AREAL POWER PLANT: AGGREGATION SYSTEM TO CONTROL A MULTITUDE OF DISTRIBUTED GENERATORS DURING POWER SYSTEM RESTORATION – DEMONSTRATION RESULTS

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Keywords: POWER SYSTEM RESTORATION, ACTIVE DISTRIBUTION GRID, DISTRIBUTED GENERATORS, PHOTOVOLTAIC, DISTRIBUTION MANAGEMENT SYSTEM

Abstract

Power system restoration (PSR) is an unlikely but critical event, that requires new approaches to cope with increasing shares of distributed generators (DG) like photovoltaic (PV), especially in low- and medium-voltage grids. One possible solution to tackle this challenge, a so called *"Flächenkraftwerk"* / areal power plant (APP), will be examined in its prototype stage. The core idea behind an APP is the provision of large(r) scale power plant characteristics with aggregated DG especially during PSR. For testing the APP it has been deployed in a virtual laboratory (virtual lab) including PV emulators which are capable to simulate active power behaviour as well as ICT aspects. Furthermore, the virtual lab has been manually interlinked with a proven training system for control centre personnel to allow the look and feel of a real restoration situation. The main result of two extreme scenarios, a worst case scenario with no DG remote controllability and a best case scenario with partial controllability, shows the APP's capability to allow a higher re-supply of loads if the assumed high PV feed-ins occur. Therefore, the APP could be a cornerstone of future PSR in PV dominated regions if the DG's bidirectional remote controllability increases.

1 Introduction

In the extreme rare event of a supraregional blackout, the network has to be restored from the scratch. The electricity market is then suspended, and the personnel in the grid operator control centres obtain time limited extra authority to allocate the power plants according to technical possibilities and necessities [1], [2], [3], [4]. First, black-start capable power plants energise predefined island grids. Further power plants will be started up and the grid islands will be synchronised with each other if possible in order to combine active power reserves and thus to improve frequency maintenance [2].

The connection of uncontrolled distributed generators (DG) with fluctuating feed-in power can have an impermissibly strong influence on the frequency during power system restoration (PSR) and lead to the disconnection of generation and / or load, which is why ICT connection to the DG becomes more and more important [5]. This is becoming increasingly relevant in Germany, as around 2.3 million photovoltaic (PV) systems with a total capacity of around 34 GW are already connected to the German low-voltage grid and around 62 GW in total today [6], [7], and according to the current legislated targets for climate-neutral electricity generation, an installed PV capacity of around 215 GW until 2030 and 320 GW by 2037 [8] or even 450 MW [9] can be expected. Accordingly, PV systems connected to the German low-voltage grids will be able to fully supply the domestic load on sunny days. If these plants cannot be controlled by the grid operator and do not behave in a grid-serving manner, PSR on sunny days will be almost impossible.

In order to be able to use the large number of DG connected to the low- and medium-voltage (LV / MV) grids in a targeted manner during PSR and thus support the restoration process, a system is needed for the targeted condensation of information on plant status and power forecast as well as for coordinated unit control. An operating software with graphical user interface (GUI) has been introduced as a part of an ICT solution in 2020 [10]. Meanwhile, the development of the backend as a central information processing and control platform took place. In addition, the development of a large number of PV unit emulators enables extensive testing possibilities under approximated realistic conditions within the framework of a virtual laboratory (virtual lab). The application possibilities as well as the operability of the system could be demonstrated by means of an operationally realistic PSR situation using a training system for grid operation management personnel.

This paper was presented at the 21st Wind & Solar Integration Workshop and published in the workshop's proceedings.

Chapter 2 describes the methodology and presents the aggregation system, the virtual lab, the training system and the covered scenarios. Chapter 3 explains the basic procedure within the situation and gives the results for the worst case and the best case scenario. Chapter 4 discusses the results while Chapter 5 closes with a conclusion and an outlook.

2. Methodology

For performing the demonstration of a PSR situation from the operation perspective, three key components are required. First, the developed aggregation system itself, secondly, an infrastructure to run it including connected PV emulators in the form of a virtual lab, and, at last, a proven grid operator training system has been applied. All three will be introduced in the following sub chapters. Finally, this chapter concludes with a description of the chosen restoration situation that has been used in the demonstration.

2.1 Areal power plant (APP)

As in [10] introduced the aggregation system, or as it is called in German, *"Flächenkraftwerk"* / areal power plant (APP), can be seen as an addition to a traditional distribution management system (DMS). Thereby the developed APP prototype allows in its current state of development different features comparable to "system monitoring" as well as "control actions" functionalities of a DMS. With regard to the first one, it primarily allows an overview over selected predefined areas, like post code areas or grid areas. Relevant information can be the current feed-in of controllable PV units or forecasts e.g. from the load or the residual load.

In the case of DG, like PV, the APP follows a specific concept of categorization [10] (see Figure 1):

1. Category A units are DG without the ability to remotely observe and perhaps even control the units. This definition includes unidirectional links like ripple control.
2. Category B units are equipped with a bidirectional remote control. However, the link is currently not available.
3. In contrast, DG of category C are currently controllable in principle e.g. due to the existence of an uninterruptible power supply (UPS) even so a power outage situation at the DG location occurred, or the communication link is available again after a certain time after voltage recovery.

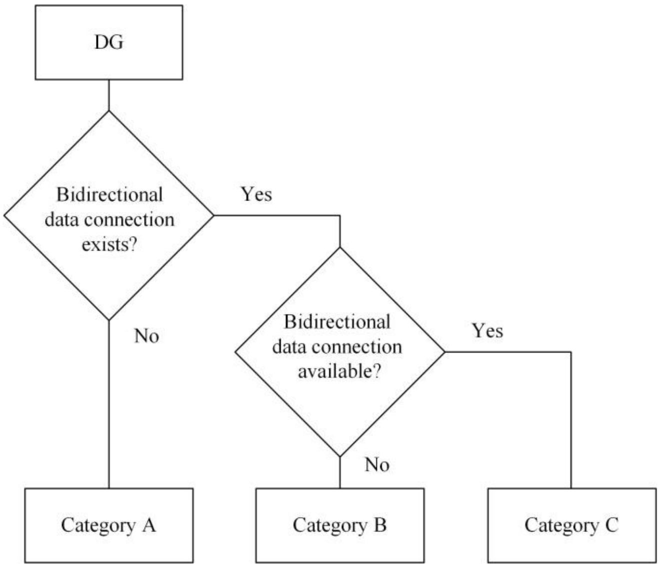

Figure 1: Distributed generation (DG) categorization regarding remote controllability (sourced from Fig. 3 in [10])

With this concept in mind the APP allows the display of selectable information like the mentioned forecasts or current power flows via a web-based GUI as depicted in Figure 2.

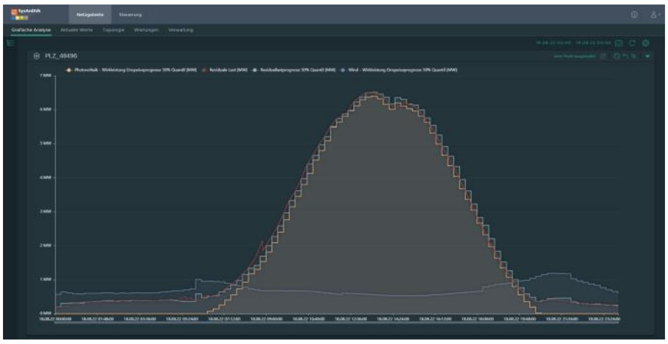

Figure 2: GUI of the developed areal power plant – monitoring interface

With regard to the second covered main functionality of a DMS, "control actions", the APP is capable to receive control personnel input. Relevant for the following system demonstration is the option to define the desired residual load of a single or multiple grid areas (in MW). Moreover, as an option, the operator can decide which ramp the residual load should follow while a set-point is active (in MW/min). The following GUI will be used for this action (Figure 3):

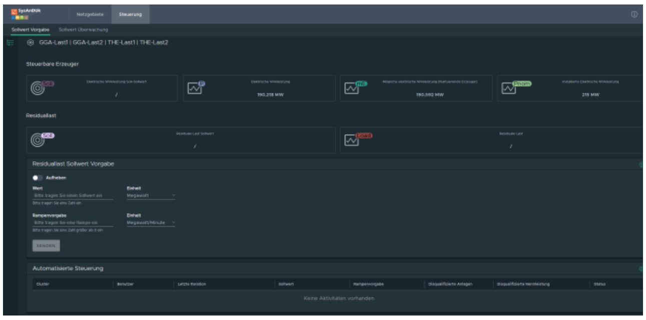

Figure 3: GUI of the developed areal power plant – control interface

To follow the set residual load, the APP applies a disaggregation algorithm in an open-loop control. Its main objective is the optimal distribution to the DG units to fit the target residual load based on the potentials of these DG units. If an imbalance between the set and actual residual load is seen by the APP, DG of category C will be dispatched accordingly. Hereby the following approach is applied in a 30 s cycle:

At first, only on-off-units are switched on or off to offset the current target-actual deviation, secondly, units via a stepped control (e.g. 0 %, 30 %, 60 %, 100 %), thirdly, fully controllable units but with a minimum technical power output greater than zero are shifted as much as required, and, if not enough capacity has been available so far, fully controllable units will receive a signal. Additionally, each unit in the four stages is sorted by the time period since a control signal has been received. As a result, the units that have not been used for the longest time are preferred.

2.2 Virtual Lab

The virtual lab itself is a "Kubernetes"-cluster [11] managed by the software tool „Rancher" [12]. It consists of five workers (nodes) with the following specifics:

1. High-performance worker node: 32 vCPUs from Intel® Xeon® Gold 5220 2.20 GHz, 126 GB DDR4 ECC RAM with 3200 MHz
2. Other four nodes: 8 vCPUs from Intel(R) Xeon(R) Gold 5220 2.20 GHz, 48 GB DDR4 ECC RAM with 3200 MHz
3. An additional central network attached storage: 105 TB hard disk drive

On this infrastructure runs the APP as well as 320 PV-emulators. While the APP runs on the high-performance node, the emulators are grouped together as a total of 40 emulators in one application to reduce the container overhead on the cluster resources. During their run time Kubernetes orchestrates them on the remaining worker nodes.

Each PV-emulator of the total 320 is especially capable to simulate information and communication technology aspects as well as limited active power behaviour. In detail the following ones are possible to be considered. For each of them the chosen configurations are listed below:

- A Modbus TCP interface between each PV unit and the APP, in this case the common "Modbus TCP DPM interface" of Solar Log GmbH [13] within the PV sector has been applied (APP's request rate: 1 s),
- Communication link availability: Full availability assumed over the entire demonstration (category C units),
- Signal latency: Normal distribution with a mean value of 2 s,
- Installed active power per emulator: 625 kW,
- Control capabilities of the unit (e.g. fully controllable or only limited due to a minimal power output): Only on/off units, meaning that only 0 % or 100 % active power output can be requested,
- Available power profile in 1s resolution: Strongly simplified constant profile of 90 % of installed power to mainly reduce the amount of human actions that is required for the manual data transfer between the APP and the simulated control centre system,
- Grid connection status: All PV units are disconnected at the beginning of the scenarios,
- Synchronisation time after a power outage: 10 s,
- Power gradient after synchronization: 300 % of nominal power per minute for 50 % of the PV emulators to represent older units without any grid regulation restrictions, and a 10 % gradient for the remaining ones. At this point capabilities of newer PV units are taken into account.

To configure and control each PV emulator, a representational state transfer (REST) application programmable interface (API) has been developed. Via the REST-API it is possible e.g. to stop or start an emulator as well as to set-up a predefined power profile. During the demonstration the most important API feature is the option to change the grid connection status via a REST call. Specially, from a disconnected to a connected status when selected grid areas have been re-energized.

2.3 Training System

For the real-life demonstration of the APP application in the context of power system operation, an operator training system is used. The training system briefly consists of a control room replica including SCADA/EMS functionalities, a power system replica and dynamic models representing the power system performance delivering the control centre view [14],

[15]. The implemented generation models are feasible to represent conventional as well as wind and PV units.

In the power system replica PV units installed on the low voltage level are clustered and represented as APP connected to the mid voltage level. The APP controller application is installed on mid voltage level of the high voltage/mid voltage transformers. The control options are implemented in the control centre's human machine interfaces. Using this setup delivers the look and feel to integrate APPs in power system operation.

2.4 Restoration Situation

Figure 4 shows the generating units and loads used for the restoration situation. The grid consists of a 110 kV high-voltage grid whose connections to the transmission grid have been opened. Two black-start capable gas turbine power plants (GPP), each with a rated power of 50 MW, can energise the grid. An urban medium-voltage grid with feedback-free load is connected to the high-voltage grid by three substations. Furthermore, there are other subordinate regional grids which are PV-dominated and thus feed power back into the high-voltage grid when there is sufficient solar irradiation. There are two regional medium-voltage grids in which an APP is installed, meaning that the PV-units can be controlled in feeding in active power, while this is not the case in the six other regional grids.

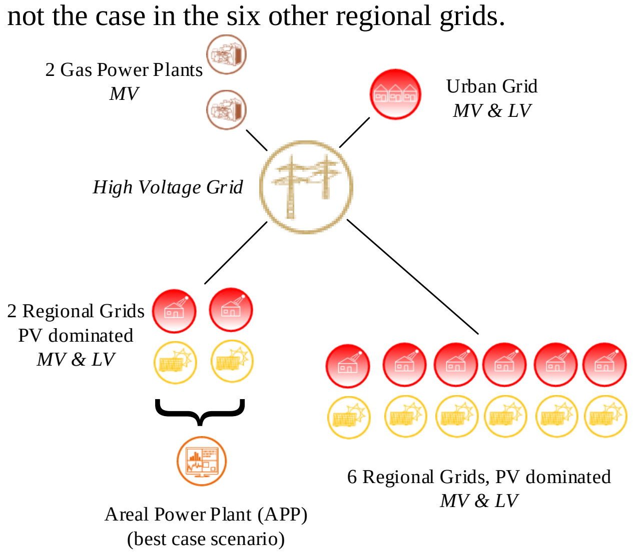

Figure 4: Restoration situation (simplified grid representation)

Each subordinated grid is connected to the high-voltage grid via a substation consisting of two transformers. All circuit breakers within the high-voltage grid can be operated via remote, which is also the case for the medium voltage feeders inside the substations. Table 1 provides the available power within the different grid areas. Since the objective of the investigations is to identify the possibilities arising from the application of the APP, the forecast error is ignored here and the forecast is assumed ideal.

Table 1: Available power of load and generation within the different grid areas

	Urban grid	Regional grid		
		Total	**With APP**	**W/o APP**
No. of substations	3	8	2	6
Load in MW	50	262	85	177
PV in MW	0	468	180	288
Wind in MW	0	0	0	0

3 Results

3.1 General Restoration Procedure and initial Situation

In the selected situation, the GPP are black-start capable and they are the only grid-forming generation units. They operate in power control with superimposed frequency droop of 5%, so that in parallel operation after a load connection, the additional load is distributed equally between the two power plants.

First, one GPP energises the grid. To increase the power reserves and thus gain room for manoeuvre, the second GPP is synchronised. Then load is reconnected in the regenerative-free urban grid, so that the operating point of the GPP is at half their nominal power and thus positive and negative control reserve are equally available. This represents the initial state for the following two scenarios, in which further loads are resupplied in order to the technical and operational possibilities. In the first one, not a single PV-unit is controllable, meaning that the two grids equipped with the APP are not used in the worst case scenario. However, they will be used in the second one, the best case scenario.

3.2 Results Worst Case Restoration Scenario

Figure 5 shows the initial situation and the frequency and power curves for the worst case scenario. At the beginning, the urban grid with 50 MW is the only load (turquoise) that is completely supplied by the GPP (black). The operating point of the GPP provides symmetrical control reserve.

When a feeder is connected, the load initially increases, and as a result, the frequency is reduced and settles at a lower value (red). As the PV-units connected to the feeder are not controllable, they reconnect automatically a certain time after voltage recovery and increase active power feed-in up to the maximum possible value according to the availability of solar radiation (yellow). As a result, the GPP reduce active power feed-in. This is repeated with the connection of each feeder. By relieving the GPP, the frequency in the network increases, which is meanwhile brought back towards the nominal value of 50.00 Hz by pre-setting new power set-points for the GPP.

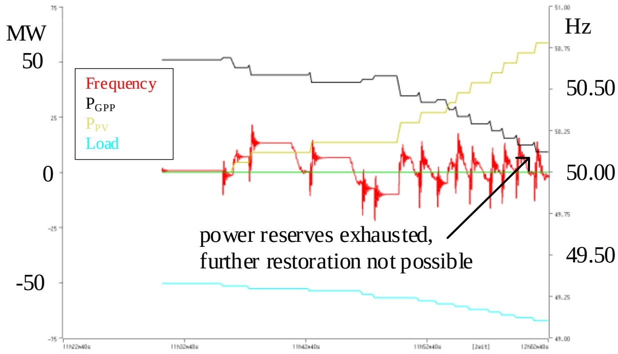

Figure 5: Simulation results of the worst case scenario

Once the 13th feeder has been reconnected, the GPP are relieved to such an extent that they have reached their minimum technical capacity and it is no longer possible to connect further PV-dominated areas. So, restoration has come to its end for this scenario, and loads with a capacity of only 70 MW out of around 310 MW could be resupplied.

3.3 Results Best Case Restoration Scenario

The best case scenario differs from the previous one in that two subordinate regional grids are equipped with an APP. As soon as this system is activated, the residual load at the substation between the regional grid and the high-voltage grid is controlled to a given set-point in dependency of the available plants and capacities.

Figure 6 shows the curves for load (turquoise), PV generation (yellow) as well as the residual power (orange) and its set-point (violet) for one area equipped with an APP. Initially, the areal power plant is deactivated and reconnection of the first two feeders shows the already seen behaviour: increasing of load followed by a delayed reconnection of the PV-units.

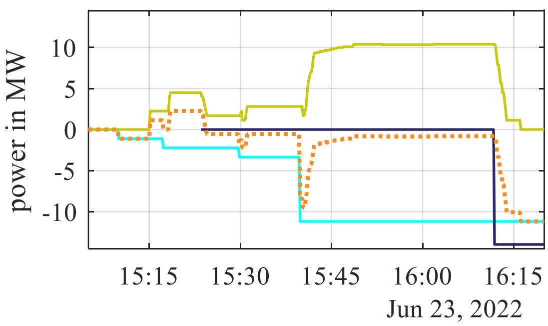

Figure 6: Simulation results for the best case scenario, regional grid with an APP

At around 15:25, the system is activated and a set-point of 0 MW for the residual load is provided (violet curve). As a consequence, the system reduces PV-power feed-in by providing new set-points to different generating units.

In the following, at 15:30 one and at 15:40 seven more feeders are reconnected. The residual load first shows a peak due to the reconnected loads, and after a few 10 seconds, the APP has brought back residual power closely to the set-point. The remaining control error can be explained with the discrete nominal power of the PV generating units (emulators).

At around 16:10, the set-point was set to 14 MW load for overriding reasons. As a result, the APP sets the feed-in power of all PV units to zero, and the residual load corresponds to the actual load after about two minutes.

Figure 7 shows the results of the best case scenario for the whole grid. The feed-in power of the GPP is drawn in black, the yellow curve shows the total PV power, and the turquoise curve represents the total load, while the frequency in the grid is drawn in red.

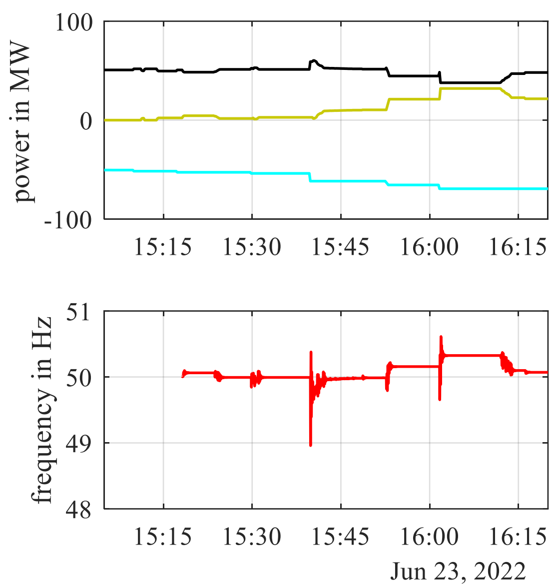

Figure 7: Simulation results for the best case scenario, whole grid

While reconnection happens only in the regional grid with the APP (until 15:50), the steady state power of the GPP remains almost constant. The course of the frequency shows some peaks due to reconnection of loads, but the steady state value is kept almost constant as the result of the actions taken by the APP. But when feeders inside the regional grids without an APP are reconnected at around 15:52 and 16:03, uncontrolled PV-units reconnect again and feed-in power of the GPP plant is reduced like it could already be seen in the worst case scenario. In order to compensate that, the set-point for the residual load for the grid with the APP is set to - 14 MW, which brings back the GPP to their original point of operation. Compared to the worst case scenario, a similar amount of load has been resupplied while the

GPP have not reached their technical limit. Consequently, supply of further loads is still possible.

4 Discussion

In the PSR situation, no forecast errors were taken into account for both load and generation. If the APP is used as an open-loop controller in reality, the forecast error is noticeable as a difference in active power flow at the control node. This can be avoided by measuring the power at the control node and by using a closed-loop controller.

Compared to the worst case scenario, systems in reality will show better behaviour, as communication links such as ripple control systems of radio links will be available promptly with voltage recovery. Compared to the best case scenario, the reality will not look quite as optimistic, as at least some of the communication links will only start operating with a certain delay, and thus initially at most partial controllability is given. The reality will lie somewhere between the two scenarios. However, the comparison of the extreme situations clearly shows the possibilities provided by the APP. In this regard, the authors would like to explicitly mention that in the distribution grid, and especially in the low-voltage grids, there is often no communication connection between the network operators control centres to small-scale generating units at all today. In order to ensure PSR in grids with a significant penetration of small-scale PV systems, appropriate control options like the APP should be established. The most likely solution in Germany will be the use of the future advanced metering infrastructure which is currently in its early rollout phase [3].

In many cases, the communication link depends on the public power supply, as communication devices in private homes are often not buffered by an emergency power supply [16], [17]. Therefore, it is to be expected that immediately after voltage recovery, a significant part of the PV-generators cannot be reached. As the restoration process progresses, communication links are successively put into operation, which increases the number of units that can be controlled.

Moreover, the PV emulators were not connected to the grid models; only the reconnection of a feeder was transferred as a digital value, and the PV feed-in power was returned to the training system. Therefore, no voltage- and frequency-dependent behaviour of the PV systems could be simulated. The data was transferred manually, which led to a time delay. Due to the uniform power of the emulators of 625 kW, the discretisation steps are relatively large compared to reality. Common systems connected to the low-voltage grid have outputs in the single to double-digit kW range, and in individual cases can also have low three-digit kW ranges.

As the training system is optimized for network operation, the frequency is modelled by a single rotating mass. All PV emulators “see” the same and constant solar radiation. Both lead to the fact that regional effects with regard to the power-frequency behaviour cannot be mapped.

5 Conclusion and Outlook

The use of the areal power plant enables the integration of a large number of small PV systems into the active power management during PSR. The aggregation of information by the system as well as the disaggregation of control commands gives the units power plant characteristics. The need for such a system increases with the increasing share of PV generation in the distribution grids, especially if feedback power into upstream grids is possible. In an operationally realistic restoration situation using a training system for grid operator’s operational personnel, the authors investigated and presented the advantages offered by the areal power plant in active power management during power system restoration. The application simplifies the restoration of PV-dominated grids and enables a faster resupply of customers as well as increases the possible resupply level.

The system has been examined at the concept level. For a comprehensive introduction in the field, bidirectional remote controllability of the plants must be available or created. In Germany, the expected rollout of the smart meter gateway with corresponding control options provides a perspective [3]. Furthermore, the connection of the APP to higher-level power management systems, which transmission grid operators use for grid restoration, should be examined and developed. This will enable an increase in the degree of automation during grid restoration and will avoid delays due to complex coordination processes between different grid operators.

6 Acknowledgements

The presented research has been carried out in the joint research project “SysAnDUk” (FKZ 03EI4004A) funded by the German Federal Ministry for Economic Affairs and Climate Action.

Supported by:

Federal Ministry for Economic Affairs and Climate Action

on the basis of a decision by the German Bundestag

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