Investigation of Resynchronisation Process and its Influence on Microgrid Components

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ABSTRACT

One of the most challenging aspects regarding the control of microgrids is the reconnection with the bulk power system. During this process, high stresses can occur for the microgrid components, depending on the alignment of the voltages of the two systems. How deviations in frequency, amplitude and angle of the voltages, as well as a time delay in the switching of the control of the grid-forming generators in the microgrid to grid-feeding control affects these stresses is investigated in this work. Simulations are carried out in two real MV networks with power electronic-based and synchronous generators. It is shown that an angle deviation can strongly affect the stresses of synchronous generators, while delays in the switching of the control mode result in high loads for inverter-based generators. The results can be used to determine the dimensioning of generators in microgrids as well as the layout of the protection system.

INTRODUCTION

Microgrids are a viable solution for future smart grids to avoid outages or to enhance power quality. With the increasing penetration of the distribution system with distributed generators (DGs), it has become possible to operate parts of the grid in islanded mode, independent from the bulk power system. If a disturbance occurs, the network dissociates into cells in order to isolate the faulty element and to keep as many customers supplied as possible [1].

Table 1: Microgrid reconnection requirements [2]

Avg. rating of DR/MVA	$\lvert\Delta f\rvert$ /Hz	$\lvert\Delta U_b\rvert$/p.u.	$\lvert\Delta\delta\rvert$/°
0-0.5	0.3	0.1	20
0.5-1.500	0.2	0.05	15
1.5-10	0.1	0.03	10

A critical aspect of microgrid operation is the transition between the islanded and grid-connected mode after the fault has been remedied and the bulk power system is able to supply the loads again. During this transition, high stress of the microgrid equipment can occur. These transient states, with possibly high overcurrents or generator torques, can trigger the protection system and affect the ageing of the components. In this paper it is investigated to what extent an imperfect synchronization of a microgrid with the bulk power system can influence the stress of the system components, such as inverter-based and synchronous DGs. This is of interest because the frequency, amplitude and phase of the voltage in the microgrid are usually not exactly aligned with the bulk power system due to measurement errors, fluctuating loads and generators in the microgrid, fluctuating frequency of the bulk power system or the response time of circuit breakers. They can even deviate immensely from the values required (see Table 1, where Δf, $\Delta\delta$ and ΔU_b are the differences of the voltages of the microgrid and the bulk power system at breaker closing in frequency, angle and amplitude) in case of faulty operation of the synchro-check. Moreover, it is required to reconnect the microgrid as fast as possible sometimes, for example, due to looming stability problems in the microgrid. Then a compromise needs to be found between the speed of the resynchronization and the voltage alignment at the breaker closing.

Numerical simulations are carried out using dynamic power system simulation software. The focus in this work is on the stress after the circuit breaker closing. Hence, a simple approach is chosen for the resynchronization control before the breaker closing as its impact on the behavior after the breaker closing is minor. Moreover, protective devices that would trigger under certain circumstances during the resynchronization process are not considered.

Table 2: Characteristic data of test systems

	Rural grid	Urban grid
R/X	1.39	1.58
Total/average line length (km)	274/0.78	175/0.5
Max./min. load (MW)	43.4/12.6	34/10.3
Generation capacity (MW)	51.8	24
Number of distributed Gen.	82	176
Number of substations	223	294
Power of the two grid-forming units (MW)	9.1 and 3	1.33 and 0.64

MODELLING AND CONTROL

Medium voltage power systems

For the simulations two test systems based on real German MV distribution system parts, one urban with high and one rural with low load density, are used. The parameters characterizing the considered grids are shown in Table 2. The MV power systems were adjusted to allow for islanded operation. In the islanded grid, there need to be some units that provide the voltage reference for the other units i.e. that control their voltage amplitude and frequency (grid-forming) while the other units control their output real and reactive power (grid-feeding) [3]. The two largest DGs of each grid are chosen as grid-forming units. The rest of the DGs, which are aggregated at the substations, are modelled as grid-feeding units. The loads are modelled as static PQ-nodes and are scaled accordingly to obtain the balance between generation and load, which is needed in the islanded mode.

Control of grid-forming units

The droop control is used for the operation control of the grid-forming synchronous generators (SGs) and voltage source inverters (VSIs). It can be described by the following equations [4]:

$$f_{DG} = f_0 - k_p(P_{set} - P_{DG}) \quad (1)$$

$$U_{DG} = U_0 - k_q(Q_{set} - Q_{DG}) \quad (2)$$

where f_{DG} and U_{DG} are the DG voltage frequency and amplitude, f_0 is the rated frequency of the grid, k_p is the real power droop coefficient, k_q is the reactive power droop coefficient, P_{set} and Q_{set} are the setpoints for the real and reactive power of the DG (given, for example, by the microgrid central controller) and P_{DG} and Q_{DG} are the measured output real and reactive power of the DG.

The grid-forming (SG) is controlled using standard models for the automatic voltage regulator [5] and the governor [6].

Synchronization control

A slightly simplified approach compared to the one given in [7] is used to synchronize the microgrid with the bulk power system. The frequency of the microgrid is adjusted to the frequency of the bulk power system by regulating the voltage reference of the grid forming SGs and the VSIs. The voltage is adjusted by manipulating f_0 and U_0 in Equations (1) and (2), respectively. Unless otherwise stated, the frequency deviation is controlled to amount to 20 mHz in order to allow for the alignment of the voltage angles. Simulations have shown that a small frequency deviation of 20 mHz has a negligible impact on the network stresses when closing the breaker. As it is not focused on the dynamics of the synchronization process before the breaker closing, the voltage of the bulk power system is assumed to be stable at 50 Hz with amplitude of 1 p.u. Only when a voltage deviation between both grids is simulated, it is assumed that the difference is shared between the grids. For example in case of a voltage difference of 0.1 p.u. the voltage in the microgrid will be set to 0.95 p.u. and in the bulk power system to 1.05 p.u.

SIMULATION RESULTS

The simulations can be divided into three different main cases and for each of them multiple scenarios where simulated. In the first case the influence of closing the breaker close to the edge of the reconnection requirements is investigated. In the second case, the stress when closing outside the reconnection requirements is examined. In the last case the breaker is closed at the edge of the requirements, similar to the first case. Here however, a delay in the switching mode of the grid-forming units to grid-feeding mode when the circuit breaker is closed and the bulk power system provides the voltage reference, is simulated.

Table 3 Results for closing at edge of requirements

Voltage deviation			Resulting generator loads					
Δf/ mHz	$\Delta\delta$/ °	ΔU_b/ p.u.	$I_{G,max}$/ p.u.		$P_{G,max}$/ p.u.		$U_{G,max}$/ p.u.	
Two SGs as grid-forming units								
			U	R	U	R	U	R
0	0	0	0.96	0.98	1.00	1.00	1.04	1.05
250	0	0	1.25	0.99	1.23	1.01	1.04	1.05
-250	0	0	1.15	1.15	1.17	1.16	1.04	1.05
0	15	0	1.52	1.33	1.51	1.36	1.04	1.05
0	-15	0	1.89	1.57	1.87	1.62	1.04	1.05
0	0	0.1	1.06	1.09	1.00	1.00	1.04	1.05
0	0	-0.1	0.90	0.97	1.00	1.00	1.11	1.07
250	15	0.1	1.74	1.50	1.60	1.39	1.04	1.04
250	-15	0.1	1.81	1.60	1.70	1.44	1.04	1.04
250	15	-0.1	1.45	1.11	1.43	1.11	1.11	1.07
250	-15	-0.1	1.80	1.27	1.67	1.27	1.11	1.07
-250	15	0.1	1.67	1.56	1.55	1.43	1.04	1.05
-250	-15	0.1	1.75	1.56	1.66	1.41	1.04	1.05
-250	15	-0.1	1.33	1.19	1.36	1.19	1.11	1.07
-250	-15	-0.1	1.70	1.28	1.58	1.28	1.11	1.07
One VSI and one SG as grid-forming units								
			U	R	U	R	U	R
0	0	0	1.00	0.98	1.00	1.00	1.04	1.05
250	0	0	1.06	0.98	1.09	1.00	1.04	1.05
-250	0	0	1.09	0.98	1.11	1.00	1.04	1.05
0	15	0	1.46	1.10	1.52	1.06	1.04	1.05
0	-15	0	1.76	1.18	1.82	1.19	1.04	1.05
0	0	0.1	1.06	1.08	1.00	1.00	1.04	1.05
0	0	-0.1	0.92	0.96	1.00	1.00	1.11	1.07
250	15	0.1	1.67	1.23	1.56	1.00	1.04	1.05
250	-15	0.1	1.75	1.30	1.62	1.07	1.04	1.05
250	15	-0.1	1.54	0.97	1.61	1.00	1.11	1.07
250	-15	-0.1	1.91	1.11	1.84	1.08	1.11	1.07
-250	15	0.1	1.67	1.29	1.56	1.07	1.04	1.05
-250	-15	0.1	1.75	1.25	1.63	1.12	1.04	1.05
-250	15	-0.1	1.31	1.04	1.42	1.05	1.11	1.07
-250	-15	-0.1	1.86	1.16	1.80	1.17	1.11	1.07

The results are represented in RMS-values as the voltages are assumed to be balanced in all simulations. It is focused on the stress of the grid-forming DGs as the worst loading occurs here. At the circuit breaker for example, only transient currents flow after the reconnection because generation and load is balanced in the islanded grid before the closing. These currents are much smaller than in case of the maximum load or a short circuit fault and are therefore not considered.

Closing at edge of reconnection requirements

Simulations in both considered MV grids were carried out to show the impact of closing the circuit breaker at voltage deviations close to the edge of the corridor given in the reconnection requirements shown in Table 1. At the exact moment the circuit breaker closes, the grid-forming units switch from grid-forming to grid-feeding control to provide active power of 1 p.u. and a power factor of 0.95 overexcited.

It was found out that the resulting loading of the VSIs is always much smaller compared to the loading of SGs due to the smaller time constants in the case of inverters. A comparison of both is shown in Figure 1, where a synchronization process with one SG and one VSI is shown for a deviation in the voltage angle of -15° (microgrid is leading). The synchronization process is started at 1 s and at about 9 s the breaker is closed. While the SG shows a large overshoot and oscillation, the VSI has only a minor overshoot and no oscillation.

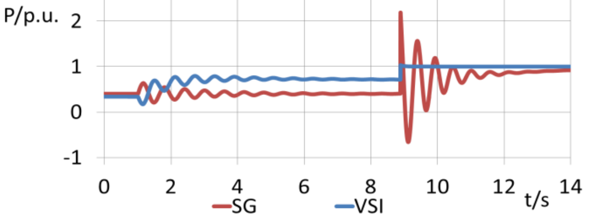

Figure 1 Comparison of SG and VSI

The results for the cases of two SGs and for one SG together with a VSI are listed in Table 3. Δf, $\Delta\delta$ and ΔU_b are the differences of the voltages at breaker closing in frequency, angle and amplitude (a negative value means that the frequency of the bulk power system is lower or its angle lags). $I_{G,max}$, $P_{G,max}$ and $U_{G,max}$ are the maximum currents, active powers and voltages occurring of all grid-forming DGs. U stands for the urban and R for the rural grid.

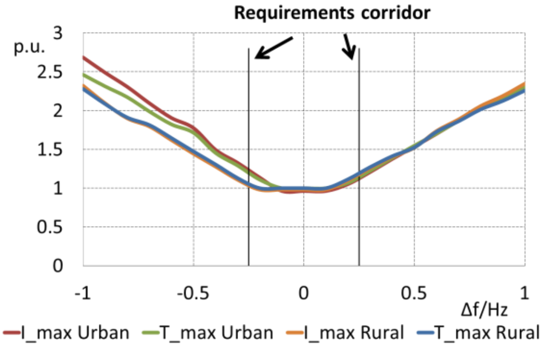

Figure 2 Results for deviations in frequency

It becomes apparent that the worst stresses (red marker) on the current and torque occur when the angles of the grids differ and a leading angle of the microgrid is worse than a lagging. Furthermore, it cannot be stated that deviations in all criteria are always worse than a deviation in only one of them. Another outcome is that no definite statement can be made whether the stress is worse with two SGs or one SG and one VSI. In the rural grid the stress is always lower when there is a VSI, but in the urban grid, it depends on the scenario. With respect to the maximum voltage, the worst cases are when the bulk power system voltage is lower than that of the microgrid. However, this is due to the voltage amplitude of the microgrid before the circuit breaker closes, which is determined by the scenario and not dependent on the dynamic interactions after the closing. Therefore, $U_{G,max}$ is not further considered in the following.

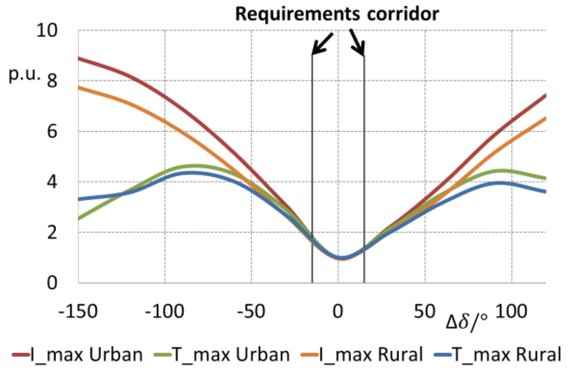

Figure 3 Results for angle deviation

Closing outside of reconnection requirements

In this chapter, it is looked at the stress that appears for varying values of the voltage deviations, including values outside the allowed synchronization corridor. Two SGs are used as grid-forming units. The interpolated results of the maximum current and torque at the SGs for a varying frequency deviation are shown in Figure 2, where the borders of the resynchronization requirements are also marked. The curves have an almost parabolic shape. The values for the maximum torque and the maximum current are similar because, in order to align the frequencies of both grids after the breaker closing, it is real power that is mainly exchanged.

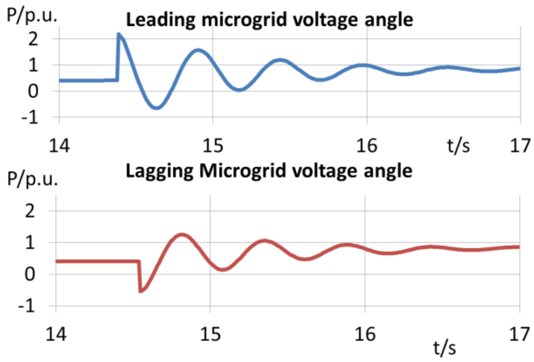

Figure 4 Comparison of leading (a) and lagging (b) microgrid voltage angle

Figure 3 shows the results for a variation of the angle deviation between -150° and 120°. For larger differences the SGs tend to lose their synchronism. Again, it becomes apparent that angle deviations are worse than frequency deviations and a leading microgrid voltage angle (negative values) is worse than a lagging. A comparison of the case of a leading and lagging angle is shown in Figure 4. For a leading microgrid angle, active power is transmitted from the

Table 4 Results for delay of control mode change

Time delay/voltage deviation				Resulting DG loads	
Δt/ ms	Δf/ mHz	$\Delta\delta$/ °	ΔU_b/ p.u.	$I_{G,max}$/ p.u.	$P_{G,max}$/ p.u.
SG					
0	0	0	0	0.98	1.00
250	0	0	0	1.05	1.00
500	0	0	0	1.07	1.00
0.00	250	0	0	1.00	1.01
250	250	0	0	1.02	1.02
500	250	0	0	1.36	1.41
0	0	-15	0	1.57	1.62
250	0	-15	0	1.76	1.82
500	0	-15	0	1.85	1.82
0.00	0	0	0.10	1.09	1.00
250	0	0	0.10	0.99	1.00
500	0	0	0.10	1.01	1.00
VSI					
0	0	0	0	0.98	1.00
250	0	0	0	1.56	1.34
500	0	0	0	1.56	1.34
0	250	0	0	0.98	1.00
250	250	0	0	4.26	4.20
500	250	0	0	5.62	5.22
0	0	-15	0	1.18	1.19
250	0	-15	0	3.01	2.87
500	0	-15	0	3.01	2.87
0	0	0	0.1	1.08	1.00
250	0	0	0.1	1.75	1.00
500	0	0	0.1	1.98	1.00

microgrid to the external grid the moment the circuit breaker closes while for a lagging angle, it is the other way round. A leading angle leads to a high overshoot in the positive direction while a lagging leads to an overshoot in the negative direction in the moment the breaker closes (at about 14.5s).

The maximum torque is obtained at around -90° which was expected as the active power exchange is proportional to the sine of the angle between the two grids. Although the maximum real power decreases for very large and very negative angles, the maximum current keeps rising. This is due to the rising absolute value of the reactive power as can be deduced from Eq. 3, which describes the reactive power exchange between two voltage sources (amplitudes $U_1$and U_2 with an angle φ between them) over an inductive line with a reactance X (resistance is neglected).

$$Q = -\frac{1}{X}(|U_2|^2 - |U_1| \cdot |U_2| \cdot \cos\varphi) \qquad (3)$$

Delay of control mode change

In the previous simulations it was assumed that the grid-forming DGs switch to PQ control mode the moment the circuit breaker closes. How a delay in the switching of the control mode affects the stress on the DGs is investigated in the following scenarios. This delay can be caused, for example, by a communication delay between the synchro-check and the DGs. The rural grid is used and the grid-forming units are one SG and one VSI. Results for switching without voltage deviation and for switching at the edge of the synchronization corridor are shown in Table 4, where Δt is the time delay and $P_{G,max}$ is the maximum real power (which is very closely related to $T_{G,max}$ for the SG). The stresses are worse on the VSI due to the smaller time constants. Here, frequency deviations cause the highest stress as the voltage angles will drift further apart the longer the switching delay. Of course, the protection of the VSI would not allow such high current values of 5.62 p.u. The SG faces the worst stress for a difference in voltage angles. Here, the large time constants prevent the angles from drifting apart quickly in case of a frequency difference.

CONCLUSION

It was shown in this paper that the worst stress on SGs during a badly synchronized microgrid reconnection occurs when the voltage angle of the microgrid lead the angle of the bulk power system. For VSIs, due to the small time constants, the worst loads appear when the there is a time delay from the grid-forming to grid-feeding control mode.

Further research is required to examine the impact of advanced control strategies and to determine the influence of other simulation variables, like grid parameters or loads with asynchronous motors instead of static loads.

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