Operation Strategies in Distribution Systems with High Level PV Penetration

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Abstract

With the tremendous increase in installed capacity of renewable energy resources in Germany, distribution network operators are facing reverse power flows and voltage violations. Different control approaches for controllable network components and distributed energy units exist to maintain a secure and reliable grid operation. This conference contribution gives an overview of the installed photovoltaic (PV) capacity in Germany, the current challenges regarding grid integration of PV and highlights future operation strategies of distribution sections. Based on the experience gained in current and previous research projects, the additional value of controllable PV systems and controllable network devices is emphasized.

1. Introduction

The structure of electricity supply is changing from a centralized system towards a decentralized system. Due to economic incentives and mature technologies the number of new installed small-scale PV systems in German distribution networks has increased rapidly during the last years. Nowadays installed PV systems in Germany have a total capacity of over 17.3 GWp with a growth rate about 70% in the last year. 80% of these are installed in low voltage networks (BMU, 2011), where ancillary services like the provision of reactive power have so far not been required.

The key challenge for a secure and reliable grid operation in future is to integrate the fluctuating power flow in distribution systems. Today, the energy from PV systems is difficult to predict, offers less controllability from the perspective of the grid operator and cannot be sufficiently buffered in existing storages. Within an increasing number of grid sections the simultaneous feed-in of active power in times of high solar irradiation can cause voltage violations and reverse power flows might overload conductors and transformers.

Since the existing distribution system was constructed to serve the local load demand, it can be considered insufficient when it comes to high amounts of local PV energy feed-in. Because of this, new operation strategies have to be investigated and developed for a technically and economically optimized integration of PV systems.

Recently, a wide range of research projects were launched at the Fraunhofer Institute for Wind Energy and Energy System Technology (IWES). The projects presented in this paper are focusing on the control capabilities of transformers with On-Load Tap Changer (OLTC), PV systems and energy storage systems (see Figure 1). The common goal of these projects is to develop operation strategies for distributed energy resources (DER) and facilitate the grid integration by providing ancillary services for the utilities to avoid unnecessarily high network reinforcement costs. For example, in the HiPerDNO project, the OLTC of a station transformer will be controlled based on near to real time State Estimation (SE) results in order to maintain the voltage quality. In contrast to the centralized control of OLTC, decentralized control strategies are investigated to maximize the PV installation capacity and reduce network reinforcement measures in the PV-Integrated project. In addition to a single PV system, a combined system with both PV and lithium-ion battery storage is developed and tested in the Sol-ion project. This allows shifting the feed-in of solar power to uncritical times for the grid operation to reduce the negative influence of injection from PV on the grid. In addition, the self consumption of the local PV generation is maximized for residential consumers.

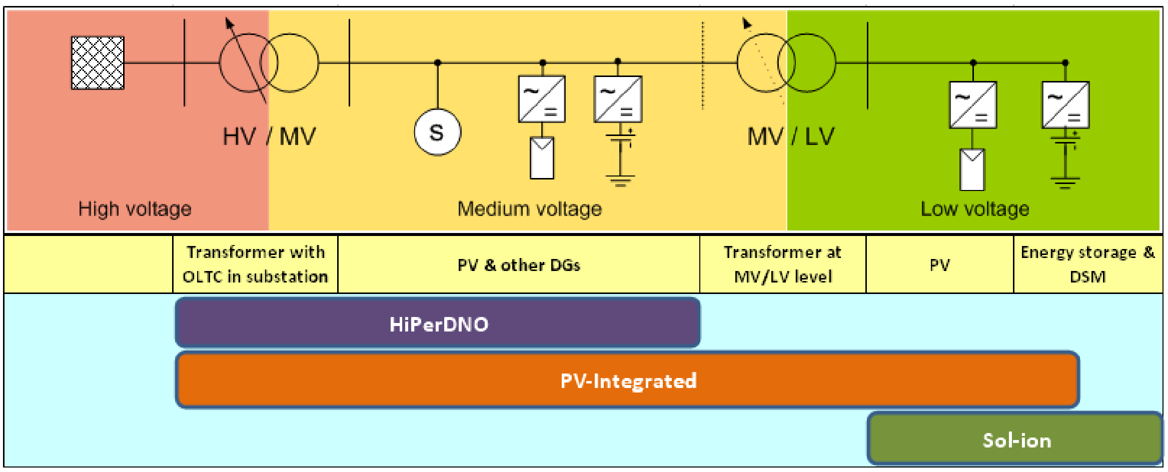

Fig. 1: Research focus of the presented projects

2. HiPerDNO

At present, most distribution networks operate passively, due to a lack of measurement sensors and limited communication infrastructures. The conventional voltage control is based on transformers equipped with On-Load Tap Changers (OLTC) which are widely used to maintain the voltage magnitude (Harlow, 2007). However, high level PV penetrations and diverse weather condition cause strongly fluctuant and even reverse power flows, which may result in voltage problems. With the help of novel information and computing technologies, near to real-time state estimation is developed to increase observability of the network status and support voltage control in distribution networks. Instead of maintaining the substation secondary voltage in a preset tolerance band, which is done by a conventional OLTC control (Figure 2 left), an advanced OLTC control method based on the accurate Distribution State Estimation(DSE) result is developed (Figure 2 right) in the HiPerDNO project[1] to keep the voltage in the whole network within the desirable range.

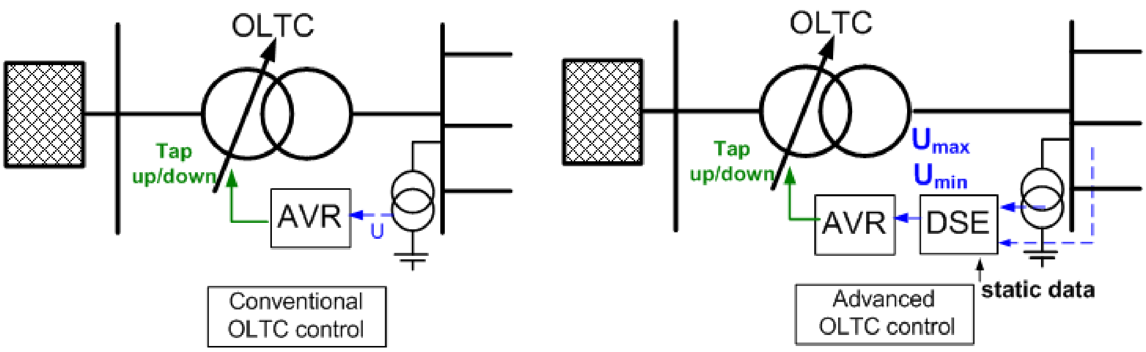

Fig. 2: Voltage control in distribution networks

Not only the real-time measurement data from sensors and the actual switch position, but also the static network data as well as a load model, deduced from historic data and different sensor characteristics are used to facilitate DSE to represent an accurate voltage profile. According to the estimated maximum and minimum voltage in the whole network, operating commands for OLTC are carried out by an automatic voltage regulator (AVR) after a time delay of 30 to 60 seconds.

In fact measurement data from sensors and transducers contains errors and the DSE is developed to smooth

[1] http://dea.brunel.ac.uk/hiperdno

them. The goal is to obtain the desired accuracy of voltage profile with a minimal number of sensors and in less calculation time (De-Alvaro and Grenard, 2011). In order to analyse the performance of advanced OLTC control regarding to different DSE accuracy and different PV penetration static simulations are carried out. A real rural medium voltage network, real solar irradiation values and synthesized load profiles are used as input to run the network simulation in the software PowerFactory from DIgSILENT. All 40 MV/LV substations are equipped with a load model and a scalable PV system. The following four simulation scenarios have been defined:

- Scenario 1 (S1): conventional control
- Scenario 2 (S2): advanced control (no DSE error)
- Scenario 3 (S3): advanced control (0.5% DSE error)
- Scenario 4 (S4): advanced control (1.5% DSE error)

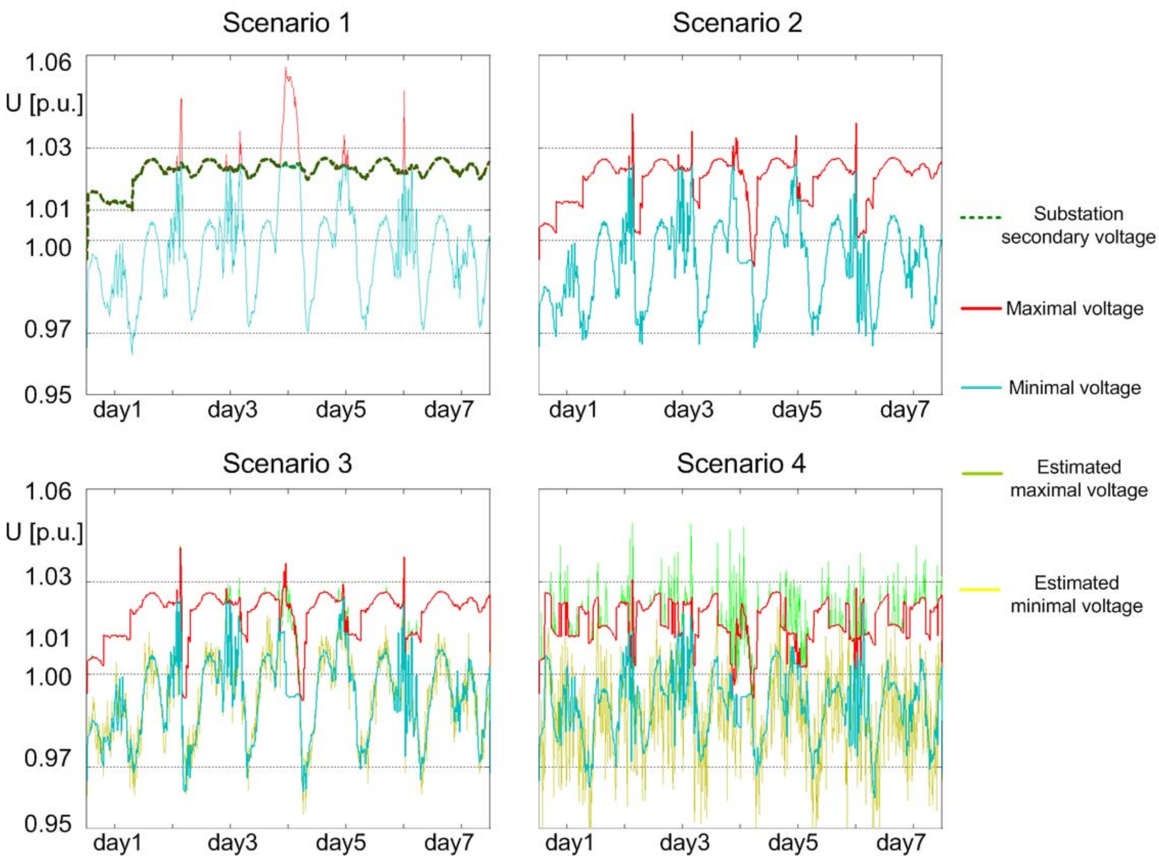

Fig. 3: Impact of estimated error for different scenarios

Figure 3 shows simulation results for the different scenarios which depict the maximum and minimum voltage profiles of one week with 0.3 MW installed PV capacity at each MV/LV substation. In scenario 1, only the substations secondary voltage is kept in the preset tolerance band between 1.01 and 1.03 per unit, while the maximum voltage caused by high energy feed-in from PV at noon on the 4th day reaches almost 1.06 per unit. According to the EN 50610 standard the 10 minute average value of voltage must not exceed ±10% at connection points of end consumers. Because of the few measurement data and few voltage control possibilities in the low voltage network and to keep network losses low, it is recommendable to keep a narrow voltage band at medium voltage level. By applying the advanced OLTC control based on the ideal DSE result in scenario 2, both maximum and minimum voltages are kept in tolerance range. Voltages outside the defined tolerance band of ±3% are referred to as 'voltage excursions' in the following. Since the OLTC starts to operate only if the voltage exceeds this limit, some unwished voltage peaks can still be found in the profile. Taking into account small estimated errors in scenario 3, the voltage profile is quite similar to that in scenario 2 and the operation of OLTC is only slightly changed. By considering the DSE result with 1.5% error in scenario 4, the green and yellow curves depict the estimated voltage profiles according to the errors. The actual maximum and minimum voltages are still maintained in acceptable range at the cost of quite a lot of additional OLTC operations.

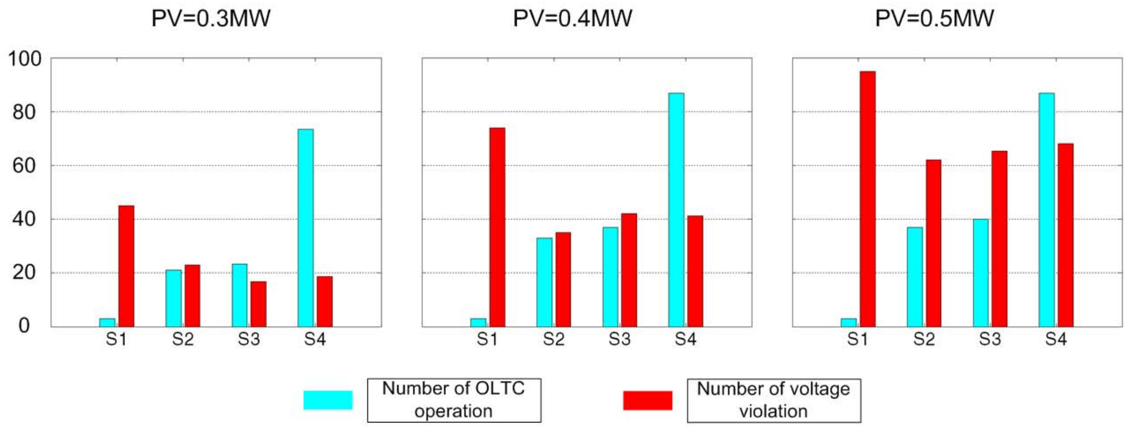

Fig. 4: Impact of PV penetration for different scenarios

In a second step the degree of the PV penetration is increased to analyze the number of OLTC switching operations and the number of voltage excursions in different scenarios (see Figure 4). When 0.3 MW photovoltaic are installed at each MV/LV substation, the advanced control approach is able to reduce the number of voltage excursions remarkably at the cost of more OLTC operations. The number of OLTC operations increases rapidly with the inaccuracy of DSE results, while the number of voltage excursions remains similar. With additional 0.1 MW of photovoltaic capacity, the advanced control approach is still able to effectively mitigate the number of voltage excursions. If the degree of PV penetration rises up to 0.5 MW at each MV/LV substation, the advanced control approach still can be used to ease the voltage problem. However, in such an extreme scenario it cannot deal with every single voltage excursion even considering ideal DSE results. The reason is that the rural network covers long distance and the difference between the maximum and minimum voltage is so large that OLTC alone cannot solve the problem.

In the next step, coordinated approach using control capability of both OLTC and photovoltaic output power should be developed to reduce the voltage excursions. An additional warning range or fuzzy control would be investigated in order to reduce unwished voltage peak near the tolerance band. Furthermore, the impact of time resolution of DSE result in voltage control will be studied.

3. PV-Integrated

Starting end of 2010, PV-Integrated[2] is the most recent of the research projects presented here. In a total of four years project duration, the various grid aspects of PV integration shall be optimized. The goal is to find solutions for grid operation and grid planning that ensure a cost-effective integration of high amounts of PV without compromising on security. The project partners believe that significant efficiency gains can be realized when PV is actually integrated into the different stages of network planning and management.

Whereas the HiPerDNO project focuses on the medium voltage level, in PV-Integrated, the topology of both the 400 V and the 20 kV network are modeled in detail. The project partner E.ON Bayern AG is contributing a real network in Bavaria to conduct analysis and to perform field tests. The test region counts among those with the highest PV penetration in Germany. There are low voltage networks in which the ratio of installed PV capacity per household is as high as 3.9 kWp (early 2010) and is expected to increase by 60 % in the coming years. Accordingly, there is urgent need for cost-effective increase of the PV hosting capacity.

The existing grid infrastructure can be utilized more effectively by actively controlling the PV inverter active

[2] http://www.pv-integrated.de

and reactive power output. (Braun et al., 2009) give an early overview of the technical and economic impacts of reactive power provision by PV inverters. For a rural and a suburban reference network, the costs of providing reactive power are compared to the potential savings. It is shown that the commercial and technical effectiveness of the measure depends on the grid topology and the PV penetration level. (Degner et al., 2011) analyze the impact of network impedance angle and short circuit capacity on the PV hosting capacity in low voltage networks in general, and on the effectiveness of reactive power compensation by PV inverters. (Braun, Ma., 2011) evaluate how much more PV could possibly be accommodated into a given low voltage network, using different strategies for controlling the PV inverters' active and reactive power output.

Considering that a PV installation is supposed to remain in the grid for 25 years and longer, the German institution of electrical engineers set up a new technical guideline, VDE-AR-N 4105 (VDE FNN, 2011), valid since August 2011. This guideline requires reactive power feed-in capability from all PV generators, even those connected to the low-voltage grid. It is common practice that grid operators include the technical guideline in force into their connection requirements for DER units. So starting this year, large numbers of inverters with Q-control capability will be installed in the field.

The control method suggested in VDE-AR-N 4105 for DER units with fluctuating feed-in is controlling the power factor at the point of common coupling via $\cos(\varphi(P))$ control. This control method is known to be stable. However, it may cause higher losses than voltage-dependant control strategies, like Q(U) control (Degner et al., 2010), or 'dynamic control', (Stetz et al., 2010). In the technical guideline, it is therefore left open to introduce voltage-dependant control strategies in the future. Grid operators will start considering voltage-dependant control as a valid option as soon as proof of stable network operation with this method has been provided.

So what is needed at this stage, are field tests of PV inverters providing voltage-dependant grid support using only locally available measurements. It has to be ensured that the system remains stable and that PV inverter controllers do not counteract each other. Additionally, the interaction with on-load tap changers and further controllable equipment has to be studied carefully.

Starting 2012, PV systems operators could be obliged by federal law to limit their active power output at the PCC to 70 % of their installed DC capacity. This would apply to all systems with an installed capacity of less than 30 kVA that cannot be remotely controlled by the utility. This opens ample opportunity for self-consumption optimization and usage of local storage. PV-Integrated will use already available research results on this topic from other projects (see section 4) and shall integrate them into an overall grid operation concept. These are some of the key topics under investigation in the PV-Integrated network operation work package.

One key argument of PV opponents is that smart grid concepts may be nice, but that eventually, they do not have any real impact on the required network expansions. Investments in grid capacity to accommodate the politically intended amounts of energy from wind and PV till 2020 have been estimated to be in the magnitude of 10-13 billion Euro for Germany[3], (BDEW, 2011). In the network planning package that takes up work in October 2011, it shall be undertaken to develop methods for integrated expansion planning. It is an explicit task and welcomed opportunity of the project to highlight potentially remaining regulatory barriers for a more cost-efficient integration of renewable energies.

4. Sol-ion

A different approach to improve the distribution network capacity for local generation is to integrate stationary storage systems to balance the fluctuations of renewable energies. PV systems in combination with battery systems have the ability to foster local consumption of the generated PV electricity.

In the project "Sol-ion - Renewable Energy System including energy storage system with Lithium-Ion

[3] Scenario 'Energiekonzept 2020'

battery for residential and small commercial application”[4] a multifunctional PV-battery system with a nominal power of 5 kVA for private and small commercial application was developed to assess the benefits of such hybrid systems for the owner and the grid operator (see Figure 5).

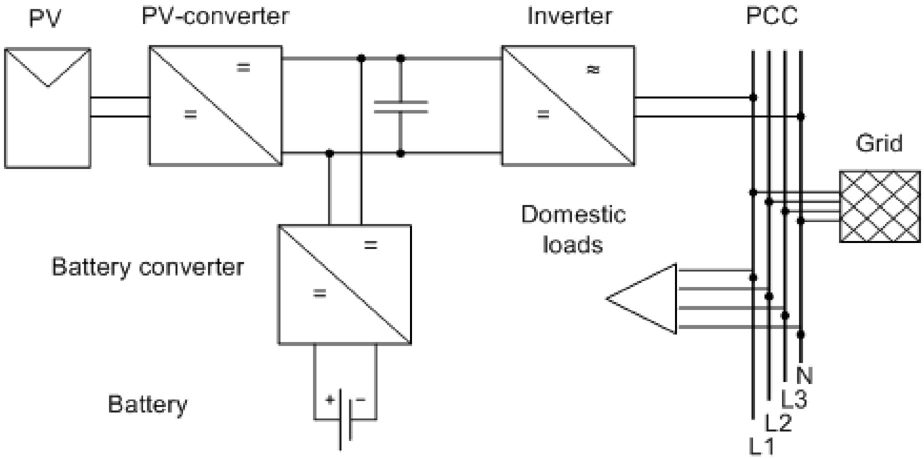

Fig.5: Sol-ion system layout (Büdenbender et al., 2010)

The setup allows an assessment of different energy management strategies regarding different electricity tariff structures which would facilitate the PV integration into the distribution system. Therefore three different incentive-based strategies are under investigation (Büdenbender et al., 2010):

- Self consumption of PV energy: Increased self consumption at the local PCC is rewarded by a special tariff. The battery is used to consume as much PV generated electricity as possible to benefit from the special tariff.
- Time variable electricity prices: Time variable electricity prices incentive the usage of the battery to perform load management to avoid high electricity prices.
- Capacity depending base prices: Introducing capacity payment for private customers would incentivize using the battery for peak shaving purposes and limit the power flow at the PCC.

The impact of the different control strategies of PV battery systems is shown in Figure 6.

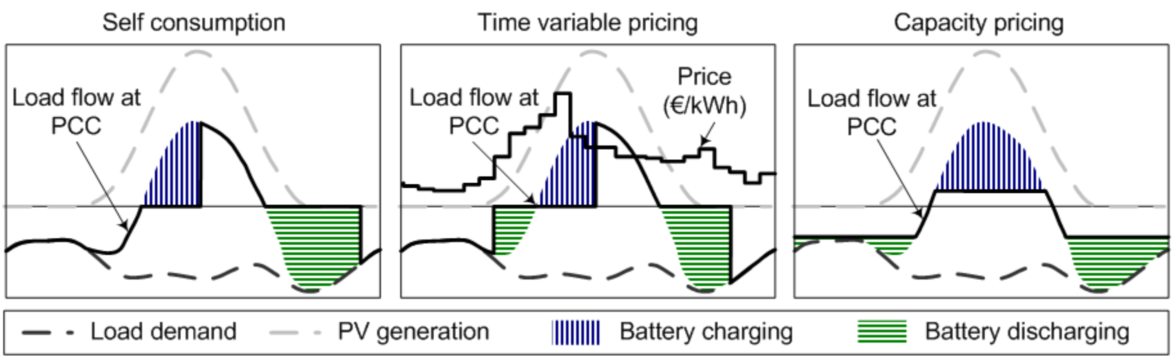

Fig.6: Control of grid connected PV-battery system in different incentive scenarios (Büdenbender et al. (2011))

Assuming a higher future deployment of PV-battery systems within a low voltage grid allows assessing the practicality of the different tariff options for supporting network operations. An analysis of the influence of the tariff options on the load flow at the individual PCC as well as at the connection point to the higher voltage level is possible.

In (Büdenbender et al., 2010, 2011) the influence of the three tariff options on the voltage in a rural distribution grid of southern Germany is analyzed. Results are displayed in Figure 7. In the base scenario, the distribution grid connects 54 households with a total installed PV capacity of 220 kWp to the 20 kV level via

[4] http://www.sol-ion-project.eu

a 250 kVA transformer. The future scenario describes a grid with increased PV penetration, in which 20 households receive an additional 5 kWp PV system. Then, during times of high solar radiation, violations of the 3 % voltage limit occur. A more detailed analysis including the influences of different strategies on the load flow, the losses and the electrical loading of the components can be found in (Büdenbender et al., 2010, 2011).

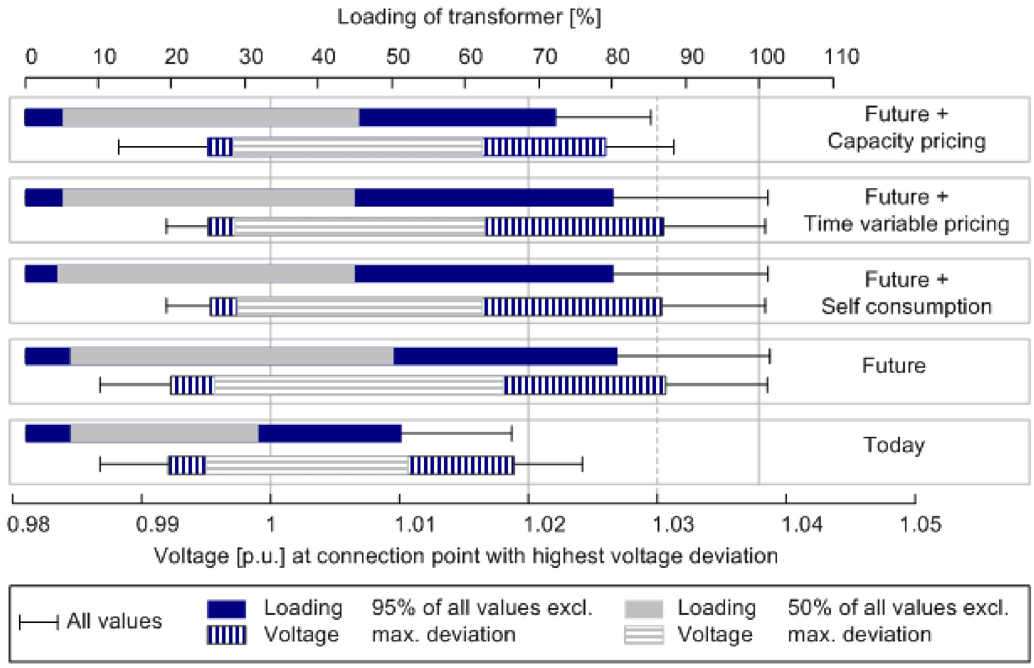

Fig.7: Influence of PV energy on the distribution grid

The analysis shows that the tariff options ‘self consumption’ and ‘time variable pricing’ do not differ a lot compared to the future scenario without incentives. These tariff options do not lead to a significant reduction of the voltage as well as of the loading of the transformer. The capacity tariff is the only effective incentive that helps maintaining the voltage below the increase of 3.0% in 95% of the cases. Nevertheless even in this case additional investments in the grid are necessary; the transformer has to be replaced to avoid additional connections to the medium voltage level or a replacement of cables is necessary.

To foster the usage of PV battery systems for small scale applications a capacity based tariff provides the highest incentive. This research indicates that such an incentive would help to mitigate the increasing network costs related to the growing PV installation in the distribution system. Future research will investigate how higher scaled PV-battery systems can positively affect the PV expansion. Different control strategies for the batteries, especially utility usage of storage devices at the substations to avoid transformer overloading will be examined.

5. Conclusions and future scope

This paper has presented three selected research projects of the Fraunhofer Institute for Wind Energy and Energy System Technology (IWES) focusing on the impact of high level PV penetration in distribution systems. These projects illustrate the variety of possibilities to solve the current and future challenges in grid operation. Concerted control of all available controllable network components is the key to ensure and improve the power supply quality of the future. Results from field tests will complete the investigations and will show the daily application of the suggested approaches. At a later stage, concepts shall be developed that suggest how to convert the technical findings into an appropriate regulatory framework.

6. Acknowledgements

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