Smart Grid Services Provided by Building Energy Management Systems

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***Abstract* – The integration of decentralized energy resources is associated with new challenges for the operation of low voltage distribution grids. At the same time, the interconnection of these systems offers large potential for providing smart grid services to increase power quality and grid stabilization in areas with a high penetration of renewable energy sources. Therefore, new operation strategies for photovoltaic inverters are presented in combination with building energy management systems. The effect of a locally controlled feed-in is discussed based on simulation results of exemplary rural grid structures.**

***Index Terms* – Building Energy Management System, Smart Grid Services, Photovoltaics, Power Quality, Smart Grid**

I. Introduction

The energy transition in Germany ("*Energiewende*") is a politically initiated accelerated shift from nuclear and fossil fuels to *Renewable Energy Sources* (RES). A successful realization requires a fundamental paradigm shift concerning the usage of infrastructure and operation strategies for power grids. In 2014, 27.8 % of the produced electricity in Germany were provided by RES. The installed power of photovoltaic plants has been 28.2 GW in 2014 [1]. Due to the continued expansion of RES in Germany during the next years, the amount of intermittent generation will continue to increase.

Contrary to wind power, which is mostly connected to the mid and high voltage grids, a vast majority of the photovoltaic capacity in Germany is installed in low voltage grids [2]. This has considerable influence on grid operation strategies. The resulting need for changing *consumption-oriented generation* to *supply-oriented consumption* creates new challenges especially in areas with high penetration of photovoltaics [3].

On the one hand, these challenges affect the grid condition: The usual load flow from medium voltage to low voltage grids may reverse its direction in particular in rural areas, due to the net production of electricity in the low voltage grids. Additionally, the voltage is increased locally according to the electricity generation of photovoltaic systems. This effect can cause local voltage violations in the distribution grids, which are historically designed for top-down energy supply. In rural areas with a high penetration of photovoltaic plants and long distances between the local transformer and the prosumers, the voltage control is already a huge challenge today. Figure 1 visualizes exemplary voltage curves of a sunny and a cloudy day (same week-days in November) at the grid connection of our lab (see Section II). It illustrates that voltage fluctuation caused by photovoltaic feed-in already occurs in urban areas. This effect is even more significant in rural areas [4]. Therefore, we focus on the presentation of the potential in rural grids, although we have analyzed several different grid setups. Additionally, due to the fact that measurement equipment is rarely installed in low voltage grids, the detection of voltage violations is challenging.

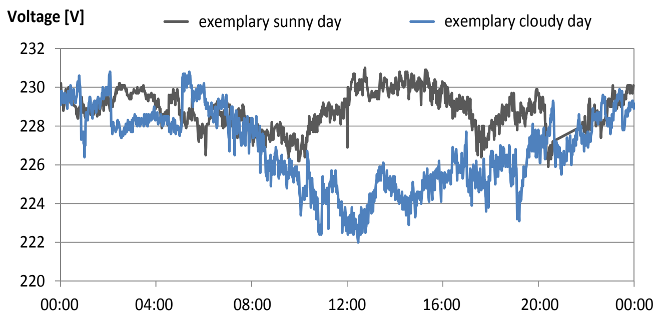

Figure 1: Voltage level during sunny and cloudy days; low voltage node in an urban power grid

On the other hand, it is very difficult to predict the energy production of photovoltaic plants precisely, as it strongly depends on the very local weather conditions. An imprecise prediction increases the risk of voltage violations and uncontrolled imbalances between supply and demand within the grid segment, when control strategies are based upon these predictions. Current approaches in Germany provide a feed-in management (reduction of generation to 60 %, 30 %, and 0 % of peak power), which can be controlled remotely by the *Distribution System Operator* (DSO) [5]. This control is implemented for most of the photovoltaic plants >13.8 kW_p.

In addition to the technical challenges for providing smart grid services, the development of regulatory guidelines is a major prerequisite for a successful integration of RES into the distribution grids. Currently, existing regulatory guidelines in Germany limit the technical options available by an intelligent integration of *Distributed Energy Resources* (DER). Such restrictions include limits on feed-in of reactive power, no direct communication between DER respective *Building Energy Management Systems* (BEMS) and DSO, and regulations regarding asymmetric power feed-in.

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In this paper, we present a smart grid service approach (see Figure 2), which is integrating BEMS into the power grid for providing services to improve the stability and reliability of future grids. The major tasks of BEMS are predicting, identifying, and providing flexibility of the energy supply and demand in buildings [6], [7]. In this paper, we focus on the ability of BEMS to provide flexible grid services by photovoltaic and storage systems.

Contrary to traditional operating strategies for low voltage grids, our approach uses photovoltaic inverters to control the feed-in of active and reactive power at certain grid connection points. The main objective is to improve the voltage quality, using the integrated measurement equipment of the photovoltaic inverters for detecting the local grid condition.

II. Related Work

The idea of using reactive power of decentralized installed inverters to increase the active power capacity of low voltage grids by avoiding violations of voltage limits has been a subject to recent research.

For instance, Kerber et al. [3] introduce an approach of regulating the grid voltage levels using a simple autonomous reactive power control. However, their work limits the power factor to 0.95 or 0.9 complying with present German legal requirements with respect to the minimum possible power factor. Furthermore, the work takes the knowledge of the grid position of each inverter into account in order to minimize the overall usage of reactive power.

In [8], Hatta et al. propose a more detailed autonomous control method, which is designed in a way that inverters recognize other inverters in the grid being active with the goal of respecting or even helping them to achieve a certain voltage level.

Demirok et. al. [9] compare a static *Q(U)* control mechanism with more intelligent *cos φ(P)* and *cos φ(P,U)* control mechanisms. They focus on the performance regarding grid losses and voltage variation of a simulated suburban low voltage grid. They evaluate their control mechanism for supplying reactive power with regard to its effect on the PV capacity of the associated grid segment.

However, the focus of this paper is not limited to control methods provided by inverters but considers also the possibility of including the potential load flexibility of a fully controllable household with time-variable loads as well as battery storage units. Some work including battery energy storage systems is presented by Kabir et. al. [4], who introduce a method of not only using reactive power but also energy storages to realize peak shaving and smart grid services.

Our approach (see Figure 2) combines the benefits of a Building Energy Management System (see Section III) and the consequential possibilities of using load management and storage systems. At the same time, it considers the theoretical possibilities of inverters to feed-in inductive or capacitive reactive power, which is controlled separately of any produced active power while being only limited by the latter and the inverter size.

III. Building Energy Management

Although our approach is implemented and evaluated in simulations (see Section IV), we used the infrastructure of a real building, *FZI House of Living Labs* (HoLL), to feed the simulation with realistic data. The HoLL is a research lab which is equipped with a comprehensive range of producers, consumers (e.g., several smart home systems), storage systems, and measurement systems [10]. Electric energy is supplied by a photovoltaic system (15 kW_p) and a combined heat and power plant (5.5 kW_p) within the building. The photovoltaic system is connected to a battery storage system (30 kWh).

All components of the building are equipped with communication interfaces that enable their integration into a BEMS. This BEMS is implemented using the software framework *Organic Smart Home* (OSH) [6]. The OSH software framework focuses on both, the integration of a large number of components with heterogeneous communication protocols and the optimization algorithms to control the whole system while complying with superordinated objectives (e.g., maximize the consumption of locally generated energy) [11]. The OSH is capable of real-world building energy management as well as the simulation of such systems on different levels of the grid, while providing a bidirectional interface (observation and control) for the DSO and enabling *Demand Side Management* (DSM) [12].

The BEMS records data of the components' operation and the energy flows in the whole building. Additionally, the BEMS controls the operation of the suppliers, consumers and storages. Thus, various operation strategies for the internal control of the systems and in particular for providing smart grid services by the BEMS can be tested and evaluated with real hardware components.

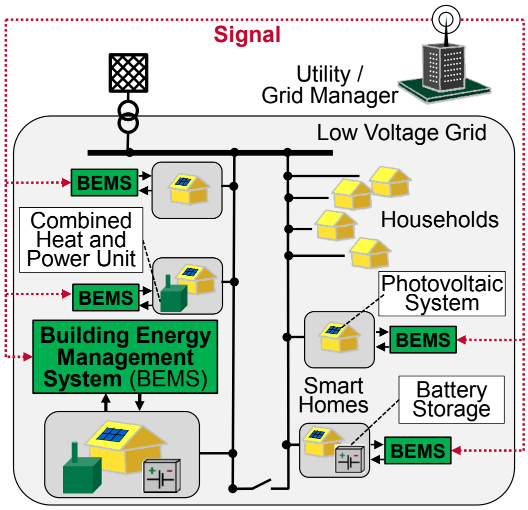

Figure 2: Visualization of a future energy system combining decentralized BEMS to supply grid services

To evaluate the impact of providing smart grid services by decentralized systems in low voltage grids, we implemented the operation strategy on several nodes of a grid simulation. The grid simulation enables the analysis of the load and the voltage level within certain grid structures. As the measured data of the HoLL can be simulated to a specific set of nodes (original or scaled to other building sizes) within the grid simulation, the simulation of the building is closely interlinked to the grid simulation resulting in a co-simulation of grid and building.

We handled the BEMS as an independent player on behalf of system services and grid control while adopting a decentralized control approach with centrally provided control objectives. These objectives should aim on achieving an optimal state of the energy grid while considering grid specific characteristics for the particular grid. Since a standard objective (e.g., *Q(U)*) is predefined on each grid node, the centrally provided objectives are optional in this approach. The BEMS is responsible to integrate all devices, e.g., battery storage and PV inverters, in a single control and optimization.

This method is in contrast to approaches with a central control of providing system services. In a central approach, measurement data of the decentralized systems are sent to a central control station and operation instructions are returned to the decentralized systems. The disadvantage of that approach is that in case of communication faults, which may occur especially during grid failures, the centralized control mechanisms will fail, since the decentralized systems will not receive the centrally communicated control signals properly.

IV. Grid Simulation Setup

With the aim of getting insights on potential contributions of inverters to improve voltage quality as well as the compliance with voltage ranges, we developed a simulation setup for low voltage grids that allows for the simulation of power flows and control strategies. The simulation focuses on the integration of photovoltaic inverters and electrical storages.

The simulation has been designed to be fed with predesigned low voltage grid structures in order to test different control strategies and their effects on the voltage levels in these grid structures. Based on this, it is possible to get insights on the benefits of an intelligent integration of decentralized photovoltaic systems. In particular, the subjects of our investigation are low voltage grids, in which critical system states are occurring even today during times with a high solar radiation even (e.g., rural grids with a high density of distributed photovoltaic systems).

The grid simulation setup consists of two components interacting with each other. First, the surrounding framework and the simulation of control strategies are implemented in MATLAB. Second, a grid simulation is implemented to provide power flow calculations for the different grid setups. In a first attempt, we calculated the grid in MATLAB with the Jacobi iterative method, as presented in [14].

In further work, we replaced our own implementation for the grid calculation by the open source power distribution analysis tool GridLAB-D [13]. The goal was to improve the flexibility of analyzing complex grid setups and the computing speed of the power flow calculations. The interconnection of the two simulation components combines the advantages of both, the extensive power flow simulation features of GridLAB-D and the capabilities of MATLAB to implement a multi-agent simulation with individual control strategies. Thus, a MATLAB routine uses GridLAB-D to calculate power flows and voltage levels in 15 minute time steps (96 steps per day) and certain load levels.

The simulation routine calculates a day's voltage curve for each connection point of the simulated grid setup. At first, the "normal" state (i.e., without generation) of the selected low voltage grid setup is calculated based on the grid topology and the corresponding load data taken from standard load profiles. The state description of the grid is represented by a matrix of voltage values, one for each node and time step of the calculation period.

In a next step, the implementation of the control strategy improves the voltage quality with respect to different objectives for grid conditions, specifications, and technical flexibilities (depending on what is installed; e.g., batteries, bus bars on the PV side, size of inverters etc.). The objectives of these strategies are given with different priorities and limits and include the compliance with regulations, the maximization of potentially fed-in solar active power and the reduction of reactive power in the grid. The compensation of voltage asymmetries of the different phases as an objective of control strategies has been analyzed in further studies and shall not be considered in this paper.

The decentralized grid control approach is realized by a selection of grid services at certain grid connection points. These grid services are provided by the simulated inverters, which are basically controlling the load distribution (e.g., charging batteries, feed-in of active and reactive power).

In order to achieve the grid's target condition and in order to use individual control strategies, the actors in the grid are controlled independently from each other and are based on the voltage level at their grid connection point only. The adaption of fed-in apparent power is realized by an iterative approach, using the measured node voltage as the input parameter. This *S(U)* control runs until the constraint regarding the selected control strategy (e.g., avoiding voltage violations) of the particular node is satisfied. The implementation of the control is not real-time capable but a steady state approach where it is assumed that the behavior of several inverters is homogeneous. A dimensioning of a PI controller or similar real-time controls has to be considered separately.

Such a decentralized optimization will ensure that, at every grid node, the voltage level satisfies the particular constraints as far as possible. In this way, we investigated the impact of adjusting the power factor or the feed-in power on the simulated grid setup. Thereby, the specific control strategies and the associated restrictions could be analyzed for individual grid nodes as well as for the whole grid segment.

As already mentioned, we integrated several control strategies into a MATLAB based simulation, each of them designed to work with a certain complexity and thereby achieving different levels of optimization: The most simple of the strategies is a controlled feed-in of the effective power generated by the photovoltaic cells combined with an adapted power factor to smoothen the voltage variability and prevent a violation of the legal voltage range.

To increase the variability concerning the influence on the voltage level, the possibility of setting the power factor freely regarding only technical limits of the inverter has been included in a second control strategy. In this context we decided to consider the usage of available solar power as more valuable than the feed-in of reactive power to regulate the voltage. Thus, the minimal power factor is given by the quotient of the fed-in active power of the inverter and its nominal apparent power (see Figure 3).

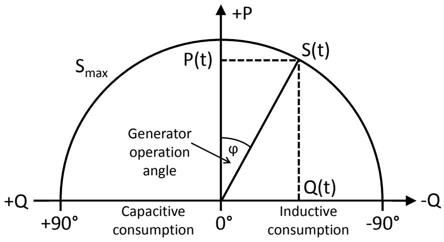

Figure 3: Inductive and capacitive reactive power [2]

For the simulation of the control strategies we used different setup specifications: In a first step, batteries are integrated that can be used as energy storage, supplying the connected building but not feeding into the grid ("load only"). In a second step, the batteries are integrated bi-directionally ("load and feed-in") to improve the flexibility of energy usage and the voltage quality at the local grid connection (see Figure 4).

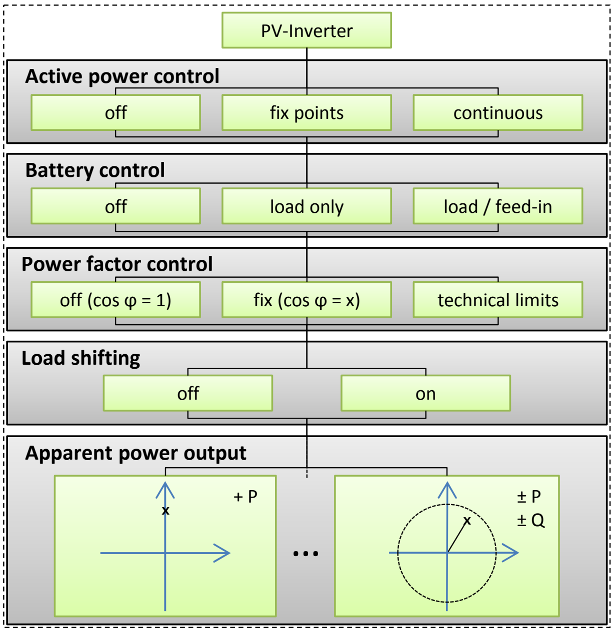

Figure 4: Setup specifications and control schemes

The "specifications of work" for those control strategies are given to the simulation separately, which include the legal power factor that is allowed to be set, the already mentioned voltage range, and the preset transformer voltage as well as the optimization target related to the selected control strategy. A restriction for the use of reactive power can be given (e.g., "compensate the own generated reactive power" or "achieve a certain amount of fed-in reactive power").

The low voltage grid that has been used for applying the simulations is designed as a typical rural grid in Germany. It consists of ten four-person households ("H0") and four agricultural holdings with attached residential buildings ("H0 & L0", "H0 & L1"), which are all connected to the grid in a line (see Figure 5).

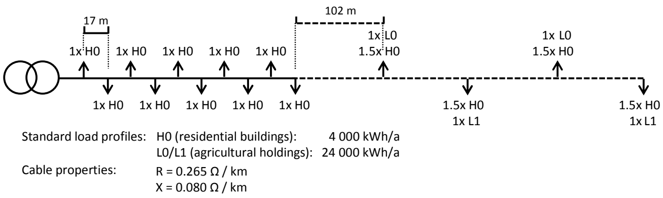

Figure 5: Rural grid setup

The simulation setup is strongly connected to the current development of the German power grid. In this context, the Federal Network Agency ("*Bundesnetzagentur*") has proposed a concept for the interaction of "Smart Grid" and "Smart Market", which distinguishes three major grid conditions [15]: In the green grid condition, the present power flow is far away from the maximum capacity. In this situation, the market is expected to control consumption and supply. In the red grid condition, the maximum capacity is already exceeded in certain grid segments. In this situation, only the DSO (grid side) has the task and responsibility to restore grid stability.

The approach of supplying grid services by BEMS focuses on the yellow grid condition, which is located between the green and the red condition. Since in this situation the energy flow in certain grid segments is not far away from the maximum capacity although not having reached a critical grid condition, yet, control targets combining grid and market aspects are able to adjust the supply of grid services provided by decentralized systems. Control strategies for providing grid services in the yellow grid condition are also based on predictions for consumption and supply in the grid segment.

V. RESULTS

In a first step, we analyzed the impact of decentralized photovoltaic systems on the voltage level of the simulated low voltage grids. In a second step, we examined how those effects can be used for improving the voltage quality and grid stability. Therefore, we integrated several operating strategies (e.g., optimizing the grid load concerning reactive or active power) into the simulation, simulated different installation setups (e.g., urban and rural) and analyzed the results. In this paper, we focus on the results of a single-phase simulation.

In Figure 6, a typical result graph that illustrates the simulated voltage levels at the grid nodes in a rural low voltage grid without the influence of installed photovoltaic systems is presented. Each curve describes the voltage profile at an individual node during one day (midnight to midnight) as a result of using standard load profiles (households and agricultural holdings) for each node in the grid simulation. The voltage variation increases with growing distance between the particular node and the transformer (235 V predefined). Thus, the lower curves (high voltage variation) refer to nodes that are at the rear end of the low voltage connection.

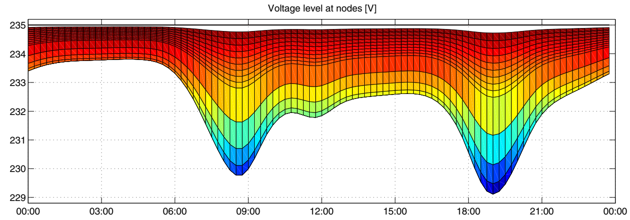

Figure 6: Simulated voltage levels at nodes in the rural low voltage grid

In the majority of our tests we weighted the usage of provided solar active power higher than the compensation of reactive power in the relevant grid segment. More clearly, in our analysis we came to the conclusion that the control of reactive power feed-in can be used meaningfully in low voltage grids in order to meet predefined voltage ranges and to maximize the supply of solar active power.

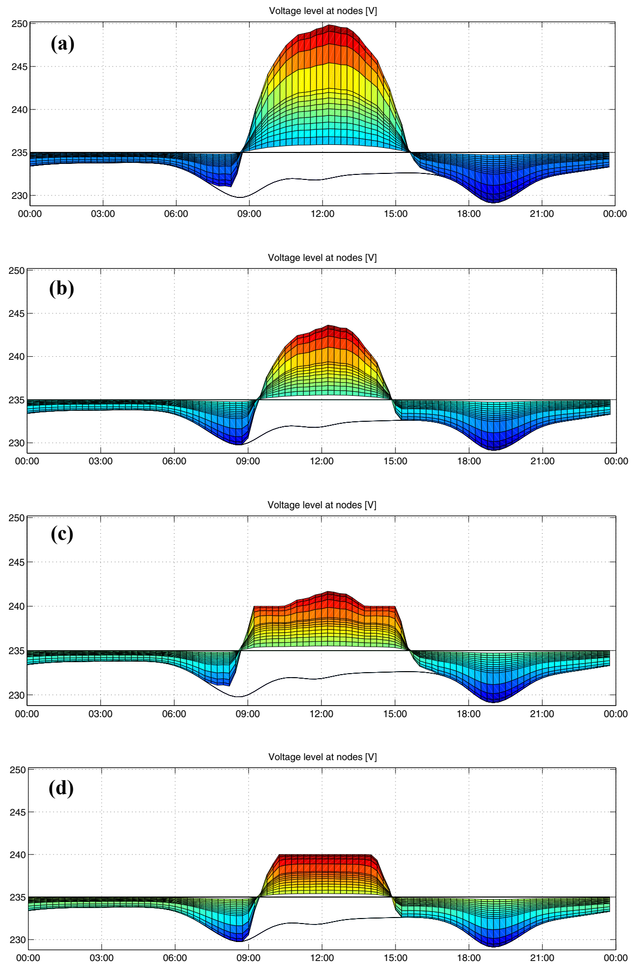

Figure 7: Simulated voltage levels at nodes in the rural grid, with uncontrolled feed-in (a), with controlled battery charging (b), with power factor adjustment (c), and with a combination of both (d)

Figure 7 shows exemplary results of the voltage variation in four simulated scenarios: In scenario (a) PV inverters feed their generated power into the grid without any control. Thus, the voltage increases close to the lawful limit especially at faraway nodes. In comparison to the traditional top-down energy supply, even reversed load flow occurs (U > 235 V).

In scenario (b) batteries are used to reduce voltage peaks caused by solar feed-in. Thereby, the charging strategy can be controlled by the BEMS depending on forecasts of consumption and supply of the individual building. The diagram presents the resulting voltage curves based on a constant battery charging power (2.6 kW). In this case, the control strategy ensures that the battery is fully charged at the end of the PV generation period. As a result, the voltage is constantly decreased during the time span of high PV generation.

However, scenario (c) does not contain batteries. The reduction of voltage peaks is realized by adjusting the power factor of the PV inverters in the simulated grid. The control strategy of each individual node is configured to keep the voltage at its grid connection point below a certain threshold (240 V). This threshold can be predefined or corresponding to a centrally provided target objective. During low PV generation in the morning and in the evening the inverter is able to provide enough reactive power to ensure the decentralized voltage constraint without reducing the feed-in of active power. As the feed-in of active power has the highest priority in our approach the voltage constraint is violated (> 240 V) during the period of high PV generation around midday.

Scenario (d) finally combines scenario (b) and (c) with the result that the voltage peak is decreased by battery charging and adjusting the power factor in parallel. Thereby, the control strategy is always able to comply with the given voltage limit (240 V). Hence, the application of both strategies provides most flexibility for the operation of the devices controlled by a BEMS, which uses forecasts for the optimization of the individual schedule. In this case, the BEMS is able to schedule charging of the battery and adjusting the inverter's power factor to comply with the requirements of the building and the grid (e.g., controlled by the DSO).

In summary, voltage quality can be improved by the integration of smart grid services. Nevertheless, some side effects have to be taken into account: E.g., by adjusting the power factor of photovoltaic inverters to increase the feed-in of reactive power, the load will increase on individual grid segments. Therefore, the regional selection of BEMS providing smart grid services must be carried out carefully.

For this reason, the corresponding current flows in the simulated grid with controlled feed-in have been analyzed for each connection between two nodes. Analogously to the voltage curves, the load varies depending on the corresponding apparent power. Thus, increasing the grid load (e.g., by power factor adjustment) must be weighed against improving the voltage quality and maximizing photovoltaic power feed-in.

As introduced in Section III, the potential of supplying grid services, e.g., the stabilization of low voltage grids, can be achieved decentralized using BEMS. The greatest potential lies in interconnecting the intelligent devices of a modern building into a prosumer that provides the opportunity of providing smart grid services to the grid operator as well as to the utilities. The BEMS realizes the decentralized operating strategy based on grid specific objectives.

By coordinating the operation of available systems in the building decentralized, BEMS are able to provide smart grid services according to the following basic control strategies:

a) *Restriction of feed-in power:* The most common control strategy for photovoltaic systems is the remote restriction of the maximum feed-in power during times of overproduction, voltage violations, or capacity constraints.

b) *Additional integration of storage:* The combination of photovoltaic systems with battery storage opens further opportunities for the reduction of feed-in peaks and the maximization of the consumption of locally generated energy.

c) Flexible adjustment of inverter's power factor: Especially to ensure voltage quality in rural power grids the power factor of an inverter can be adjusted locally to feed-in reactive power at certain grid nodes.

d) Integration of Demand Side Management Services: In conjunction with storage systems the load shifting potential provided by flexible loads and load management systems promises great potential in avoiding peak loads as well as critical voltage levels, whether high or low.

While other approaches (see Section II) mostly keep their power factor within lawful limits we considered or rather require a potential future change of regulations such that the full technical possibilities of inverters can be used. The necessity of knowing the grid state in order to define control objectives has to be discussed separately.

VI. Conclusion and Outlook

The results of several simulations with different operation strategies and grid setups demonstrate that *Distributed Energy Resources* (DER) have a huge impact on the power quality especially in rural grids with a high distribution of photovoltaic systems. Nevertheless, these systems can be used to provide smart grid services that ensure local voltage quality and grid stability. In our approach, the control of a large number of DER is aggregated by BEMS which are able to provide bidirectional communication interfaces for the DSO. In this setup, the potential of controlling DER systems is even increased by the combination with *Demand Side Management* (DSM) technologies and the integration of algorithms to predict load and feed-in. Thus, typical daily loads of devices can be shifted automatically to time slots with high solar irradiation and battery charging processes may be adapted.

In addition to the technical challenges for providing smart grid services, the continuous development and adaptation of regulatory guidelines is a major prerequisite for a successful integration of intelligent control mechanisms into the distribution grids. As of today, existing regulatory guidelines in Germany limit the technical options available for an intelligent integration of DER, although this may be revised in the future to cope with the new situation in low voltage grids.

Furthermore, new market models are essential to provide incentives for the decentralized operators. Today, the supply of smart grid services is not remunerated adequately. So there is very little incentive to invest in new technology which is able to provide smart grid services in a decentralized setting.

All in all, photovoltaic inverters have significant potential to provide smart grid services for low voltage grid stabilization, especially in rural areas. Additionally, it is reasonable to combine smart grid services and measures of DSM. The BEMS may provide the interface to the numerous signals and commands that are distributed by the DSO and combine them into a decentralized and cross-device optimization. In order to use the entire potential of photovoltaic inverters, modifications are necessary regarding technical interfaces, regulatory guidelines and market models. In particular, incentives for providing smart grid services to prevent the occurrence of grid problems and thus grid expansion have to be developed. Therefore, consumers have to be more closely integrated into future energy markets. The integration can be realized for individuals as well as for system service alliances, which are able to aggregate the supply of system services by several decentralized systems or buildings.

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