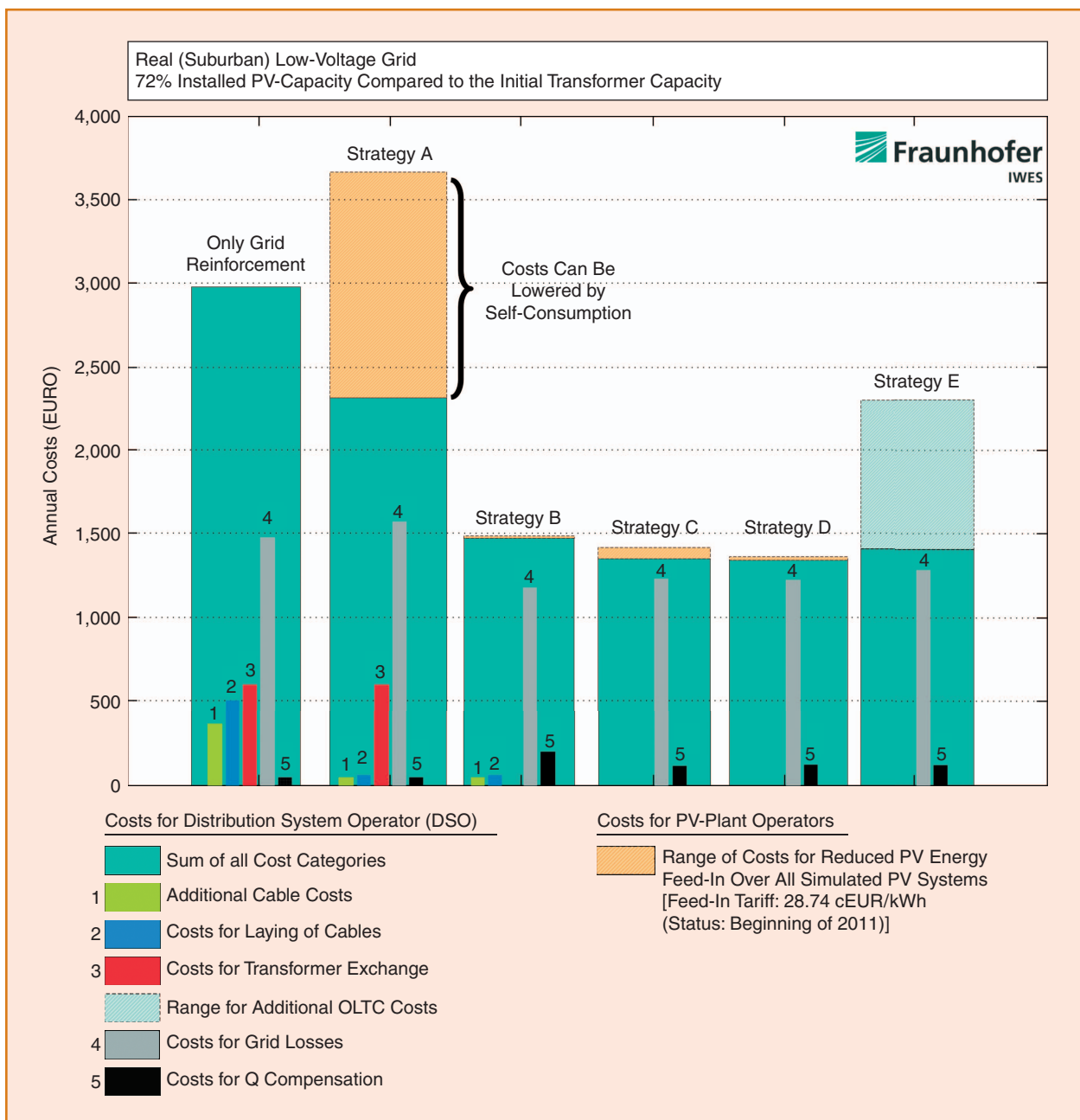


figure 8. Cost comparison of different voltage-control strategies (source: Stetz, Marten, and Braun, 2012).

In the research project called Active, Intelligent Low-Voltage System, the Fraunhofer IWES and its partners investigate decentralized control methods. The aim of the components and control approaches developed is to assure that the voltage within an LV system is kept within the allowed voltage tolerance band—under the boundary condition of minimal grid reinforcement.

Components of an Active, Intelligent LV System

Figure 9 shows the structure and components of an active, intelligent LV system.

The controllable medium- and low-voltage (MV/LV) distribution transformer is able to change the transformer ratio using an integrated OLTC. The voltage curves of the MV and LV are thus decoupled. In this way, a voltage control method for the complete LV system can be achieved that is independent of grid topology. The compact design of the newly developed OLTC transformer allows the mounting form of standard distribution transformers to be retained. Additionally, a robust and maintenance-free design guarantees about 700,000 switching operations. These advantages are accompanied by additional hardware and a marginal increase in no-load losses.

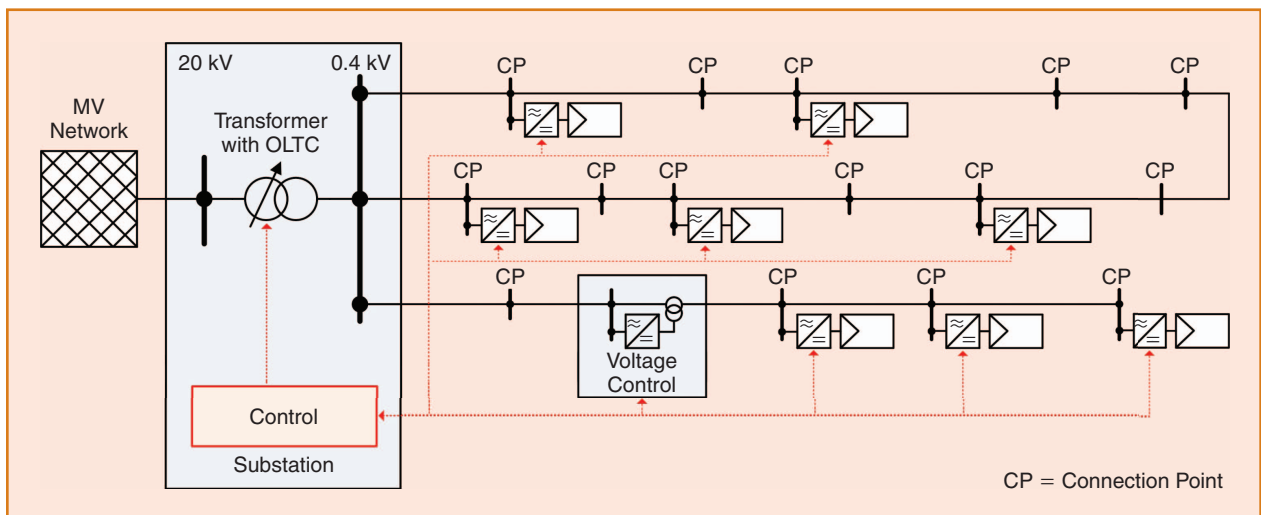


figure 9. Principal design and components of an active, intelligent LV system (source: Bülo, 2012).

Controllable PV inverters offer the possibilities of reactive-power provision (Q) and active-power reduction (P) in order to contribute to grid control. Both local characteristic curves and remote control of P and Q can be implemented.

Decentralized voltage controllers influence voltage curves by adding a voltage step using a transformer with in-phase regulation. This approach seems to be suitable, especially for long single-grid branches.

The control and operating-control unit contains the intelligence and deploys the grid components in a way to achieve optimal operation of the local grid. The modular approach allows for the possibility of upgrades to extend functionality. Bidirectional communication interfaces to the grid control

unit are in place, as well as to the components of the local LV system.

System Concepts

Depending on the particular case, the available components can be used in different combinations, from which several appropriate system concepts can be derived (see Figure 10). The voltage rise caused by DER in the LV grid is not allowed to exceed 3%. Installing an OLTC transformer allows the voltage rise to be mitigated. A voltage rise of up to 10% is therefore possible because the voltage at the busbar at the transformer can be controlled over a large range.

System Concept		Substation	PV Inverter	Type of Communication
Conventional		Passive	Passive	None
Active Inverter		Passive	Active	None (Voltage Control According to Fixed Set Points or Droop Functions)
Smart Substation		Passive	Active	Bidirectional (Substation Controls Inverters)
Active Substation		Active	Passive	None (Substation Controls Voltage According to Substation Measurements)
Active and Smart Substation		Active	Active	Bidirectional (Substation Controls Voltage at Transformer and Inverters)

figure 10. Various concepts for an LV system, including the MV/LV substation being considered for decentralized control approaches (with communication) and local control approaches (without communication) (source: Bülo, 2012).

The choice of system concept will be based on several criteria. In addition to economic considerations, the potential to increase the capacity of the system to host DER is of great interest, especially from a technical perspective. Research results highlight that system concepts using an OLTC transformer allow a significant increase in the system hosting capacity for PV. In these cases, the hosting capacity is no longer limited by the narrow voltage tolerance band. More of the existing grid infrastructure capacity can be used.

Decentralized and local control strategies help to stabilize grid operation or relieve the system during peak feed-in. For an active control of DER during system operation, novel central control strategies can be used. Such control strategies allow for a coordinated operation of grid components so that PV can be used to provide additional ancillary services.

Central Voltage-Control Strategies

In the course of a European research project known as HiPerDNO, a central voltage-control approach was developed for distribution systems. The approach is based on the provision of reactive power by distributed generators as well as the control of OLTCs installed in the distribution system. In contrast to decentralized voltage-control strategies, where subsets of the distribution system are controlled

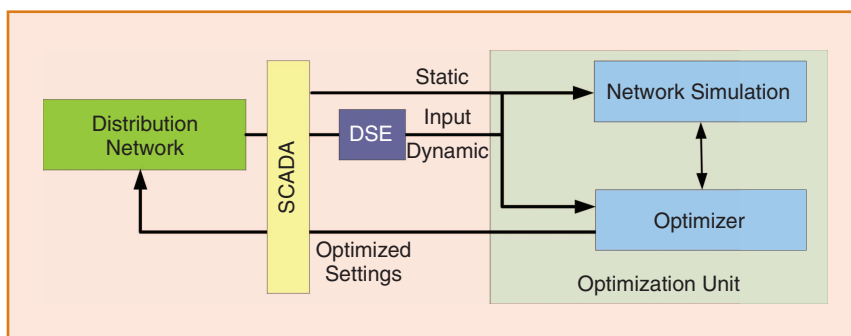


figure 11. Scheme of the central control strategy (source: Yan et al., 2012).

independently, central control aims for coordinated control of the complete system from the distribution system control center. It thus requires a set of information with which to establish the current system status, as well as knowledge of the boundaries in which the system needs to operate. The information required by a central voltage-control approach includes both static and dynamic system information. Static information (e.g., grid topology and the characteristics of components installed in the system) can be acquired directly from the system operator. Dynamic information (e.g., information on bus voltages and on active and reactive power levels of DERs) is acquired from distributed state estimation of the grid. This is because such information is usually only available for a few locations in the system, where sensors are installed.

Figure 11 outlines the architecture of the control mechanism developed. The voltage controller contains a grid simulation unit and an optimization unit. The optimization

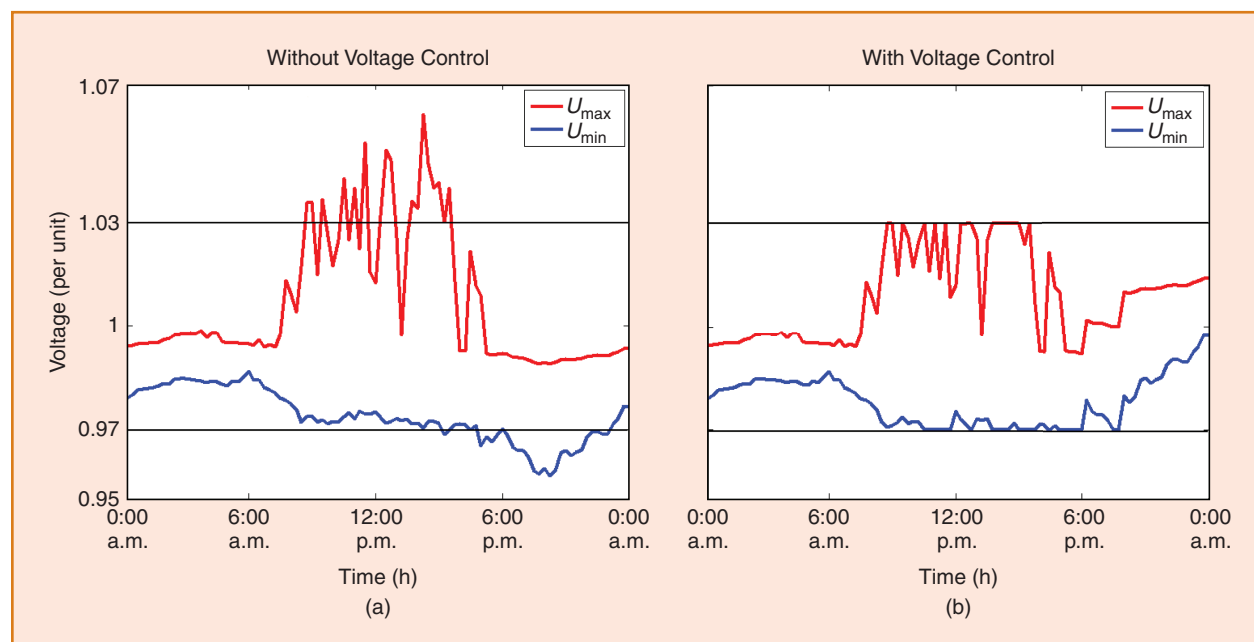


figure 12. Minimum and maximum voltage magnitude (a) without and (b) with central voltage control (source: Yan et al., 2012).

unit uses the grid simulation unit to assess power quality under different grid settings—in this case, tap positions and reactive-power feed-in of distributed generators. This is done via load flow calculations, which require the above-mentioned static and dynamic information of the system. Given the desired quality of a grid setting, the optimization unit will apply a heuristic search strategy to find a grid setting that minimizes the number of voltage violations in the grid with minimal reactive power and tap changes.

Such a heuristic-based central voltage controller was demonstrated to be able to resolve voltage violation in distribution systems. The controller was tested given the topology of a real rural distribution system, as well as real solar radiation data and synthetic load profiles (which were generated using real profiles). The grid contains two MV/LV substations. A total of 11 distributed generators—nine PV generators and two hydro generators—were installed in the grid. The voltage tolerance band was assumed to be $\pm 3\%$.

The maximal and minimal voltage profiles for the simulation of one summer day are depicted in Figure 12. Without any sort of voltage control, as shown in Figure 12(a), the grid experiences overvoltages around noon, which are caused by the high feed-in of the PV generators. In addition, peak loads in the early evening cause undervoltages. Using the voltage-control strategy, as shown in Figure 12(b), it is possible to hold the voltages in the grid within the tolerance band of $\pm 3\%$ over the entire day. These results are promising, as they demonstrate that voltage violations within a distribution system can be solved utilizing the provision of reactive power by distributed generation.

Summary and Outlook

Germany's goal is to transform its electrical energy supply to one that is based on a renewable energy share of more than 80% by 2050. The so called Energiewende—energy transition—will be accompanied by high PV penetration in certain regional distribution grids. These high-penetration scenarios will create challenges for existing grids and thus bring a demand for advanced control concepts to guarantee reliable and cost-efficient future grid operation.

To meet their responsibilities as pillars of the German energy supply system, PV systems must provide ancillary services based on multiple layers of control. Pure local-inverter control concepts can be used to mitigate local voltage rises and so increase the hosting capacity of certain grid sections for further PV deployment. They will fail, however, in situations where coordinated power control is necessary (e.g., in cases of temporal congestions at higher voltage levels).

Smart PV grid integration in Germany is just beginning, and new questions will arise about how best to integrate even greater amounts of PV into the grid. This situation demands

even more fully integrated approaches that consider local, decentralized, and central strategies, as well as their technical effectiveness and economic efficiency for all stakeholders. Appearing on the horizon are new concepts that will allow for the provision of more ancillary services by PV systems and the consideration of energy storage options—e.g., power-to-heat and power-to-mobility schemes.

For Further Reading

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