Distributed Ancillary Services in Smart Distribution Grids: Demand, Requirements and Benefits

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***Abstract* — The progressing distribution of the electricity supply necessitates redesigning the mechanism for providing ancillary services particularly by the distribution grid. Methods of voltage regulation and congestion management particularly have to satisfy new standards since, although the development of renewables is increasing the number of resources with an impact, these resources' individual contribution is comparatively slight. Taking the state-of-the-art and the basic regulatory conditions in Germany as a point of departure, this paper analyzes the requirements for algorithms and communication systems that provide distributed support to distribution grid operation. A novel mathematical method that prevents voltage range deviations and feeder overloads based on sensitivities is presented and validated in simulations by a case study. An analysis of the communications systems for monitoring and control technologies for distributed energy resources, including the available communication channels, serves as the basis for an evaluation of the suitability of current control mechanisms in the future. The findings of a live field test in a real 110 kV distribution grid corroborate the necessity for coordinated grid support by distributed energy resources and demonstrate the limits of current methods.**

***Index Terms* — Ancillary services, distribution network, active/reactive distributed power control, renewables integration, communication standards for distributed energy resources, live test.**

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I. Using distributed energy resources to support the grid

A. Introduction

Electrical grids and distribution grids in particular are currently undergoing a transition. Distributed sources, flexible loads and (stationary and mobile) storage systems will affect their operation in the future [1]. The growing number of distributed energy resources [2] will be operated primarily based on market factors [3]. This is the case in Germany in particular. Resources will supply energy at times when it is not necessarily expedient in terms of benefit to the grid and sometimes even detrimental to grid stability [4]. Distribution grids will have to be made smarter [5] and be able to use distributed electricity generation, loads and storage systems optimally for the current grid situation [6]. Distribution grid control centers will have to coordinate optimal operation and the requisite data exchange between control centers and distributed resources will have to be integrated [7], [8]. Good observability of the distribution grid will also be essential.

This paper presents the requirements that smart distribution grids ought to meet and methods for implementing them technically. Optimization algorithms and concepts for linking information systems of distributed resources are also presented. Although some aspects of observability are examined, readers are primarily referred to other literature.

B. State-of-the-Art Power System

An analysis of the situation in Germany reveals a rated generating capacity of 183.6 [9] at a peak demand of 82 GW. Around 94 GW (51%) of this rated capacity comes from renewable and thus distributed energy resources alone. They are supplemented by distributed energy resources operated with fossil fuels. The trend is toward an increasing share of renewables, thus making generation even more important on the distribution grid level [10]. For comparison, the rated capacity of storage systems

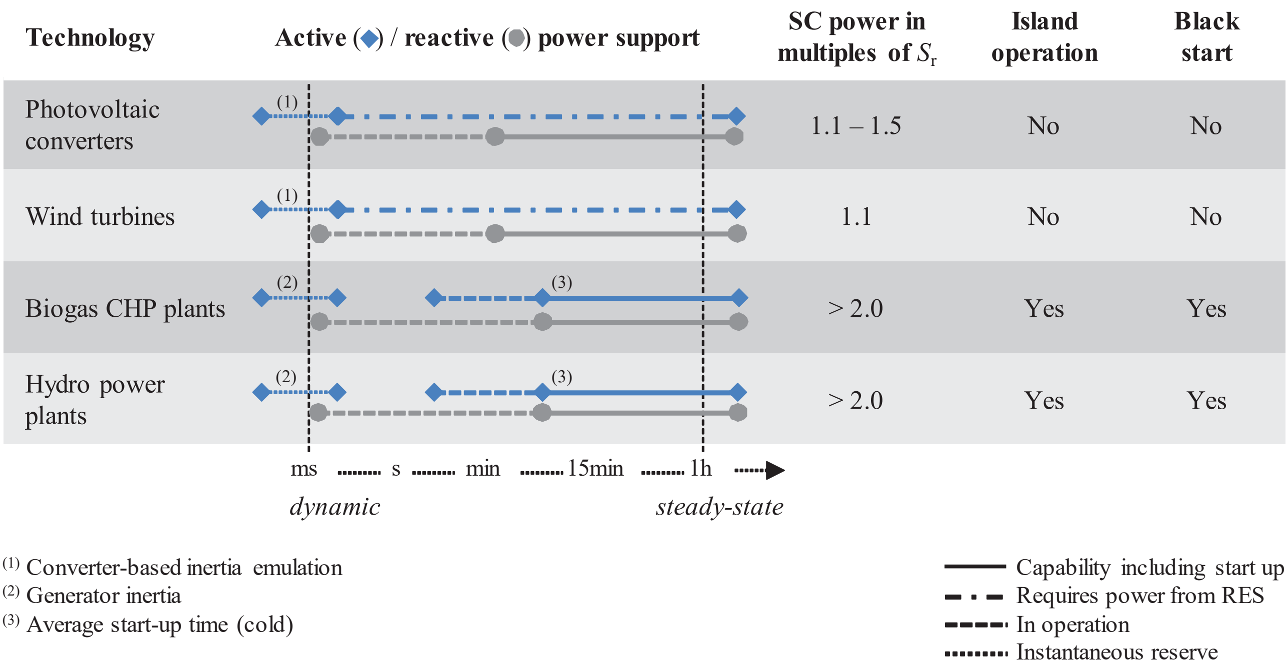

Fig. 1. Overall structure of the proposed aggregator.

is relatively low, the largest number being conventional storage systems such as pumped-storage power stations with 37 GWh in Germany [11], [12]. While technologies such as compressed air energy storage and battery systems are in use, their numbers are insignificant at present [13], [14], [15], [16]. Around 34000 battery energy storage systems with PV systems were installed in Germany in 2015. Assuming an average storage system has a capacity of 15 kWh, the total capacity of PV energy storage systems is approximately 510 MWh [12], equivalent to merely a fraction of energy storage capacities.

Distributed resources injecting power into the grid are primarily operated to maximize energy output and commercial profit. Benefit to the grid thus plays a subordinate role and grid operators can only take action to prevent equipment overloads in critical situations. In Germany, such actions are regulated in Section 13 of the Energy Industry Act [17]. This law stipulates that grid operators first have to perform appropriate switching operations, take market-related actions or activate additional reserves in order to ensure an electrical grid's reliability. Only when such actions are insufficient, grid operator may take-grid-related actions to curtail (the active power of) energy resources. Market factors are subordinate in this second step.

A grid operator usually takes action in the context of grid stability management, solely reducing the active power injected by resources [18]. Other potential capabilities of resources, e.g. supplying reactive power for voltage backup or microgrid capability, are not utilized at present. There is no regulatory and economic framework to offer system operators an incentive to provide resources for this. Moreover, sufficient measurements for system state estimation and thus suitable dynamic control algorithms for integration of distributed resources beneficial to the grid are not always available for grid operation.

C. Analysis of Ancillary Service Capabilities of Distributed Energy Resources

Relevant requirements ought to be listed first in order to assess distributed resources' capabilities. In principle, resources should be able to contribute to providing ancillary services [19] [20]. Their contribution is relevant on every level of the electricity supply and has increasingly to be covered by the growing number of distributed resources in the distribution grid. The typical features of each resource technology are crucial to capability. An overview of researchable capabilities beside storage systems as in [21] is presented in Fig. 1.

RES power plants are already able to supply active and reactive power within a very short time. Synthetic inertia emulation even enables converters to contribute instantaneous reserves [22]. Regardless of a resource size, they are not necessarily conditional on the availability of incoming power since power can be drawn from the intermediate circuit. Conventional generator systems still obtain this power from their inertia. Frequency support as well as grid restoration capabilities are nevertheless the domain of non-volatile resources alone [23], [24].

Reactive power is normally injected within a few grid cycles [24] regardless of its generation [25]. Increased use of converters decreases short-circuit power in the electrical grid. Protection necessitates usually limiting short-circuit current to 1.1 - 1.5 times the nominal current for [26], [27]. Only generator resources are able to supply much more nominal current [28].

Other services, e.g. supplying short-circuit current, improving power quality, and supplying microgrid capability and black-start capability, will presumably gain importance in the future. This will also generate new opportunities for the use of renewable and distributed energy resources, appropriate control algorithms having to be created and suitably adapted to the regulatory framework.

II. Active and Reactive Power Adjustment Beneficial to the Grid

A Three-Level Approach

An analysis can be performed on three different levels corresponding to the increasing contribution to ancillary services to utilize distributed resources capability to benefit the grid. On the simplest level, a distributed resource can be controlled so that it selects an optimized operating point at its connection point from the available measurements. To do this, the resource's local control system must continuously record voltage and frequency values at the connection point. These values are used to adjust the resource's operation to attain active and reactive power values that maximize system support based on the situation at the resource's connection point.

On the second level, the resource is run not only optimized, given the local connection point, but also with the goal of benefitting the grid in the section of the distribution grid with which it is connected. For voltage regulation, this can mean that voltage level is monitored along the grid branch (or ring) and distributed resources are controlled locally and regionally so that the voltage level has an optimal value within the grid branch (or ring). The active power supply is controlled in keeping with the requirements of the primary substation. Local and regional grid segments are incorporated for restoration of supply and microgrid capability to ensure a stable supply to these sections in the event of a malfunction.

The control of distributed resource on the third level goes beyond a local and regional analysis and is utilized to contribute to ancillary services in coordination with the primary grid. Direct or indirect communication must be ensured to transfer setpoints required for active and reactive power between primary grid operators and the particular resource, possibly in the form of a schedule. Whereas only the surrounding grid up to the primary substation is relevant for the operation of distributed resource on the other two levels, this does not constrain contributions to ancillary services on this level. Coordination with other distributed resources is essential to obtain optimal results since this maximizes the contributions to ancillary services [29], [30]. This requirement and the resultant requirements of requisite information and communications technologies (ICT) and coordination additionally makes this the most complex option of all.

The third level, which contributes most to global system stability, always ought to be striven for to stabilize operation. Moreover, the requirements of the two lower levels are taken into account during operation on these levels so that local and regional stability as well as the contribution to global ancillary services can be implemented.

B. Iterative Control Algorithm Using Sensitivity Analysis

An optimization algorithm that provides distributed support to the electrical grid is presented here. It ascertains an optimal setpoint value for individual resources in order to provide an ideal value for voltage response in the grid and to ensure that no equipment is overloaded. It is based on a method based on standard network theory, which depicts the distribution of flows of different resources between loads and lines. Approaches based on demand response using sensitivity matrices have been studied in [31]. Priority is given to renewable energy sources. Network structure parameters can employ diversity factors to identify the power diversity. This method can be used for economic dispatch and power flow analysis.

The active and reactive power adjustment necessary in each case is determined based on the Jacobian matrix J determined with the Newton–Raphson method for power flow studies. This matrix depicts the correlation between the active and reactive power buses and the electrical system state variables (voltage magnitude U and angle θ):

$$\begin{bmatrix}\Delta \boldsymbol{P} \\ \Delta \boldsymbol{Q}\end{bmatrix} = \begin{bmatrix} \boldsymbol{J}_{P\theta} & \boldsymbol{J}_{PU} \\ \boldsymbol{J}_{Q\theta} & \boldsymbol{J}_{QU}\end{bmatrix} \begin{bmatrix}\Delta \boldsymbol{\theta} \\ \Delta \boldsymbol{U}\end{bmatrix} \quad (3)$$

The following correlation results for the influence of purely reactive power control on the bus voltage level:

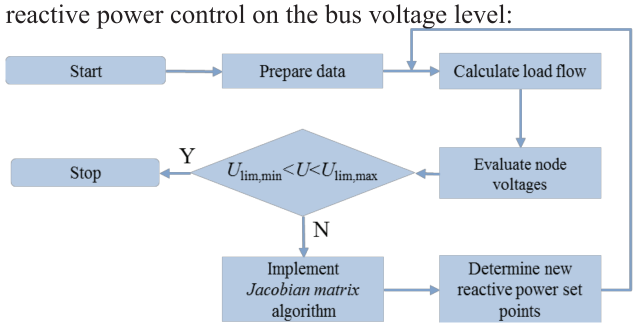

Fig. 2. Iterative optimization method for grid support

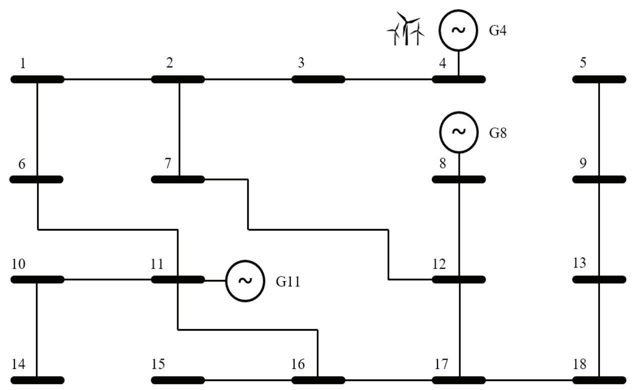

Fig. 3. Distribution grid structure for the field test

$$\Delta\boldsymbol{Q} = \left(\boldsymbol{J}_{QU} - \boldsymbol{J}_{Q\theta}\boldsymbol{J}_{P\theta}^{-1}\boldsymbol{J}_{PU}\right) \cdot \Delta\boldsymbol{U} = \boldsymbol{J}_R \cdot \Delta\boldsymbol{U} \quad (2)$$

The influence of reactive power control $\Delta\boldsymbol{Q}$ in the grid area analyzed can consequently be ascertained by inverting $\boldsymbol{J_R}$ according to (X).

$$\Delta\boldsymbol{U}=\boldsymbol{J}_{\boldsymbol{R}}^{-1} \cdot \Delta\boldsymbol{Q} \quad (3)$$

The coefficients in the matrix $\boldsymbol{J}_{\boldsymbol{R}}^{-1}$ indicate which buses have the greatest sensitivity to other buses, a higher value indicating a greater correlation. An analogous approach can be applied to active power control.

The optimization function is flowcharted in Fig. 2. The algorithm uses the Jacobian matrix in every iteration to verify the voltage values. In the event of voltage problems at the system buses, the reactive power adjustment is retrieved selectively until the grid malfunction has been eliminated. This algorithm runtime has proven practicable in tests since it completes the calculation in 0.5 s. This applies to the analyzed grid computed on a standard computer. It can be scaled up for larger systems. This also makes the algorithm suitable for operative use by CHPs controlled with parameters for a control strategy considering forecasts in less than one second [32].

C. Simulation Evaluation

Since thresholds were not exceeded during the entire period, the control algorithms did not automatically activate. Different operating points were therefore created in an 18-bus test system (see Fig. 3) to verify the algorithm developed to regulate voltage. At the start of every scenario, every dispatchable generator (at buses 4, 8 and 11, designated G4, G8 und G11) is assumed to supply 10 Mvar of reactive power. The outcomes of the simulations are presented in Table 1. Supplying reactive power stabilizes high voltage more efficiently. Adjusting active power would additionally entail undesired actions in the electricity market.

The simulation results presented in Table I (scenarios 1 to 6) confirm the optimization algorithm effectiveness. In scenario 1, generator G8 is selected to support the grid actively by supplying reactive power. The reactive power setpoints are adjusted to 1.13 Mvar. The voltage at bus 1 has already returned to the feasible value of 1.1 pu after the third iteration. Similar effects are observable in scenarios 2, 3 and 4. In the latter, generators with low sensitivities are additionally included for support since the technical limits of G8 have been reached. The number of iterations needed to calculate new setpoints rises to eleven loops. Scenarios 5 and 6 confirm the method effectiveness even when voltage is unduly low. Increase in reactive power at G4 and G8 also eliminates the stability problem.

D. Remote Control and Monitoring of Distributed Energy Resources

1) Introduction

Distributed energy resources integrated in an existing grid have to meet standard technical specifications and communications interface specifications, thus ensuring that they can be monitored with sufficient accuracy and time resolution, and controlled when necessary [33]. The interface of communications systems has to be designed accessibly so that different systems are interoperable [34]. Using open standards and standard interfaces is expedient [35], [36]. Practicable methods for this are presented below.

2) IEC 60870 and IEC 61850 Interface

Established and advanced remote control protocols such as IEC 60870 and IEC 61850 improve distributed resources' interface [37], [38]. This enables every relevant measurement to be continuously transmitted to a control center [39]. Any setpoint value desired can also be implemented within the limits of a particular resource technical capability. This means that both active and reactive power setpoint values can be varied dedicatedly in fine steps [40]. For instance, power electronic converters in advanced wind and PV systems can contribute substantially and flexibly to the local supply of reactive power. This can only be activated for grid operation with a proper communications interface, though. Although advanced and large resources have such interfaces, grid operators do not take full advantage of them at present [41]. Moreover, since the number of resources equipped with interfaces is very limited, conventional solutions still have to be employed.

Table 1. Simulation results

Before optimization			**After optimization**					
Scenario	Min. bus voltage in pu.	Max. bus voltage in pu.	Q_{G4} in Mvar	Q_{G8} in Mvar	Q_{G11} in Mvar	Min. bus voltage in pu.	Max. bus voltage in pu.	Iteration
1	U_{17} = 1.028	U_1 = 1.102	10.00	1.13	10.00	U_{17} = 1.028	U_1 = 1.100	3
2	U_{17} = 1.028	U_1 = 1.107	10.00	-22.65	10.00	U_{17} = 1.028	U_1 = 1.100	7
3	U_{17} = 1.028	U_1 = 1.108	10.00	-29.64	10.00	U_{17} = 1.028	U_1 = 1.099	8
4	U_{17} = 1.028	U_1 = 1.114	3.49	-30.00	-10.00	U_{17} = 1.028	U_1 = 1.099	11
5	U_1 = 0.899	U_{17} = 1.028	10.00	18.25	10.00	U_1 = 0.901	U_{17} = 1.028	2
6	U_1 = 0.885	U_{17} = 1.028	40.00	30.00	10.00	U_1 = 0.900	U_{17} = 1.028	7

3) Grid Stability Management Interface

Since the majority of distributed resources can only be controlled by a grid stability management interface, upgrades of installed equipment must be allowed. Such an upgrade enables the transmission of current measurements so that previously "blind" control systems of resources also deliver current measurements by wireless control signal and the grid operator is immediately notified of the resource's response. Even though this interface only facilitates relatively rough control of active power, while not permitting any control of reactive power, it improves the use of distributed resources to apply the aforementioned algorithm.

The additional technology that has to be installed to implement this control system and to transmit measurements basically consists of an additional current and voltage transformer measurement logger and an interface to the existing grid stability management interface, which normally consists of four main switching contacts. Every contact corresponds to one of four stages (100% - 60% - 30% - 0%). Conventional control systems (programmable logic controllers) provided by remote control interfaces can both log measurements and connect switches. MODBUS/TCP, IEC 60870, IEC 61850 or DNP3 can be used as the communications protocol for a remote control interface, thus enabling the grid operator to access resource parameters directly. A biomass CHP plant serves as an example in the design for upgrading existing resources diagrammed in Fig. 4.

4) Adding RTUs

Retrofitting with an RTU is a more flexible but also more expensive way of equipping an existing resource with a suitable remote monitoring and control system than that described in section 3). An additional RTU provided by such interfaces as IEC 61850 and IEC 60870 is subsequently integrated in the distributed resource's process control system. Normally, this is done by using Profibus, CAN bus or EtherCAT to link the retrofit RTU with the distributed resource's existing process control system. This makes the retrofitted RTU a gateway that exchanges defined data (measurement and setpoint values) between the resource's process equipment and the grid operator's remote control system. The RTU must be carefully configured since, in the worst case, direct access to the resource control system can damage the resource if the RTU has been configured incorrectly. The grid operator has to configure and test the IEC 61850 or IEC 60870 interface based on the resource features and the specifications.

E. Selecting Appropriate Communication Channels

1) Dedicated Lines through Grid Operators

A line installed by the electrical grid operator and dedicated to transmitting the resource measurement data and setpoint values can be used to connect distributed resources. This is a state-of-the-art approach to interfacing the communications system of substations but is inconsistently employed for distributed energy resources. The advantage of this approach is its provision of a very reliable interface explicitly established for this purpose, which is highly reliable and available. The relatively high installation costs are a drawback.

2) Public Network DSL or ISDN Line

The advantage of using existing lines of operators of public telecommunications networks such as DSL or ISDN is that they are already virtually ubiquitous and can be used to connect distributed resources. A landline telecommunications infrastructure may inadequately cover rural regions where the majority of distributed resources are installed. While ISDN lines and DSL suffice for the quantities of data normally transmitted, they may also be used for other public communication purposes, thus causing congestion. A factor viewed critically by grid operators in particular is property rights to the respective lines and thus also monopolies on lines. This can cause trouble in the event of a malfunction. Data security is more serious. Since public telecommunications networks are physically linked directly with the public Internet, actions have to be taken to prevent unauthorized access to the resource's or the grid operator's data network. Complex security measures and gateways have to be planned between the grid operators' internal network and the public network.

3) Mobile Broadband

Along with landline public telecommunications networks, public cellular networks can also be employed to monitor and control distributed resources. Since this does not necessitate installing additional lines to the particular resource, the capital expenditures are relatively low. This communication channel is the most unreliable in practice though. Cellular coverage may be inadequate in rural regions and is heavily dependent on weather conditions. Packets may be transmitted incompletely or the transmission bandwidth may not suffice at times, depending on the connection quality. Since this telecommunications network is public, the security constraints and associated additional security measures for landline public telecommunications networks also apply (see section 2)).

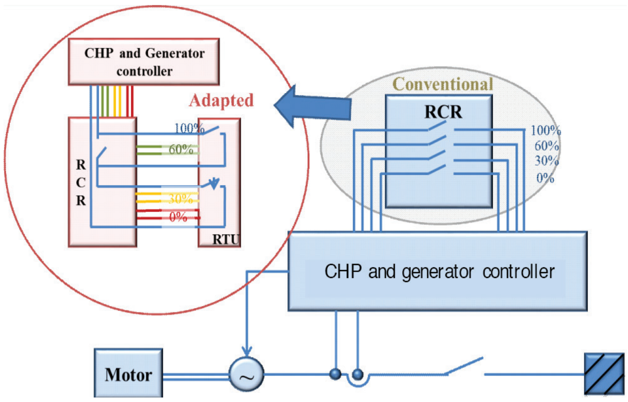

Fig. 4. Interface design.

4) Selections in Comparison

The relevant features of the different technologies are compared in Table II.

5) Future Communication Channels

Additional communication channels can be expected to gain importance in the future. Power-line communication systems, for instance, can transmit data from a distributed resource to the nearest substation where other technologies forward them. This approach could grow more prevalent in the future [42], [43], [44], [45].

Efforts are also made to regulate radio frequency bands dedicated to transmit data for electrical grid operation [46]. Frequencies of 400 MHz and 450 MHz that provide a channel bandwidth sufficient to transmit a sufficient payload are especially relied on here. The band frequency should be low enough to expand physically (with appropriately low free-space path loss) to connect to respective distributed resources reliably.

III. Practical Limits of Active Power Adjustments

A. Field Test Environment

A 110 kV voltage section of an 18-bus distribution grid (see Fig. 3) served as the field test area. The grid is highly saturated with RES (160 MW of wind and 40 MW of photovoltaic power) and has a peak load of 220 MW. An 80 MW wind farm was used to test actions using active power to stabilize voltage. Two high voltage transformers connect it with the grid. The large electrical distance to the 110/380 kV connection point (bus 14) minimizes influences from the high voltage system.

Voltages were recorded directly at the wind farm connection point U_4 to analyze the effects of active power control on the rest of the grid and additionally at substation U_2 approximately 20 km away. The wind farm is represented by generator G4.

B. Findings

The recorded curves of the incoming power supplied by the wind farm and the related voltage values at the wind farm U_2 and at the adjacent station U_2 are presented in Fig. 5.

The active power was curtailed when the load was low for monetary reasons. The control signal was sent at t_1 = 30 min. Instruments verified the complete cessation of active power injection after about 4 min. The curtailed power was 8.1 MW and accompanied by a voltage drop of 0.3 kV at both the connection point and the nearby substation. The grid stability management interface was reactivated at t_2 = 40 min.

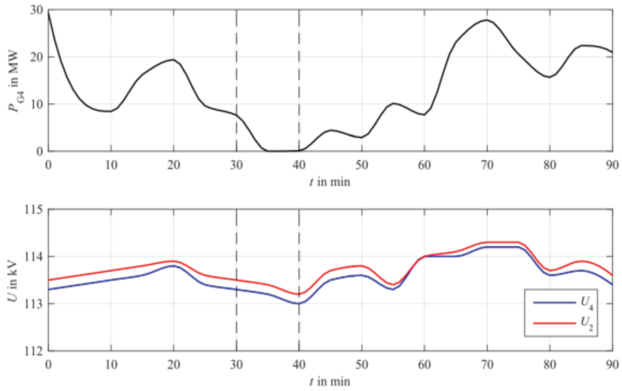

Fig. 5. Active power and voltage curve in the field test.

C. Evaluation

A correlation k [47], [48] of the voltage curves with the active power curve can be discerned. The mathematical correlation factors of the active power P_{G4} with the voltage at the wind farm connection point U_4 or the active power P_{G4} with the nearby substation voltage U_2 at bus 2 are as follows:

$$k_{PG4-U4} = \frac{\sum_{i=1}^{n}\left(P_{G4,i} - \overline{P_{G4}}\right)\left(U_{4,i} - \overline{U_4}\right)}{\sqrt{\sum_{i=1}^{n}\left(P_{G4,i} - \overline{P_{G4}}\right)^2 \cdot \sum_{i=1}^{n}\left(U_{4,i} - \overline{U_4}\right)^2}} = 0{,}84 \quad (4)$$

$$k_{PG4-U2} = \frac{\sum_{i=1}^{n}\left(P_{G4,i} - \overline{P_{G4}}\right)\left(U_{2,i} - \overline{U_2}\right)}{\sqrt{\sum_{i=1}^{n}\left(P_{G4,i} - \overline{P_{G4}}\right)^2 \cdot \sum_{i=1}^{n}\left(U_{2,i} - \overline{U_2}\right)^2}} = 0{,}73 \quad (5)$$

Factoring in a potential range of the correlation factor from -1 (completely negative correlation) to 0 (no correlation) to +1 (completely positive correlation), the field test demonstrated that:

1. the active power control influences voltages both at the connection point and in the nearby grid,
2. the voltage effect diminishes greatly as distance increases, and
3. although an active power variation–voltage causality is

Table 2. Telecommunication technologies in comparison.

Parameter	Dedicated network operator lines	Public lines (ISDN, DSL)	Public wireless (GPRS, UMTS, LTE)
Availability (space)	Limited	High	Variable
Availability (time)	Constant	Very high	Variable (weather-dependent)
Reliability	Very high	High	Low
Cost	High	Medium	Low
Security	Very high	Low	Medium

present, its impact is unduly low.

Consequently, the standard grid stability management interface is "not suited" for limiting active power. On the one hand, economic losses ensue since available renewable power cannot be injected into the electrical grid. Therefore, additional battery storage systems could be used to minimize impacts [49]. On the other hand, the simulation tests have demonstrated that smart and coordinated reactive power control by distributed resources has a greater impact on the grid while keeping costs the same.

IV. Conclusion

The capabilities of renewable energy plants and distributed energy resources to play a role in certain ancillary services was scrutinized and the technical, communication and regulatory requirements for this were analyzed. Capabilities to eliminate voltage problems by adjusting reactive power in selected resources while minimizing the impact on ongoing grid operation and not taking market-related actions were presented in simulations. A field test demonstrated the technical limits of conventional curtailment of renewable energy plants. The moderate influence of unilateral control of active power on voltage as well as the shortfall renewable energy at equal cost caused by it was decisive.

An increasing response to critical situations directly at the local level and with more intensive coordination (among distribution grid operators as well) will therefore be expedient in the future. This approach will guarantee a globally optimized result while minimizing the impact on grid operation and components [50]. Advanced renewable energy plants already have the technical capabilities to implement fine operating points while employing advanced communications standards [51], [52]. More intensive monitoring of low voltage levels and the use of available communication channels to interface field devices are therefore an important prerequisite for a more dynamic and accurate control system [53]. Germany requires few regulatory changes to implement such a system. Part of the standards have already been incorporated in amendments (e.g. to the 2017 German Renewable Energy Act [19]) and regulations (e.g. 2015 Regulation of Ancillary Services by Wind Turbines [54]).

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Mathematical Symbols

k	Correlation factor
J	Jacobian matrix
P	Active Power
Q	Reactive power
S	Apparent power
t	Time
U	Voltage

Abbreviations

CHP	Combined heat and power
DER	Distributed energy resource
DSL	Digital subscriber line
DSO	Distribution system operator
EEG	Erneuerbare-Energien-Gesetz (German Renewable Energy Sources Act)
GPRS	General Packet Radio Service
ISDN	Integrated Services Digital Network
LTE	Long Term Evolution
RCR	Remote Control Relay
SDLWindV	Verordnung zu Systemdienstleistungen durch Windenergieanlagen (Regulation of Ancillary Services by Wind Turbines)
TSO	Transmission system operator
UMTS	Universal Mobile Telecommunications System

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