Strategy for Implementing Black Start and Islanded Operation Capabilities on Distribution System Level

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***Abstract* — Due to a change in load situation caused by the installation of decentralized generation plants accompanied by distinct advantages and disadvantages for grid operation, distribution system operators seek an advanced degree of supply autonomy. Embedded in an appropriate environment of controllable plants, storages and extended demand-side management using intelligent automation, local distribution systems can bear major faults of the transmission system, safeguard infrastructure in graded extent and facilitate supply restoration in the transmission system. Implementing capabilities of islanded operation, black start and crisis-resilience can be considered a comprehensive task concerning various areas of grid operation. Substantial fields of action are presented. Analysis has been conveyed in order to allow objectified contemplation. All considerations are based on factual data of a small distribution system operator (DSO).**

***Index Terms* — Black Start Capability, Islanded Operation Capability, Ancillary Services, Crisis Management**

I. Introduction

Due to the transition of the electric power supply into a decentralized system based on renewable energy sources, schedulable, demand-actuated feeding generating plants with high rated power that provide the backbone of a reliable electrical power supply and ensure sufficient power quality are decreasingly available. As a replacement for the conventional large power plants, on distribution network level smaller plants based on different generation technologies with low rated power each are installed. Public utility companies are increasingly becoming power plant operators and managers of owner-operated plants in their network area. DSO may turn the initial challenge to control those plants in a grid-conducive manner into the advantage of being able to cope with major faults in the superposed transport network through coordinated black start of suitable generating units, activate plants without black start capability, operate the distribution grid islanded and, finally resume the supply of loads. In case of a voltage collapse or a blackout, the grid is out of order and loads remain unsupplied. If the interruption of supply affects a larger network area, for example the transportation network level and lasts for a longer period of time, a crisis situation can arise, in which it is no longer possible to supply the population with electrical energy, heat energy, drinking water and as a consequence with other goods. This has a significant impact on society and the result is the emergence of national crises [1]. For that reason, on distribution grid level measures of network restoration are required in order to resume a stable network operation. Most commonly, network restoration of distribution networks is executed by renewed connection to the transmission network. Because of increased installation of decentralized plants, DSOs are interested in islanded operation capability and black start capability of their systems. In order to gain an understanding of the essential questions regarding grid operation in the event of a black start and islanded operation, initially elementary basics are outlined. Then, for a real distribution network, the characteristics of generation and consumption are drafted, which are challenges in the area of self-sufficiency. Finally, the theoretical basics and the findings of the analysis are used to derive a general approach for the systematic implementation of self-supply capability.

The ability of a plant to put itself into operation in absence of voltage of the grid and to operate stably in a low operating point as idling or to provide on-site power

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http://dx.doi.org/10.25729/esr.2018.01.0001
Received January 5, 2018. Revised March 8, 2018. Accepted March 12, 2018. Available online April 25, 2018.

demand is referred to as black start capability. Thus, those plants independently attain an operational status in which they are ready for synchronization with the grid. Whether a particular plant is black start capable can be determined by thoroughly disconnecting it from the grid including all ancillary units. In volt-free state, operation of ancillary units for provision of on-site power is continued or restored. Now the plant will be started up and set to idle. In the next step, the plant is made ready for coupling to the grid by increasing the voltage to network level. As prolonged supply disruptions may occur in case of a major outages, black start capable plants have to be able to independently sustain this particular operating point [2].

Islanded operation capability of a plant requires the capability to permanently provide a stable supply of an independent (sub-) system, including voltage and frequency regulation. In comparison to black start capability the implementation of the island operation capability can be considered to be a comprehensive task, as the control of the plant generators have to provide active and reactive power throughout the entire design range of the grid. Further, requirements have to be met by the control systems, as significant voltage and frequency fluctuations can appear, causing protective tripping during normal network operation [2, 3].

II. Characteristics Of Islanded Microgrids (MG)

Subject of consideration is distribution grids comprising low voltage (LV) and medium voltage (MV) networks. Alike micro grids, within those systems and within subsystems loads, distributed generation (DG) units and energy storage systems (ESS) can be found, which can be controlled by the network operator [4, 5]. However, in contrast to MG, arbitrary distribution grids usually operate in grid connected mode, and islanded operation is possible in exceptional case only. Aim of MG is to self-sufficiently cover the electricity demand using own resources and to minimize dependence on the grid [6]. If required, power can be provided to or borrowed from the grid [7, 8]. As a consequence, in order to become capable of self-sufficient supply and islanded operation, distribution grids have to meet requirements of MG stipulated in the definition. Of particular importance is identification of optimal MG configuration. For proper design and reliable operation, information on expected load is required. Target of optimization algorithms is to determine cost minimal configuration of generating units as RES and storage systems to reliably supply the demand [9]. Control of MG occurs on the three levels of primary control, secondary control and tertiary control. Voltage control, current control and power sharing control are executed by primary control. Secondary control is responsible for adaptation of system frequency and voltage to nominal values in the aftermath of deviations observed as load changes. Energy management and optimization is dealt with on tertiary level [5, 10]. By means of integration of renewable energy sources in MG, life cycle cost as well as electricity cost can be reduced and system reliability can be increased [11, 12]. A large share of RES in total DG complicates frequency control due to imbalances resulting from RES variability [6, 11]. Control and management of MG is a complex task due to dynamic and uncontrollable behavior of its components. Electricity production of RES strongly depends on uncertain and volatile weather conditions. Consumption and storage are strongly influenced by the behavior of loads and consumers [6].

A. *Operation and Control of Micro Grids*

To obtain as much energy as possible from scarce resources and to reduce operating costs, MG are to be run at optimum operating point [13]. Unlike conventional power grid, operation of micro-grid requires control of a large number of small fluctuating DG units, ESS and consumers. Aside from optimization of energy exchange in MG and best possible utilization of RES in MG power quality and system efficiency are to be investigated. For control of a large number of devices within a MG in order to ensure reliable MG operation, intelligent automation technology is required. Application of conventional control concepts as stand-alone controllers for individual plants or centralized SCADA systems is limited, due to restrictions of communication, complexity of the control task and others. For that reason, artificial intelligence as (centralized) artificial neural networks (ANN) as well as decentralized control concepts are gaining importance. Multi- agent technology, which can be considered an advancement of artificial intelligence, is capable of fulfilling the desired control tasks. Multi-agent systems (MAS) consist of communicating, interacting agents, which are equipped with artificial intelligence and provide new opportunities in solving the desired control tasks [14–18].

Classification of MAS is possible according to the three basic concepts of centralized MAS, distributed MAS and hierarchical MAS. Centralized MAS feature a master-slave structure for control of the agents by a single control unit. Distributed MAS consist of communicating agents that share information and collaboratively coordinate their actions to solve the control problem. In hierarchical MAS, some agents are authorized to influence the behavior of other agents [19].

Control of the devices of a MG using MAS is implemented by representing each element of the MG by a dedicated, intelligent agent, which controls its actions by means of mathematical algorithms or artificial intelligence. The behavior of the agents as well as the scope of control tasks in the case of the micro grid connection to the network differ from the case of islanded operation [20]. In grid connected mode, proper scheduling or energy exchange between plants, storages and loads is a control task that can be optimized in terms of economic, ecological, supply engineering or other targets [21, 22]. Islanded MG operation requires the MAS to provide control of MG voltage, frequency and phase angle [20, 23]. It is expected that transition between grid connected mode and islanded operation is fulfilled rapidly and seamlessly [15].

B. *Ancillary Services in Micro Grid*

As MG may be operated in islanded mode, all ancillary services necessary for grid operation are to be rendered within the MG. Based on trading information of the MG members, a market for reserve capacity can be established. Objective of optimization is minimization of customers expense [24, 25]. Typical disturbances within MG requiring ancillary services are deviations of voltage amplitude and frequency, harmonics and inter-harmonics, voltage fluctuations and flickers caused by active power output and load reactive power. For analysis of power quality, approaches as Fourier Transform (FT), spectrum analysis, short time Fourier Transform (STFT), wavelet transform (WT), S-transform, Hilbert-Huang transform (HHT), Taylor-Fourier Transform (TFT) or an atomic decomposition algorithm may be applied [26–28].

C. *Frequency control in islanded grid*

During islanded operation, frequency control is of particular importance, which is why it is presented here separately from the other ancillary services. Today, in normal grid operation, frequency control is mainly provided by conventional power plants with rotating generators. The (local) level of MG requires both technical equipment for frequency regulation and market mechanisms for control of generation and load. In islanded grids, significant variations of frequency can occur due to imbalances of generation and consumption. Accordingly, both automatic generation control (AGC) and load-frequency control (LFC) can be considered necessary [29]. Obstacles to an integrated approach to frequency control in MG are real-time determination of fluctuating production and consumption [29]. Real-time pricing is regarded as a proper instrument for influencing the behavior of smart loads that are able to react flexibly to varying electricity prices due to frequency changes [30]. In case of market failure, immediate grid stabilization measures have to be held available as load prioritization [31]. For use of inverter-based renewable feeders for grid stabilization, consideration of their virtual inertia is promising [32].

D. *Battery Management in Micro Grid*

Power imbalance problems can be mitigated using ESS for storing excess production of RES by charging ESS on increased grid frequency and discharging on frequency drops [11]. Those ESS support MG by provision of a limited energy reservoir, which can absorb and release energy for integration of RES. Owing to their limited capacity, diligent management of state of charge (SOC) of ESS is an integral part of MG. Battery Energy Storage Systems (BESS) compensate for fluctuating generation in MG and thus support stability as well as maximization of power production. Proper dimensioning of storage and management of SOC are essential [33].

III. Analysis Of Structural Data Of The Distribution Network Under Consideration

Contemplation is based on structural data of a real distribution network from the year 2014, which included 660 generating plants with a gross rated power of 19.4 MW. Among those plants are 622 photovoltaic plants, 20 gas cogeneration plants, 9 biogas plants, 4 biomass plants, 2 wind power plants, 2 hydropower plants and one digester gas plant. Volatile plants as PV plants and wind power plants contribute 14.8 MW rated power and 76 percent of the gross rated power. The remaining capacity of 4.7 MW or 24 percent is attributed to demand-actuated plants, which form the basis for further considerations concerning black start and islanded operation capability of the distribution grid. As 2.1 MW of those plants are owner-operated plants, the DSO has immediate access to demand-actuated plants with 2.6 MW rated power, which can be controlled by the control center. Accordingly, the generation structure can be considered highly heterogeneous, which is exacerbated by the diversity of individual plants, especially regarding photovoltaic plants. Electricity generation within the distribution network is consequently limited seasonally and during the day depending on the availability of environmental factors as insolation and wind speed. For photovoltaic plants, an annual utilization degree of 12.8 percent corresponding to 1.100 annual full-load hours can be assumed. In Fig. 1, the prevalence of certain power intervals in percent of rated power of a photovoltaic plant within the distribution grid during one year is depicted in blue. The red line demonstrates the percentage of time during which a certain percentage of the rated power is produced.

Onshore wind power plants feature an annual utilization degree of approximately 18.8 percent and 1.650 annual full-load hours. Consequently, photovoltaic plants and wind power plants may only be considered with their expected level of generating power for considerations

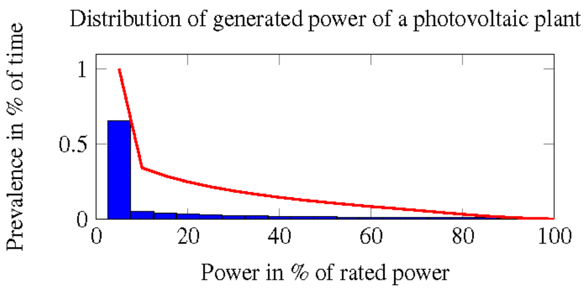

Figure 1. Distribution of generated power of a photovoltaic plant over time.

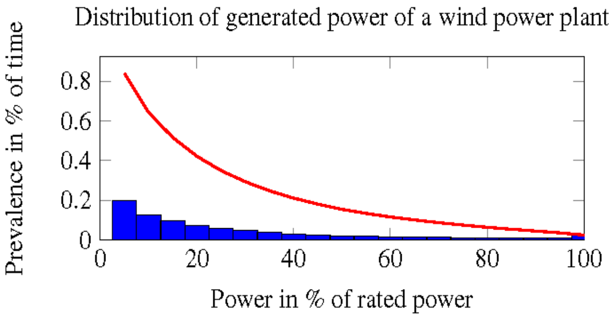

Figure 2. Distribution of generated power of a wind power plant over time.

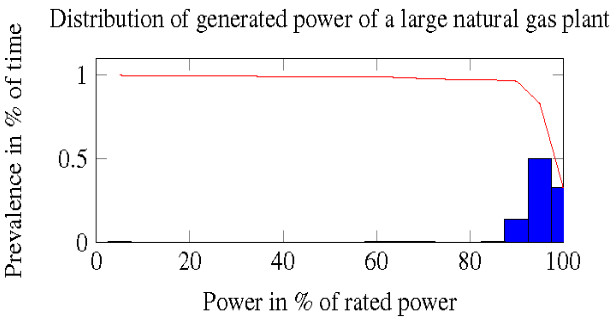

Figure 3. Distribution of generated power of a natural gas plant over time.

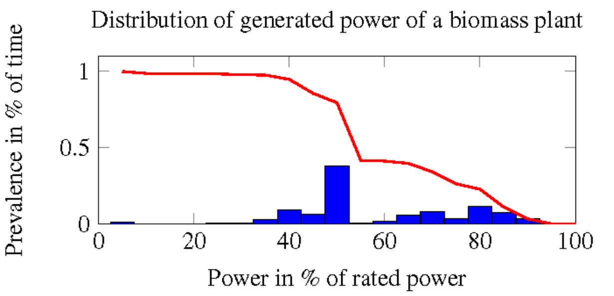

Figure 4. Distribution of generated power of a biomass plant over time.

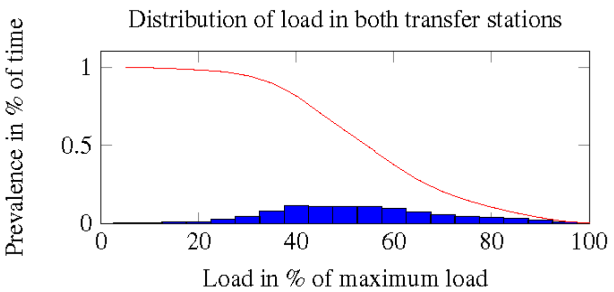

Figure 5. Load of the entire grid over time.

regarding islanded operation. In Fig. 2, the prevalence of certain power intervals in percent of rated power of a wind power plant within the distribution grid during one year is depicted in blue. The red line demonstrates the percentage of time during which a certain percentage of the rated power is produced.

A quite different behavior can be observed for plants based on plannable energy sources. In the distribution network under consideration, a natural gas combined heat and power plant (CHPP) exists with a rated power of 0.8 MW, which is used perennially in order to generate the largest possible amount of electrical energy (Fig. 3).

Accordingly, the prevalence of power intervals with high percentage of rated power is high in comparison to fluctuating plants. Furthermore, there are biomass CHPP based on wood pellets within the grid for supply of local heating networks. Those plants are operated on a seasonal basis, as thermal heat is required mainly during the heating period (Fig. 4).

Apart from electricity production, load situation and grid structure are also relevant. The distribution network under consideration is supplied with electric energy from the adjacent 110 kV transmission network via two transfer stations (electrical substations). From there, energy is distributed on medium voltage level (20 kV) to secondary substations or mains connections on medium voltage level. In total, the distribution network includes 220 secondary substations in a grid area with large spatial expansion. Approximately 20.000 people and diverse commercial customers are supplied. Within the observation period of one year, an average load of 6.4 MW was drawn from the superimposed HV grid with a standard deviation of 2.2 MW. A maximum load of 12.6 MW was observed as well as a minimum load of 0.0 MW. Analysis is based on 15-minute load measurement in the transfer stations. As all amounts of electrical energy, which are fed into the MV grid, lower the load in the transfer stations, effective load within the grid exceeds the measured values. Due to the circumstance that most plants within the MV grid are renewable plants and feature 15-minute measurement of the fed-in electricity, refined approximation of the load situation is possible. With an average generation of 5.3 MW, average load is 11.7 MW. Maximum load was 20.3 MW and minimum load 1.7 MW. However, due to a lack of measured data with sufficient temporal resolution, especially for numerous small photovoltaic plants, effective gross electricity consumption within the distribution grid can only be estimated containing error. In Fig 5 the data on power obtained from the superimposed transmission grid in certain power intervals in percent of maximum power consumption within the distribution grid during one year are shown in blue. The red line demonstrates the percentage of time during which a certain percentage of maximum power is consumed.

IV. Network Restoration Strategy On Distribution Level

Well-known strategies for network restoration on transmission system level can be applied to distribution grids in a modified manner. In general, network restoration strategies describe a logical structure of separate principles in form of a decision tree, which is repeatedly run through until network operation and supply of all loads are successfully restored. In the event of a blackout, a loop is entered and for all zones of the grid, all plants and all loads defined measures are executed as exemplarily visualized in Fig. 6 [34].

V. Structure Of Analyzed Distribution Grid

The medium-voltage distribution network under consideration is connected to the superimposed high-voltage level by two transfer stations. According to the network plan containing all transfer stations, substations and lines as visualized in Fig. 7, the distribution grid can be subdivided into 11 areas. Subdivision is carried out in a way that the respective segments form an independent unit each without modification of the network structure, switching is possible with little effort and there are at least two connections to the rest of the network. Another

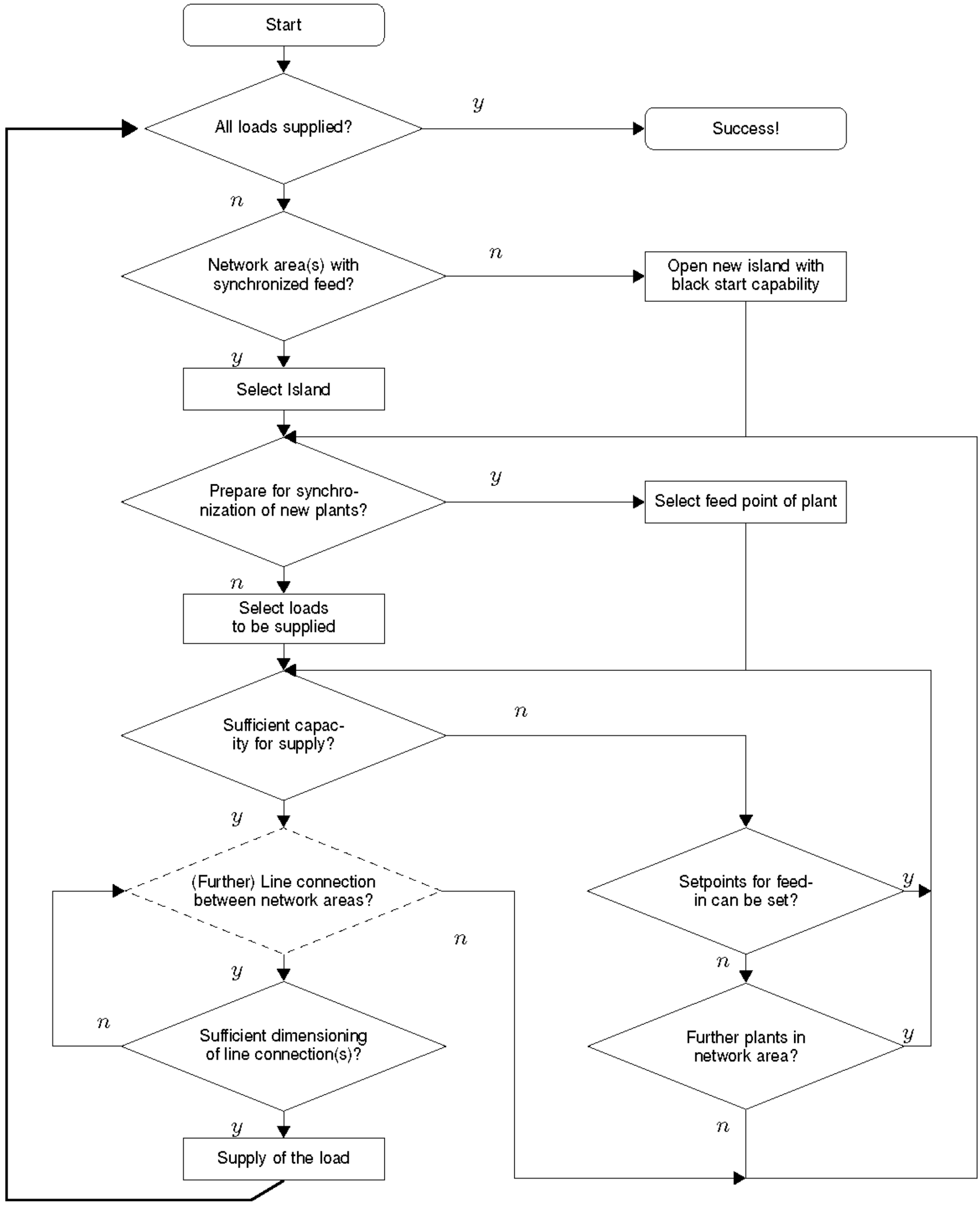

Figure 6. Generic network restoration strategy [34].

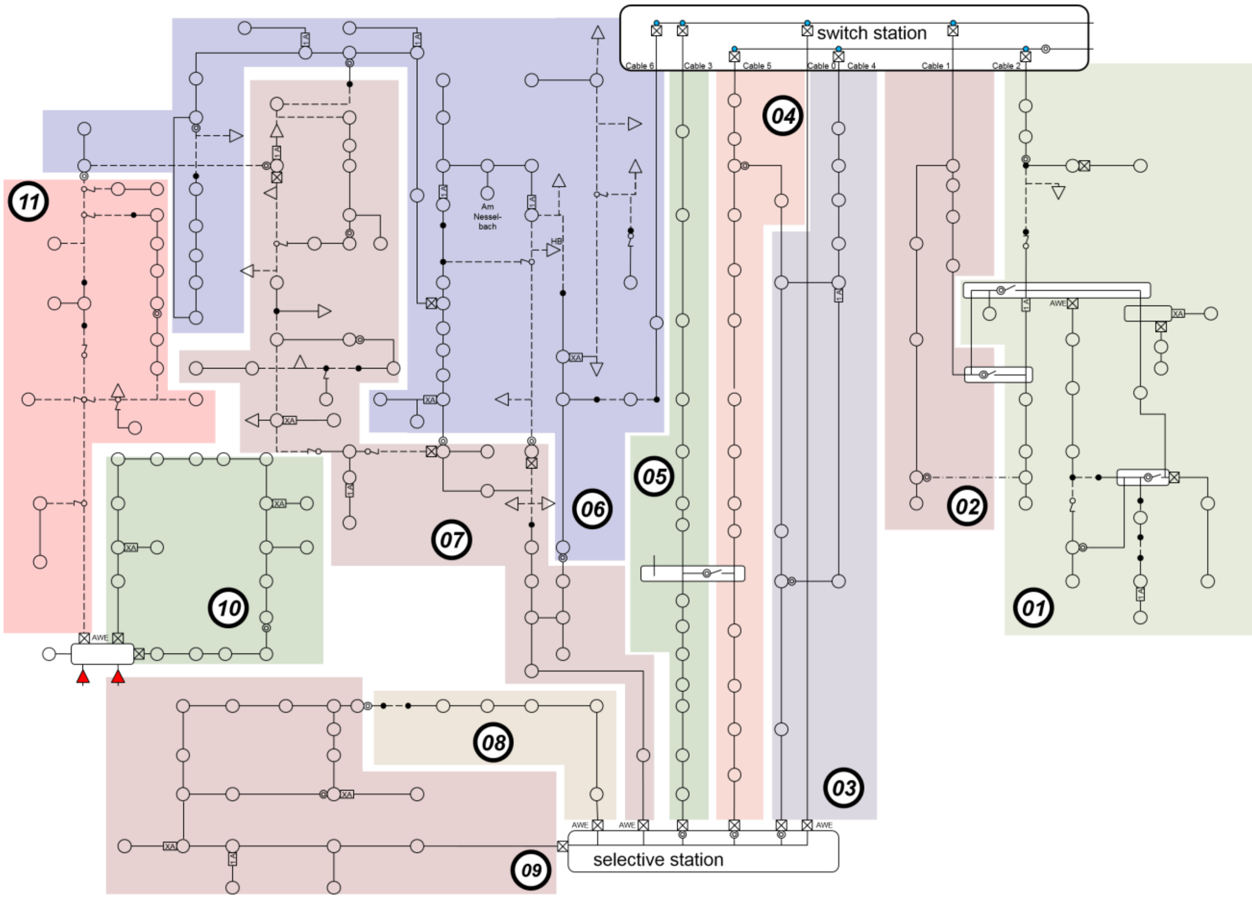

Figure 7. Grid structure and segmentation into 11 network areas.

criterion is that each segment can directly be supplied by at least one transfer station. Hence, those areas can be isolated from failures in other areas by switching in the transfer stations. Those areas can be considered independent islands, which have to be equipped with suitable storage, controllable plants and an individual concept for demand-side management in order to enable islanded operation. The next criterion for subdivision of the grid in the depicted 11 segments is the circumstance that currently switches for connection of the sub-stations to the MV grid are manual switches. In order to reduce the effort for upgrading, the switches in all substations, initially only the switches in the switch stations, have to be renewed.

In the rural distribution grid under consideration, the network areas show diverging properties regarding load structure, generation capacity, critical infrastructure and equipment. The transfer station switching cabinet supplying 9 of the 11 network areas via 7 lines is extremely important. It supplies the urban areas of the distribution grid, which exhibits relatively high load density. The second transfer station is located in a sparsely inhabited, remote network area with low load density. Altogether the network is meshed and the n − 1 criterion is broadly respected. Several stubs supply remote settlements and facilities.

For the individual grid segments, analysis of basic parameters of load and generation was carried out. While it was possible to attribute plants to particular substations, the assessment of load parameters within the grid segments was imprecise, as only large industrial consumers feature 15-minute measurement of consumption. As no data on the allocation of individual consumers to network nodes and thus to grid segments could be obtained, it was only possible to estimate the load by evaluating the maximum value pointers of the substations with reference to maximum load of the grid. Data on load and generation within the individual grid segments in megawatts (MW) are presented in Table 1.

According to the data, network area 1 can be considered the distribution grid's powerhouse, as it includes 9.6 MW generation capacity, representing 49 percent of the total installed capacity. As large industrial customers are situated there, network area 1 also accounts for 18 percent of overall load. Moreover, it is the only area where rated generation power exceeds the demand, and the rated generation power of the plannable plants is almost equal to the demand. Thus, segment 1 is selected to serve as starting a point for network restoration and islanded operation considerations. In addition, the rated power of controllable plants exceeds the average load and achieves

Table 1. Estimated data on load in the grid segments (i) for maximum load $P_{L,max}$, average load $P_{L,av}$ as well as on rated power of generating plants P_G, controllable plants P_{GC} and uncontrollable plants P_{GU}.

i	$P_{L,max}$	$P_{L,av}$	P_G	P_{GC}	P_{GU}	P_{GC} /$P_{L,max}$	P_G /$P_{L,max}$
1	3.7	2.1	9.6	3.3	6.3	0.9	2.6
2	1.2	0.7	0.8	0	0.8	0.0	0.7
3	1.5	0.8	0.2	0.1	0.1	0.1	0.1
4	1.7	1.0	0.2	0	0.2	0.0	0.1
5	1.3	0.8	0.6	0	0.6	0.0	0.5
6	3	1.7	1.7	0	1.7	0.0	0.6
7	2.5	1.4	2.4	0.5	1.9	0.2	1.0
8	0.2	0.1	0.3	0.1	0.2	0.5	1.5
9	1.7	1.0	0.7	0.4	0.3	0.2	0.4
10	1.7	1.0	1.8	0.2	1.6	0.1	1.1
11	1.3	0.7	1.1	0.3	0.8	0.2	0.8
	20.3	**11.7**	**19.4**	**4.9**	**14.5**	**0.2**	**1.0**

approximately the maximum load. Moreover, the large industrial customers have emergency power plants available, so the capacity of plannable and unplannable plants can be used for network restoration. If grid segments 1 and 8 are neglected, there are no significant plannable generation facilities in most of the segments for maintaining islanded operation.

VI. Sequence Of Measures For Implementation Of Islanded Operation

Subsequently a strategy for structuring the activities in preparation of the implementation of islanded operation is developed. With due regard to the sequence of measures, DSO can determine islanded operation scenarios, understand the possibilities associated with the existing infrastructure as well as advisable expansion. Furthermore, assessment of economic matters enables DSO to safeguard investment decisions and to determine a reasonable order of implementation.

A. Identification of loads

All loads connected to the distribution grid have to be registered as well as attributed to a particular network area and network node. Characteristic features of the load as maximum and average of power rating are to be recorded as well as information on behavior and controllability. Association of loads to network areas and nodes can determine information on load parameters for the network areas and nodes determined by summarization. Thus, it becomes evident at which point in the network what load can be expected and what supply is required.

B. Determination of supply interruption durations

As all considerations on islanded operation are particularly related to the provision of electrical energy from scarce re- sources, a limitation of the supply interruption duration and development of supply scenarios appear to be reasonable. Those durations in combination with the load required determine the amount of energy to be provided. Some supply interruption durations are outlined to exemplify. Minimum supply interruption duration in Germany can be estimated at 12 minutes or 0.2 hours according to typical annual supply interruption duration per customer in the year 2014 [35]. A further, longer supply interruption duration correlates to the duration of a typical supply interruption per customer in Germany in the year 2014 of approximately one hour. Further intervals of 3, 6, 12, 24 and 48 hours. A period of ten days or 240 hours is assumed as the worst case interruption duration scenario, introduced as a crisis scenario by the German government [36].

C. Load Prioritization

As a next step, different supply scenarios in case of supply interruption are drafted. Regarding their importance for the supply of the population, the facilities can be arranged in the order of their significance.

Minimum supply scenario: only facilities essential for public services of general interest are supplied. These are the facilities of water supply, sewage treatment, health care (especially hospitals), retirement homes, public shelters, fire stations, police stations and facilities of utilities.

+ Other facilities of public interest: another scenario going beyond the minimum supply scenario includes the supply to additional facilities of public interest. Those are the facilities of food supply, food production, production and supply of energy sources, and other important supplies, including agricultural enterprises, farms or greenhouses, food-processing plants such as butchers and bakeries, warehousing facilities and petrol stations.

+ Maintenance of basic functions in private residential units: exceeding the aforementioned supply scenarios, domestic appliances such as room heating facilities, refrigerators, freezers, emergency lighting and further safety-relevant devices are supplied. Thus, it is ensured that the population is not obliged to leave their dwellings in crises.

+ Shortened supply of usual demand: most domestic appliances can be supplied, however appliances with high power consumption should be avoided.

Maximum supply scenario: all customers and loads are supplied as usual without any restrictions. This scenario corresponds to the maximum load that can be observed in the network, including special cases such as electric storage heaters.

D. Registration of available generating plants

At the next step, the available generation structure has to be captured by associating all plants to network areas and nodes. Realistic plans for capacity extension are to be included. Additionally, an overview of the distribution of the plants in the network area is made, and it becomes obvious where centers of power generation are located. Further evaluation requires information on the behavior of the plants as maximum-, minimum- and average feed-in power as well as standard deviation. Moreover, information on the plant type and its feed-in characteristics appears to be significant. Feed-in behavior is controllable for conventional plants based on storable energy sources or fluctuating for renewable plants, which are influenced by external circumstances. Type and costs of required combustibles as well as magnitude of storage provide important information for plant operation in the event of a crisis. Details about the type of the electric machine or the generator, whether it is a synchronous machine or an asynchronous machine and how great the control capacity is, allow an assessment of the contribution to regulatory activities in islanded operation. Additional information regarding islanded operation and black start capabilities of the plants in general should also be collected. Finally, the preparation of information on the controllability of the plant, its connection to the control center, and on the plant operator is recommended.

E. Prioritization of plants

After collecting data on the plants, prioritization regarding requirements of islanded operation takes place. Dimensions of prioritization are black start capability, islanded operation capability, predictability and controllability, range of combustibles and rated power.

F. Calculation of missing plannable capacities

By contrasting juxtaposition of determined supply scenarios and identified generation plants, the status quo of self-supply is acquired. Thus, it becomes evident which additional capacities are needed to cover different supply scenarios. For all scenarios, missing capacities are to be outlined individually.

G. Estimation of generation capacity expansion

Since required additional capacities for coverage of all supply scenarios are transparent, a target structure of generating plants can be elaborated. The most obvious case of implementing the required capacities in terms of conventional power stations is not optimal from a macroeconomic point of view. As a result, large overcapacities in all distribution networks would appear. For the best possible use of scarce financial resources and energy resources as well as taking into account the probability of different fault scenarios, a guideline for capacity expansion is drafted. At the first step, following the cellular approach, the missing capacities for different scenarios are distributed to network areas and nodes if possible. Subsequently the capacities have to be distributed to different generating technologies and types of power stations. For missing capacities, predictable well-controllable technologies with black start and islanded operation capabilities based on storable regional energy carriers can be recommended to cover minimum supply. If the required combustibles can be produced sustainably on site or in the area of the distribution grid, permanent operation of these plants is possible in principle. Additional capacities for supply of other facilities of public interest should be implemented as predictable island-operable well-controllable technologies based on storable regional energy carriers and other energy carriers such as natural gas. For maintenance of basic functions in private residential units both centralized and decentralized CHPPs based on various fuels are saliently suitable, in particular due to the possible sectoral coupling between electrical energy supply and heat supply. If sustainably producible regional resources are available, these should be used preferably. Supplementary fluctuating regenerative generation technologies and CHPP based on fossil fuels can be used. Shortened supply of usual demand can be met by combining CHPP, centralized and decentralized renewable generating plants. Compared to the supply of basic domestic needs, the orientation of plant structure is more decentralized, volatile and characterized by regenerative plants. Decentralized renewable plants with fluctuating generation and generation peaks coincident with demand peaks are recommended to cover maximum supply. These are in particular photovoltaic systems for demands during daytime. After assignment of required capacities to plant types, the possibilities of expansion on site of existing plants, for example for biogas plants and biomass power plants, should be examined. Enhancement of capacities of biogas plants by installation of additional natural gas CHPP is advisable in many cases, provided the connection to a natural gas network is possible.

H. Estimation of storage capacity demand

Expansion and integration of fluctuating plants into the distribution system generate the need for short- and mid-term storage for grid stabilization. Storage, especially of electrical energy, has a balancing role with regard to short-term self-supply on the distribution grid. Two positive properties can be achieved by adequate distribution of storages. On the one hand, storages, provided a sufficient state of charge at the time of the query, allow for an extension of self-supply time range. By their ability to predictably and controllably provide electrical energy, they extend the available feed-in capacity and thus the possibilities of self-supply. Likewise, an adequate limitation of the generating capacities, in particular of plannable generation facilities based on fossil or non-renewable regenerative energy sources, is possible by adequate sizing of the storage facilities. On the other hand, energy storage allows the integration of fluctuating producers into concepts for the black start and islanded operation capabilities of the distribution grid. Rated power of storage devices has to be adjusted to the rated power of the fluctuating generators. The capacity of the storage units should be adjusted to the intended time range of different supply scenarios as well as the rated power required to supplement the plannable generators in different supply scenarios. In addition to design matters, an operational strategy for the storages optimized regarding the needs of islanded operation and energy management has to be provided. Seasonal and weather-related requirements have to be taken into account and, beyond considerations of maximizing yields, possible capacity planning is made in the case of self-supply as a function of forecasts for production and demand. With increasing scope of supply in order to meet customer-specific needs or to provide regular supply, the volatility of the demand for electrical energy rises. Moreover, the desire for integration of fluctuating regenerative plants into supply of the loads increases. Correspondingly, the storage requirements are shifted into the areas of the bridging power as well as the uninterrupted voltage supply. The upper limit of total required rated power of storage is determined based on the nominal rated power of fluctuating generators, if greater than maximum load. The lower limit of required rated power storage depends on average power output of fluctuating producers. By multiplying the duration of the worst-case interruption scenario by the difference between minimum load and possible predictable self-generation as well as a factor of ensured storage charge level the lower limit of the required storage capacity is calculated. The upper limit of required storage capacity is determined by multiplying the duration of the worst-case interruption scenario by the difference between maximum load and possible predictable self-production based on sustainably regionally viable energy carriers. Subsequent to elaboration of storage capacity and rated power in total, the power ratings have to be assigned to network areas. After that, for different supply scenarios suitable storage technologies have to be identified.

- Storage technologies with decoupling of power and capacity as well as minimum self-discharge are suitable for provision of power and capacity required to maintain minimum supply. Those are, for example, Redox-flow storage and power-to-gas applications.
- Central large-scale storage with low self-discharge for the additional supply to the institutions relevant to the community.
- Decentralized storages and home storages to maintain the basic functions in private residential units, support reduced fluctuating supply of regular demands, like (Li-Ion) battery storage, and enable electric vehicle to charge in both directions.
- Central buffers with high rated power and short-term focus for collection and provision of energy from fluctuating regenerative generators in the context of maximum supply.

I. Reconcilement of storage capacity and generation capacity expansion

In order to avoid unreasonable overcapacities, expansion scenarios for generating plants and demand of storage facilities are to be coordinated, and a suitable design for the entire plant structure is to be defined.

J. Analysis of distribution grid structure

Analysis of the distribution grid with regard to the expected power flows in different supply scenarios aims to find out whether extreme load scenarios amongst grid areas can be endured by the existing equipment. Considering different switching states and supply scenarios, critical transmission lines and network areas can thus be determined. Expected load indications are included in strategic network planning and derivation of equipment to be fostered or upgraded. Moreover, equipment necessary for implementation of black start and islanded operation has to be determined. In particular, the following areas may be considered relevant. Electrical machines in generating plants have to be enabled to contribute to frequency regulation or hold control of energy reserve. Inverters of PV plants ought to be retrofitted to communication-capable systems with aptitude of remote control as well as active and reactive power feed-in. At least, the feed behavior of the PV plants should be controllable by varying the predefined frequency range for feed-in or by remote control. Adjustable transformers in local network stations can be considered necessary to maintain required tolerance bands of voltage during reversed load flow or load flows amongst network areas. Re-equipment of electrical measuring instruments is necessary to capture the data relevant for grid operation at a suitable temporal resolution. Collection of the requirements for a network control room intended for the monitoring and control of the equipment, generators, storages and consumers under operating conditions of black start and islanded operation should be developed. It is also necessary to have the requirements for smart meters regarding support of islanded network operation. Particularly relevant requirements are presented in order of decreasing relevance:

- High-resolution measurement of the electricity demand.
- Possibility of connection and disconnection of the

units by electric company.

- Ability to limit consumption and feed-in power.
- Control of internal producers, consumers and storage facilities in accordance with the requirements of the distribution grid operation coordinated by the grid operator.
- Connection to Smart-Home systems and control of the internal energy management within the housing unit.
- Enabling autonomous supply of the unit and the provision of additional services for the distribution grid.

K. Feasibility study of different supply scenarios

The feasibility study of different supply scenarios included: verification of the feasibility of different scenarios of black start and islanded operation using the generic network restoration strategy; analysis of whether a defined switching state can be applied to all the loads to be supplied by the generating plants through the plants distributed to the grid areas; checking the coupling conditions to other grid areas.

L. Assessment of cost

The costs associated with the implementation of the technical concept are calculated for each supply scenario or the stage of expansion under consideration.

M. Development of profit mechanisms and revenue models

The profit mechanisms and revenue models for the operation of the estimated production plants and storage capacities are to be developed for their entire life cycle. The revenues for new regenerative generation plants considering possible subsidies (EEG), or the appropriate average conditions from competitive tender competitions should be calculated. For micro CHPP units, the revenues are to be calculated for the expected operating time, including possible subsidies, contractually agreed minimum reductions in electrical energy and heat as well as acquisition, installation and operating costs. Preliminary forecasts for fuels are also included for the entire operating period. CHPP units and cogeneration plants supplying critical infrastructures have to be evaluated including (and negotiating) municipal budgets for the provision and allocation of alternative costs for the provision and operation of conventional emergency units, for example in hospitals and nursing homes. In addition, potential subsidies, contractually agreed minimum reductions in electrical energy and heat, acquisition, installation and operating costs have to be taken into account, as well as the establishment of price forecasts for fuels. Storage capacities should be calculated on the basis of expected revenues, initially from the provision and introduction of primary and secondary control, as well as later on the marketing of interim storage of electricity from regenerative generation plants.

N. Determination of implementation order

Comparison of cost and revenue figures in the form of a business model over the planned lifetime has to be conducted. Individual investments have to be prioritized with regard to their economic advantage. Profitability of the overall project or estimation of the resulting total loss is to be considered.

VII. Conclusion

Obviously, implementing capability of self-supply, islanded operation and black start on distribution network level is a comprehensive task affecting all spheres of duty in network operation. In the study presented, it was attempted to compose all essential fields of action to facilitate a structured design planning of decentralized grid with graded capability of is- landed operation. Comprehensive planning and consistent implementation is required to utilize regenerative energy sources within the distribution network area at best and to increase the system's resistance to crises.

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