ISLANDED OPERATION OF MODULAR GRIDS

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ABSTRACT

Increasing numbers of decentralized energy resources with fluctuating behaviour lead to higher prediction errors of the production forecast (quantity and location) and raise the risk of large-scale blackouts. With the concept of modular grids (MGs) a decentralized operation of subgrids is achievable by the use of a power electronic grid interconnector (GIC) [1]. This paper shows a novel approach for an islanded operation of MGs to supply customers with energy during large-scale blackouts of the upstream grid.

To investigate the proposed concept, controllable actors, the GIC and the CIGRÉ medium voltage benchmark network [2] are modelled in DIgSILENT PowerFactory. Achieved results are presented in this paper.

ABBREVATIONS

DER	decentralized energy resources	GIC	power electronic grid interconnector
DSO	distribution system operator	MG	modular grid
		MV	medium voltage
FC	frequency control	SOC	state of charge
GESS	grid-supporting energy storage system	SOZ	stable operation zone
		UG	upstream grid

INTRODUCTION

Due to governmental claims of reducing CO2 emissions and the nuclear phase-out, decentralized energy resources (DER) gained great importance in Germany over the last years [3]. Therefore, power generation is much more weather-dependent, whereby fluctuations in wind and solar radiation lead to large differences to production forecast values. In addition, the planned rollout of smart meter systems [4] will lead to higher numbers of controllable loads. If loads are pooled and controlled by market operators, the diversity factor decreases, leading to higher simultaneous changes in grid loads. As a result of considerable active power imbalances, the probability of large-scale blackouts increases.

The aim of grid operators is to ensure a stable and highly available supply of energy for customers. Thus, islanded grid operation is an option to minimize planned and unplanned outages. Given the current state of technology, distribution grids cannot be operated as islands, due to missing frequency control options. Using the concept of modular grids (MGs), subgrids are decoupled from the upstream grid (UG) using GICs, see Fig. 1. Voltage and frequency control for the MG are provided by the grid-forming converter by active power exchange via the DC link [1]. Therefore, the statutory quality of supply is ensured near the customers and independently of the quality in the UG. In contrast to [1], where a grid-connected operation is presented, this paper focuses on the islanded operation of MGs.

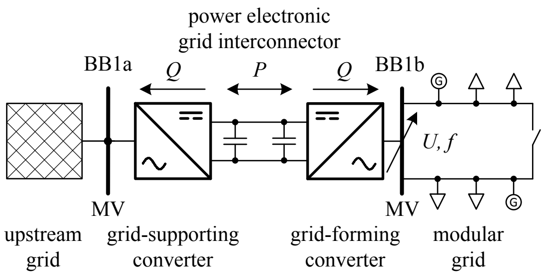

Fig. 1. Power electronic grid interconnector (GIC) decouples upstream grid (UG) and modular grid (MG)

Section II outlines the concept for islanded operation of MGs. An overview of the implemented control structure of storage units is given in section III. The simulation environments and all assumptions are presented in section IV. In section V simulation results are depicted to analyse the stability of transient behaviour during disconnecting and reconnecting the MG and UG. In addition, simulations using standardized daily load and generation profiles are executed in order to analyse stability during long-term islanded operation.

CONCEPTS OF ISLANDED OPERATION

Control of active power

When the MG is operated in grid-connected mode, the DC link voltage is controlled by the grid-supporting converter under active power exchange with the UG. During a blackout of the UG active power cannot be exchanged to control DC link voltage. Therefore, the DC link voltage is the result of active power balance within the MG. To ensure a stable islanded operation two main options for the control of active power balance are available.

Control of decentralized actors

Without adding ancillary devices, power flow to the GIC can only be compensated by controlling power consumption of customers and decentralized generation. Real-time communication with a high number of decentralized actors (DER and controllable loads) using telecommunication technologies is a challenging and cost-expensive task. In contrast, the concept of MGs provides a cost-efficient solution. Because frequency is identical within the whole MG and can be set directly by the distribution system operator (DSO) using the GIC, it can be used as an inherent and reliable communication channel [1]. Thus, control units of decentralized actors have to be extended with a frequency-dependent power control. By setting adequate frequency values, the DSO is enabled to influence active power in the MG using one control signal.

Taking into account volatile availability of power provision of DER and consumption of customers, frequency control (FC) is unsuitable to control DC link voltage directly. In addition, since customer behaviour is influenced, this method will gain low acceptance, especially for frequent, short-term blackouts.

Adding energy storage systems

Another solution for active power control is the implementation of an additional, centralized grid-supporting energy storage system (GESS) near to the GIC, as shown in Fig. 2. To ensure a grid-supporting behaviour this storage unit has to be controlled by the DSO. In contrast to FC, GESS can provide and consume active power without influencing customers. On the other hand, implementation and operation of storages are cost intensive. Additionally, depending on the power flow within the MG and the installed capacity of the GESS, time for islanded operation is limited.

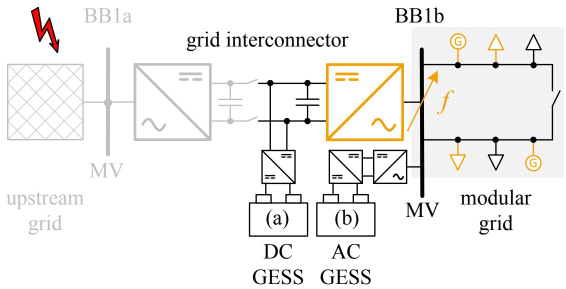

Fig. 2. Islanded operation of a modular grid using (orange) frequency controlled decentralized actors and GESS units with connections to (a) the DC voltage link or (b) the AC busbar

For connecting the GESS, two main options are available. When directly connected to the DC voltage link, as shown in Fig. 2 (a), no additional AC/DC-converter is needed, which reduces system costs. When connected to the AC busbar BB1b, see Fig. 2 (b) an additional AC/DC-converter is needed. As a positive side effect, this storage can be used to provide peak-shaving functionalities for the GIC in grid-connected mode. In cases when the actual power flow exceeds the maximum power flow of the GIC, residual power can be charged in and discharged from the AC GESS. Therefore, the GIC does not have to be designed for the worst case scenario, which results in lower costs of the overall system. Due to this advantage, the AC GESS is chosen for further investigations.

Table 1 shows a qualitative comparison of options to provide active power in order to control the DC link voltage.

Table 1: Comparison of active power control options during islanded operation

	FC	DC GESS	AC GESS
Investment costs	+	o	-
Operational costs	+	o	o
Restriction of customer behaviour	-	+	+
Peak-shaving	+	-	+
Availability	-	+	+
Limitation of power provision	+	-	-

\+ optimal o moderate - not optimal

Control strategy

By combining the options AC GESS and FC, a technical and economic optimum can be realized. Short-term islanding operation is covered by the GESS, imperceptible for customers. To withstand long-term operation, FC is additionally used for active regulation of DER and customers in order to charge the GESS during operation. As a consequence, the GESS can be designed smaller and a concurrent increase of stability of islanded MG-operation is achievable.

Grid connected mode

During grid-connected mode, the AC ESS is controlled to a fixed state of charge (SOC). In grids with load and generation behaviour, it is controlled to $SOC_{\mathrm{ref}} = 0.5\,\mathrm{p.\,u.}$, in order to ensure an optimal operation in both directions. With adequate load flow forecast the SOC reference can be adapted to maximize the operation time. In grids with dominant load behaviour the reference value can be set to $SOC_{\mathrm{ref}} = 1\,\mathrm{p.\,u.}$ For further investigations, a grid with load and generation behaviour is assumed.

Islanded operation

During islanded operation, the GESS is used to control the DC link voltage by active power provision. To extend the operating time, despite the limited capacity, critical SOC states are defined at $SOC_{\mathrm{upper}} = 0.75\,\mathrm{p.\,u.}$ and $SOC_{\mathrm{lower}} = 0.25\,\mathrm{p.\,u.}$ When reaching critical limits, FC is used to restore SOC_{ref}. By setting grid frequency within the MG to $f_{\mathrm{MG}} = 51\,\mathrm{Hz}$ when reaching SOC_{upper}, power control units of DER are required to reduce generation. $f_{\mathrm{MG}} = 49\,\mathrm{Hz}$ is set at SOC_{lower} to reduce load. Once SOC_{ref} is obtained, FC is deactivated. As a consequence, the restriction-free storage capacity is $E_{\mathrm{eff}} = 0.5\,E_{\mathrm{GESS}}$, whereas the remaining capacity is used as margin of safety.

Reconnection

After restoration of power supply in the UG, the grid-supporting converter is activated and takes over control of the DC link voltage. Power control of the GESS is deactivated and the frequency within the MG is set to $f_{\mathrm{MG}} = 50\,\mathrm{Hz}$. Since UG and MG are decoupled by the GIC, there is no need to resynchronize the MG. After reconnecting, the GESS is charged to SOC_{ref} in order to provide sufficient capacity for future blackouts.

CONTROL STRUCTURE

To enable the MG to be operated in islanded mode, the existing control structure, as proposed in [1], is extended by an island control structure, shown in Fig. 3.

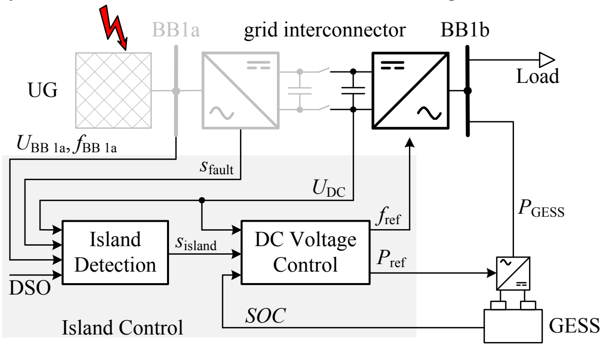

Fig. 3. Control structure for islanded operation

Detection of islanding and reconnection

As mentioned in section I, islanded operation is an option to ensure a stable and highly available supply of energy for customers, in cases of insufficient power supply of the UG. Therefore, the following causes are relevant:

- Blackout of the UG
- Grid congestions within the UG
- Failure of the grid-supporting converter
- DSO-intended islanded operation, in order to relieve grid capacity within the UG

To detect the need for islanded operation, an island detection block is implemented. The first two causes result in exceeding of AC voltage or frequency thresholds at busbar BB1a. Therefore, measurement of AC voltage is required. A failure of the grid-supporting converter is recognized by the operating system. The fault signal s_{fault} has to be transmitted to the island control. A signal for intended islanding operation can be set directly by the DSO. All mentioned causes lead to a missing control of DC link voltage. Therefore, detection of exceeding of DC voltage thresholds is a backup solution to detect islanded operation. If one of the above mentioned conditions is fulfilled, the island signal will be set to $s_{\mathrm{island}} = 1$.

The detection of returning AC voltage at busbar BB1a is also achievable with the implemented detection block. Because returning AC voltage is no adequate condition for a sufficient reliable UG, the reconnection process has to be supervised by the DSO.

DC voltage control

The voltage control strategy, proposed in section II, is implemented into the DC voltage control block, Fig. 4. The selector block chooses between power provision of GESS and additional FC, as well as charging the GESS in grid-connected mode. As long as islanded operation is detected, the GESS is activated as main device to control the DC link voltage by setting $s_{\mathrm{GESS\text{-}CTRL}} = 1$. Since the goal for the GESS is to control the DC link voltage, the same control structure as for the grid-supporting converter is applied, see [1].

When exceeding critical SOC values, FC is activated additionally by setting $s_{\mathrm{F\text{-}CTRL}} = 1$. The reference frequency is selected using the following conditions:

- $s_{\mathrm{F\text{-}CTRL}} = 1$ AND $SOC > SOC_{\mathrm{upper}}$: $f_{\mathrm{ref}} = 51$ Hz
- $s_{\mathrm{F\text{-}CTRL}} = 1$ AND $SOC < SOC_{\mathrm{lower}}$: $f_{\mathrm{ref}} = 49$ Hz
- $s_{\mathrm{F\text{-}CTRL}} = 0$: $f_{\mathrm{ref}} = 50$ Hz

Therefore, the customer behaviour and DER are actively controlled in order to restore the initial SOC. Frequency is set back to nominal frequency either if the initial SOC is achieved or the islanded mode is deactivated.

Under grid-connected operation, the charge control block ensures the restoration of the reference SOC.

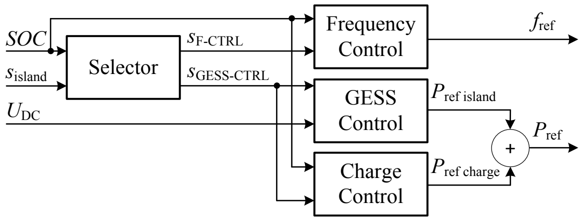

Fig. 4. Control structure for DC voltage control

SIMULATION ENVIRONMENT

Stability analyses of islanding and reconnection processes

To investigate islanding and reconnection processes, a simplified network, as shown in Fig. 3, is simulated in DIgSILENT PowerFactory. Assuming the GIC as modular multilevel converter, it is modelled as a controlled voltage source with control structures and parameters given in [1]. The GESS is modelled as controlled voltage source with an apparent power of $S_{\mathrm{GESS}} = S_{\mathrm{GIC}} = 5.5\ \mathrm{MVA}$ and a capacity of $E_{\mathrm{GESS}} = 5.5\ \mathrm{MW} \cdot 2\ \mathrm{h} = 11\ \mathrm{MWh}$.

To analyse stability of implemented control structures during disconnection, a set of different grid conditions is investigated in separate simulations. Therefore, load is varied between $-5.5\ \mathrm{MW} \le P_{\mathrm{Load}} \le 5.5\ \mathrm{MW}$ in steps of $P_{\mathrm{Step}} = 0.1\ \mathrm{p.u.}$, resulting in 21 steps. Since reactive power control of the grid-forming converter is not influenced by a blackout in the UG, the reactive power of the load is set to $Q_{\mathrm{Load}} = 0\ \mathrm{MVar}$.

Time for island detection and GESS activation has great influence on the control of DC link voltage. Therefore, a delay time for the signal s_{island} is implemented and variated between $0\ \mathrm{ms} \le T_{\mathrm{island\ delay}} \le 20\ \mathrm{ms}$ in steps of $T_{\mathrm{Step}} = 1\ \mathrm{ms}$, resulting in 21 steps. Combining these two parameter changes, 441 disconnection processes are investigated.

For analysing stability of reconnection processes, first a stable disconnection with $P_{\text{Load}} = 0$ MW is performed. Afterwards the load is changed to the desired value and the reconnection is performed. Considering the steps mentioned above, 441 reconnection processes are investigated.

Table 2: Critical values for definition of stable operation zone (SOZ)

	Upper	Nominal	Lower
U_{DC} in p. u.	1.2	1.0	0.8
U_{BB1b} in p. u.	1.1	1.0	0.85
f_{MG} in Hz.	51	50	49

To evaluate the performed simulations, results are checked for exceeding of critical values, as defined in Table 2. Critical values of U_{BB1b} and f_{MG} are based on [5], whereas values for U_{DC} are related to the implemented nominal modulation index $M = 0.8$ of the GIC. The first exceeding of a critical value is crucial for the simulation. If no exceeding of one critical value occurs, the simulation is defined as stable. The sum of all stable simulations is defined as stable operation zone (SOZ).

Analyses of long-term islanding behaviour

To analyse the proposed concept of combining GESS and FC functionalities, the CIGRÉ Benchmark Network for European Medium Voltage Grids [2] is used for simulations in DIgSILENT PowerFactory. Parameters and profiles for load and generation of decentralized actors are given in [1]. It is assumed, that half of the implemented load and generation capabilities is controllable by FC.

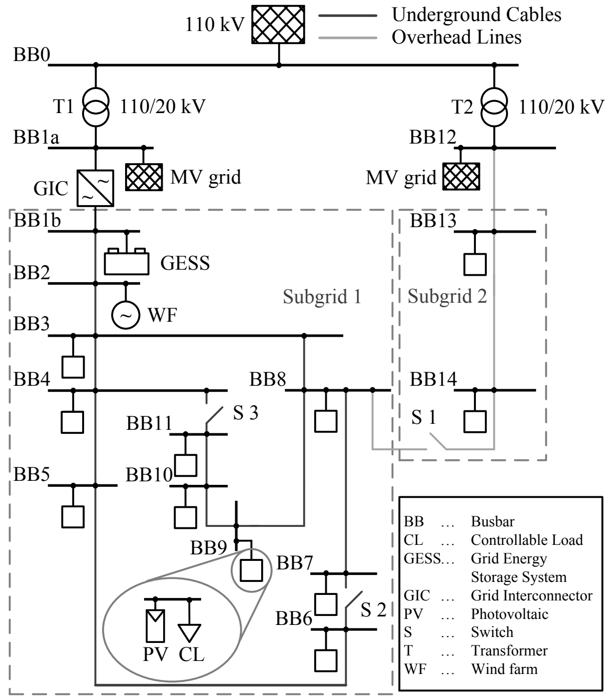

Fig. 5. CIGRÉ Benchmark Network for European Medium Voltage Grids [2] with additional decentralized actors

RESULTS

Islanding process

Fig. 6 shows simulation results for a disconnection process with $P_{\text{Load}} = 2$ MW and $T_{\text{island delay}} = 10$ ms. At $t = 0$ ms an UG blackout is simulated. Therefore, the DC link is discharged. After the delay time the GESS is activated and compensates the voltage distortion with maximum power input at the beginning. Due to lower AC voltage controller speed of the GIC, fast changes of active power at busbar BB1b lead to short-term distortions of AC voltage and frequency. This simulation is classified as stable.

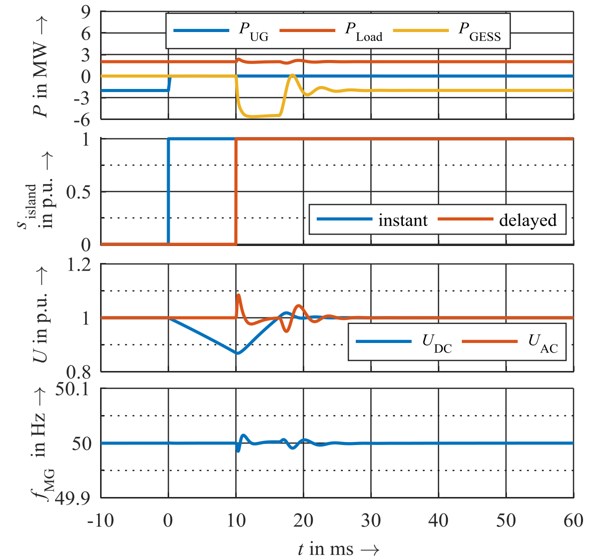

Fig. 6. Time response for islanding process for $P_{\text{Load}} = 2$ MW and $T_{\text{island delay}} = 10$ ms

Fig. 7 shows the results of 441 simulations. As it can be seen, for small load values a stable operation is achievable without dependency on time delay. For larger loads, AC busbar voltage limits are exceeded. By enlarging the time delay, DC voltage values are increasingly violated. Frequency limits are not exceeded. As a result, for time delays $T_{\text{island delay}} \leq 6$ ms a stable operation can be guaranteed over a wide active power spectrum.

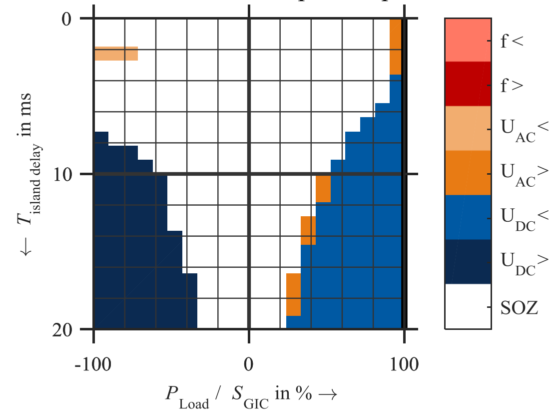

Fig. 7. Stable Operation Zone (SOZ) of islanding process dependend on active power flow over GIC and time delay for GESS activation (441 simulations)

Reconnection process

Results for stability analyses of reconnection processes are illustrated in Fig. 8. As it can be seen, time delay has no influence on the stability, since the GESS controlles the active power until the grid-supporting converter takes over control. Considering an abrubt deactivation of the GESS, larger values of P_{Load} lead to violations of AC voltage limits. When implementing a soft switch between GIC and GESS, exceeding of critical values is preventable.

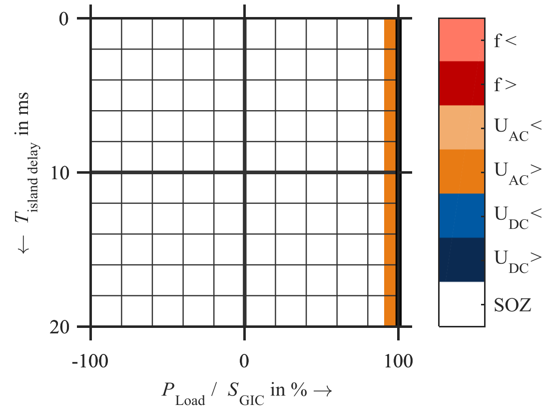

Fig. 8. Stable Operation Zone (SOZ) of reconnecting process dependent on active power flow over GIC and time delay for GESS deactivation (441 simulations)

Long-term analyses

In Fig. 9 results for a daily load profile are shown. As it can be seen, generation is dominating in morning hours, whereas load is dominant in evening hours.

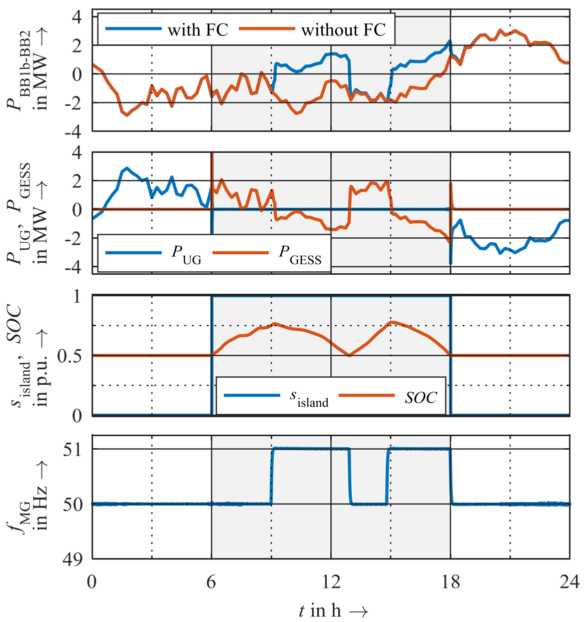

Fig. 9. Simulation results for daily load profile with islanded operation for $6.00 \leq t \leq 18.00$

At $t = 6.00$ an islanded operation of the MG is simulated. Therefore, the GESS takes over DC voltage control by providing active power. The dominant generation behaviour, leads to critical values of $SOC > 0.75$ p. u., which activates FC at $t = 9.00$. In contrast to the reference plot, which was simulated without using FC, it is noticeable, that generation is reduced significantly. Thus, the power flow obtains load behaviour, leading to a decreasing SOC. After reaching the reference SOC, FC is deactivated. Due to the domination PV generation during noon, the GESS is charged again. At $t = 15.00$ FC is activated again after reaching critical SOC values. The MG is reconnected at $t = 18.00$ and the grid-supporting converter takes over DC voltage control. To prepare for future blackouts, the GESS is charged to SOC_{ref}. Evidently, a stable operation can be ensured over long terms by combining GESS and FC.

CONCLUSIONS

This paper has proposed an approach to extend the concept of modular grids for islanded operation. Simulation results show that an uninterrupted and stable operation of islanded modular grids is achievable. An appropriate control of a grid-supporting energy storage system and controllable actors enables the distribution system operator to cover short- and long-term islanded operation and constantly provide customers with energy. Thus, islanded modular grids are a proper solution to maintain quality of service in energy systems based on decentralized energy resources.

Throughout this paper, values for storage capacity and state of charge were defined for general use. By applying adequate forecast methods, system reliability and efficiency can be optimized. In addition, future works should investigate the use of modular grids for black start capabilities.

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