INFLUENCE OF INACCURATE MEDIUM VOLTAGE MICROGRID SYNCHRONIZATION ON SYNCHRONOUS GENERATORS

Simon Eberlein
University of Stuttgart - Germany

Krzysztof Rudion
University of Stuttgart - Germany

ABSTRACT

Microgrids allow for the continuous supply of customers during outages of the bulk power system. A challenging aspect of microgrid operation is the transition from islanded to grid-connected operation mode. When the voltages of the microgrid and the bulk power system are not aligned in the event of the microgrid reconnection, components can suffer heavy loadings. This work investigates these loadings for diesel synchronous generators in MV microgrids for various scenarios of angle, amplitude and frequency deviations of the voltage of both grids. The outcome is relevant to anticipate generator loadings and to enhance the synchronization control.

INTRODUCTION

Microgrids allow for the continuous supply of customers during disturbances in the bulk power system. In this case, the power network can dissociate into independent cells to keep as many customers supplied as possible [1]. Besides challenges such as fluctuating distributed generation, one critical situation of microgrid operation is when the fault in the bulk power system has been remedied and the microgrid goes back from islanded to grid-connected mode. These transient states can entail high burden, such as overcurrents or large synchronous generator torques, for the microgrid components. This paper puts a focus on the imperfect synchronization of MV microgrids with the bulk power system and investigates the occurring stress of synchronous generators (SG) during the transition between the mentioned operating modes.

Unpredictable influences, such as measurement errors, the tolerance and response time of circuit breakers or the fluctuation of generators and loads in the microgrid, cause the frequency, amplitude and phase angle of the microgrid never to be exactly aligned with the bulk power system when the breaker closes. Even tremendous deviations can occur when there is a malfunction of the synchrocheck. In some situations, it might be necessary to reconnect the microgrid as fast as possible, e.g. during looming instability of the islanded microgrid. Then a compromise needs to be found between quick resynchronization and its accuracy.

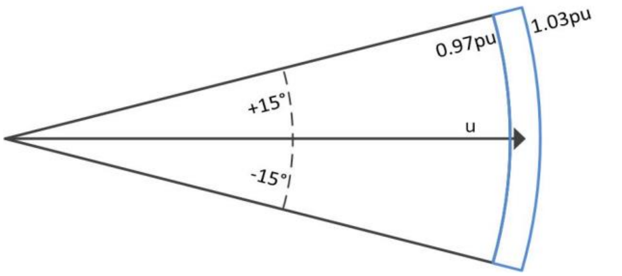

Fig. 1: Requirements for synchronization accuracy of amplitude and angle (blue)

The requirements for the synchronization accuracy for microgrids with a rated power of 1.5 to 10MVA are illustrated in Fig. 1 concerning voltage angle and amplitude [2]. A further restriction is the maximum frequency deviation of 0.1Hz.

A first step to analyze the influence of inaccurate synchronization was taken in [3]. By simulating some basic scenarios for existing German distribution systems, it is shown that inverter interfaced devices can react rapidly in the event of overloads and do not face larger overcurrents after the breaker closure due to their small time constants. Therefore, inverter interfaced devices are less interesting and it is focused on SGs. A systematic approach is made in [4] to examine various scenarios for the transition of LV microgrids. It is concluded that angle discrepancies have the most detrimental effects and that the impacts of the inertia constant magnitude of the SGs and the line R/X-ratio are minor. In this work, similar studies as in [4] for SG loading during transition are carried out, but it is looked at MV microgrids. Scenarios include deviations that are very large compared to the specified requirements [2] to include worst case scenarios, like the malfunction of the synchrocheck.

MODELLING AND CONTROL

Medium voltage network

The 20kV microgrid under study consists of a radial feeder with two lines. A SG and a static aggregated load are attached to node 1 and 2. The breaker separating microgrid and bulk power system is located at node 0. The components data are given in Table 1.

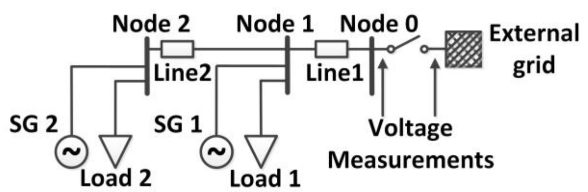

Fig. 2: Studied microgrid

Table 1: Data of grid components

Medium voltage grid and loads			
Line impedance	(0.16+j0.19)Ω/km	Line length	10km
Nominal voltage	20kV	Nominal power (loads)	2MVA
Power factor (loads)	0.95 (ind)		
Synchronous generators			
Nominal power	3.125MW	X_d''	0.17pu
Nominal voltage	2.4kV	X_q	1.06pu
Inertia constant H	1.07s	X_q''	0.18pu
Friction factor B	0.02pu	T_{d0}'	3.7s
X_d	1.56pu	T_{d0}''	0.05s
X_d'	0.29pu	T_{q0}''	0.05s

Synchronous generators

The data for the MV diesel SGs are given in Table 1 [5]. The AC5A model is used for the AVR [6]. To share the load, the SGs control is grid-forming with droop control. It is described by the following equations [7]:

$$f_{SG} = f_0 - k_p(P_{set} - P_{SG}) \quad (1)$$
$$U_{SG} = U_0 - k_q(Q_{set} - Q_{SG}) \quad (2)$$

where f_{SG} and U_{SG} are the set values for the SG voltage frequency and amplitude, f_0 and U_0 are the rated frequency and amplitude 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 set values for the real and reactive power of the SG (given by the microgrid central controller, for example) and P_{SG} and Q_{SG} are the measured output real and reactive power of the SG.
When the breaker is closed and the microgrid is in grid-connected operation mode, the SGs switch to pq-control and, after the transients have vanished, supply the same active and reactive power as in the moment before the closure.

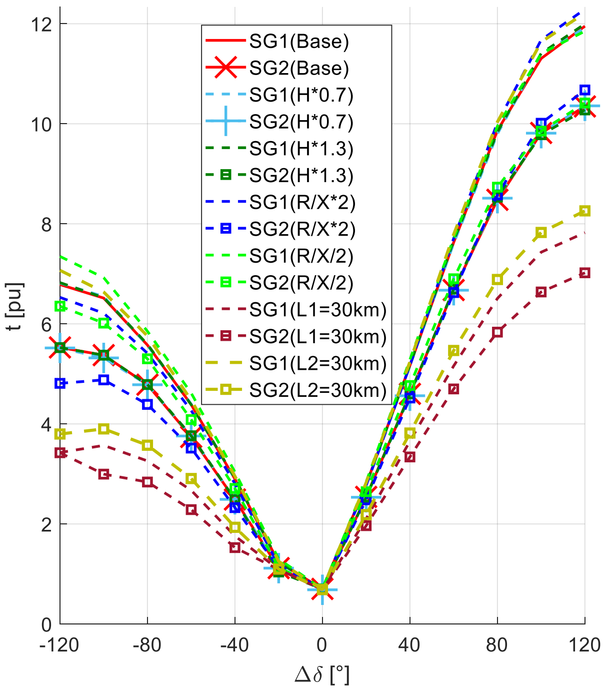

Fig. 3: Results for the torque of the SGs for various angle deviations

Synchronozation control

To align the voltages of both systems, the voltage reference of the SGs, i.e. f_0 and U_0, in Eq. 1 and 2 are adjusted using a PI-controller [8]. The input of the PI-controller is the difference of the voltages on both sides of the breaker, which is controlled to amount to a certain value. The focus of this work is not the dynamics of the synchronization process, but on the transients after the reconnection. Therefore, the bulk power system is assumed to be a stiff grid with a stable frequency of 50Hz and an amplitude of 1pu. The microgrid voltage is controlled to cause certain discrepancies at breaker closure.

SIMULATION RESULTS

In the following simulations, the maximum occurring absolute values of torque (t) and current (i) of the SGs after breaker closure are exemplified as a measure of generator loading for various scenarios using electromechanical power system simulation. Finally, results of time domain simulation are shown to provide deeper insight to the observed phenomena.

Angle deviation

The maximum torques for various angle deviations between -120° and +120° are depicted in Fig. 3. Voltage amplitudes and frequencies are aligned. In all scenarios, there is a steep increase in torques with growing positive $\Delta\delta$ values, which stand for a leading microgrid angle. The rise is less steep for lagging microgrid angles. SG1 experiences higher loadings compared to SG2, as its line impedance towards the breaker is smaller.
In the base scenario ("Base") the parameters from Table 1 are used. Decreasing the inertia constant H to 0.7-times its initial value ("H*0.7") or increasing it to 1.3-times the initial value ("H*1.3") does not perceptibly affect the outcome as the data in the plot is directly above the data for the base scenario. Doubling the R/X-ratio of the lines while keeping the absolute impedance constant ("R/X*2") leads to slightly smaller loadings for both SGs at negative angles, while the burden is larger for positive angles. On the other hand, dividing the R/X-ratio by two ("R/X/2") increases the loadings for negative angles, while it has negligible influence for positive angles. To investigate the influence of the distance between the SGs and the breaker, the length of line 1 is set to 30km instead of 10km ("L1=30km"). The loadings of both SGs are reduced considerably. When the length of line 2 is increased (while length of line 1 is 10km), the loading of SG2 is reduced, but not as much as in the scenario before. SG1 then experiences slightly higher stress compared to the base scenario.
The outcome for the maximum current for similar simulations is given in Fig. 4. There is a steep, almost monotonous increase in both directions. Similar to

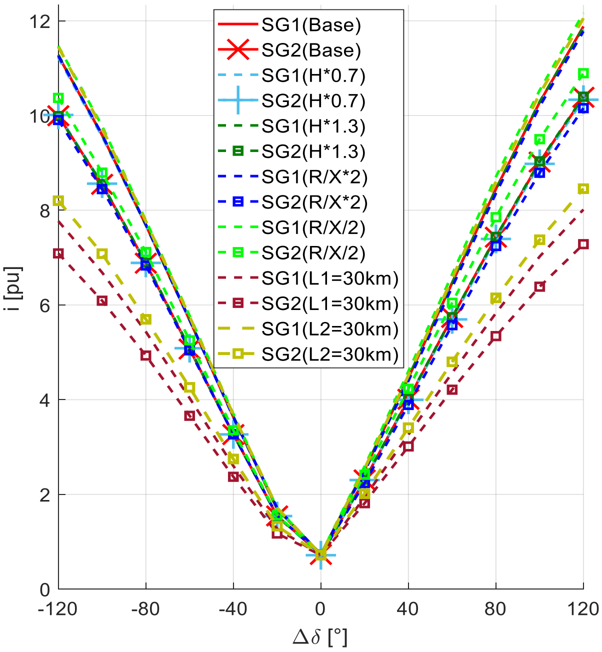

Fig. 4: Results for the current of the SGs for various angle deviations

torques, the inertia constant's influence is minor. The impact of the R/X-ratio is less significant for currents compared to torques. Again, the distance to the breaker has the most pronounced influence. Increasing the length of line 1 strongly reduces the currents of both SGs. Increasing the length of line 2 reduces the currents of SG2 while they are slightly increased for SG1. The observed currents of both SGs add up to cause very high currents at the breaker.

Frequency deviation

The results for discrepancies of the frequency are illustrated in Fig. 5. The torques are generally much lower compared to angle deviations. An almost monotonous increase for positive (microgrid frequency is higher) and negative values can be observed. As expected, the inertia constant H has the largest impact. The burdens of SG1 and SG2 are almost the same.
The characteristics of the resulting currents are similar to the torques for frequency deviations. Moreover, they do not exceed 1.6pu in any scenario. Hence, there is no danger of harming the microgrid components and it is refrained from showing the Figure.

Voltage deviation

Varying the voltage amplitude deviation also leads to much lower torques compared to angle deviations as depicted in Fig. 6. For negative voltage deviations (microgrid voltage is lower), the values stay almost constant. One reason for this is that lower voltages lead to lower power consumption of the voltage dependent loads in the microgrid and, therefore, to decreased loading of the SGs previous to the breaker closing. In case of overvoltages in the microgrid, the SG torques experience an almost monotonous increase. The lowest burden occurs when the length of line 1 is increased and the highest when the R/X-ratio is doubled. Again, it is

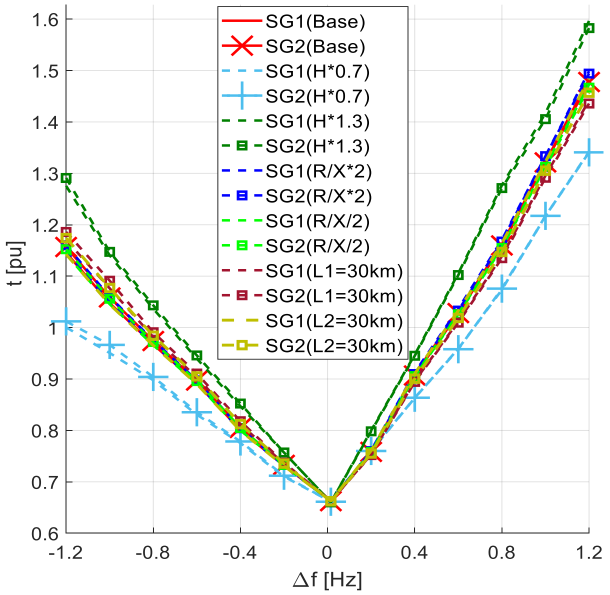

Fig. 5: Results for the torque of the SGs for various frequency deviations

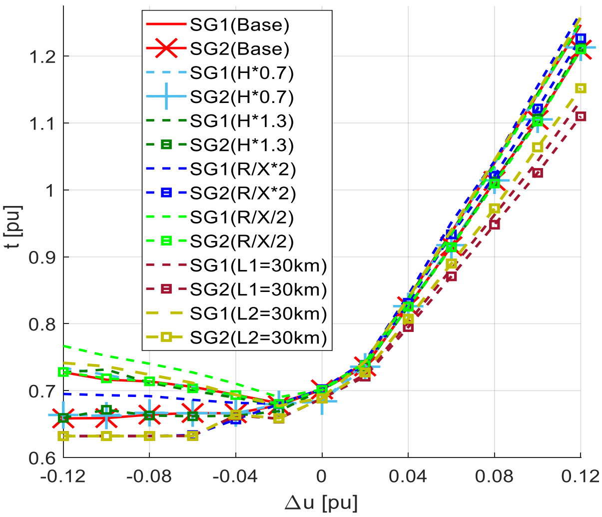

Fig. 6: Results for the torque for various amplitude deviations

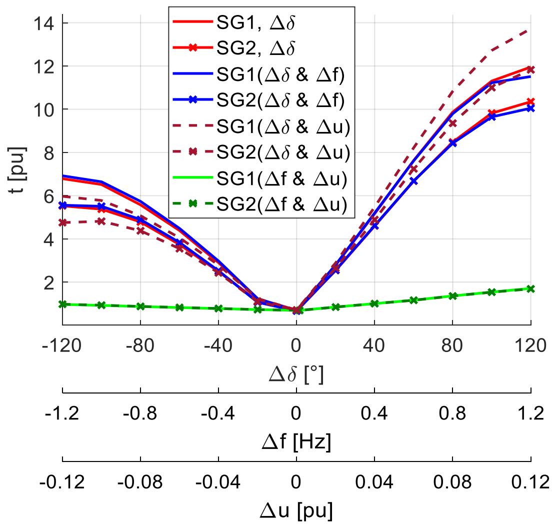

Fig. 7: Results for the torque of the SGs for combined deviations of angle (Δδ), frequency (Δf) and amplitude (Δu)

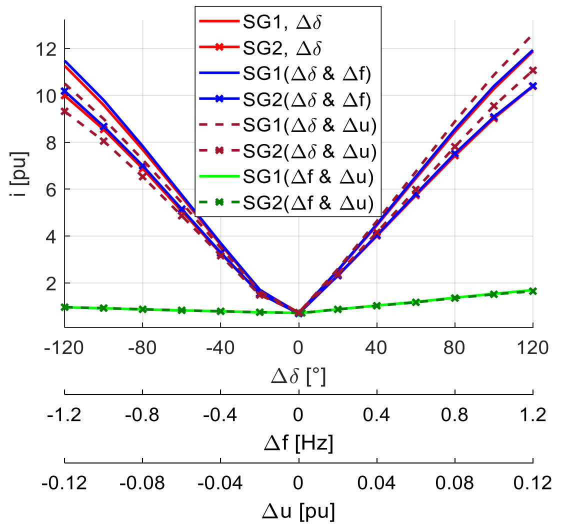

Fig. 8: Results for the current of the SGs for combined deviations of angle ($\Delta\delta$), frequency (Δf) and amplitude (Δu)

refrained from showing the results of the current loadings as they are comparatively low.

Combined deviation

In this chapter it is looked at scenarios where deviations in angle, frequency and amplitude are combined as depicted in Fig. 7, where also the base scenario with only angle deviations ("$\Delta\delta$") shown for comparison. For example, for a combination of angle and frequency deviation ("$\Delta\delta$ & Δf"), the deviations from the $\Delta\delta$-axis and Δf-axis are combined. The combination of positive angle and amplitude deviations lead to the highest torques while it results in lower torques for negative values. It is interesting that combining angle and frequency deviations does not significantly worsen the loadings. Again, the risk of harming components is low for amplitude and frequency discrepancies, even when they are combined.
Currents in this scenario have similar characteristics as the torques as illustrated in Fig. 8, but with a steeper increase. Combinations of positive angle and amplitude deviations cause the worst burden.

Time Domain Simulation

Finally, to get further insight in the described phenomena, the results of time domain simulations for the torque of SG1 for the first 200ms after the breaker

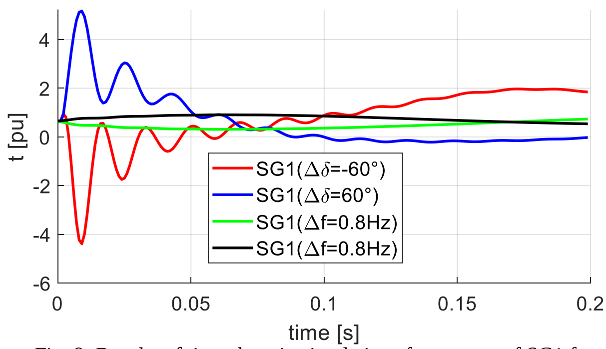

Fig. 9: Results of time-domain simulations for torques of SG1 for angle ($\Delta\delta$) and frequency deviations (Δf)

closure are illustrated in Fig. 9. When the microgrid angle leads ($\Delta\delta$=60°), SG1 provides higher active power to the external grid in the moment the breaker closes. In case the microgrid angle lags, the SGs in the microgrid receive active power and the torque is reduced to large negative values. As the SGs provide positive active power before the breaker closure, the initial torque value is above zero. Hence, the absolute torque is larger for leading microgrid angles compared to lagging. Similar phenomena occur for positive and negative frequency deviations, but resulting modes are slower and torques are much lower, as seen in Fig. 9.

CONCLUSION

In this work, various scenarios of inaccurate microgrid synchronization and its influence on diesel synchronous generators have been investigated. Similar to [4] where LV microgrids are studied, it is found that angle deviations cause the worst stresses by far in MV microgrids. From the viewpoint of generator loadings, the requirements for frequency and amplitude deviations [2] are very strict, as the influence on torques and currents is minor. In contrast to LV microgrids, the impact of the R/X-ratio and especially the line length is more pronounced. In future, the influence of asynchronous motors instead of static loads ought to be investigated. The results should be validated by hardware tests.

REFERENCES

[1] M. Zhang and J. Chen, "Islanding and Scheduling of Power Distribution Systems With Distributed Generation," *IEEE Trans. Power Syst.*, vol. 30, no. 6, pp. 3120–3129, Nov. 2015.
[2] "IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems," *IEEE Std 1547-2003*, pp. 1–28, Jul. 2003.
[3] S. Eberlein and K. Rudion, "Investigation of Resynchronisation Process and its Influence on Microgrid Components," *Cired Workshop*, pp. 119 (4 .)-119 (4 .), Jan. 2016.
[4] S. Eberlein and K. Rudion, "Influence of Inaccurate Low Voltage Microgrid Synchronization on Synchronous Generators," *IEEE EnergyCon*.
[5] K. E. Yeager and J. R. Willis, "Modeling of emergency diesel generators in an 800 megawatt nuclear power plant," *IEEE Trans. Energy Convers.*, vol. 8, no. 3, pp. 433–441, Sep. 1993.
[6] "IEEE Recommended Practice for Excitation System Models for Power System Stability Studies," *IEEE Std 4215-2005 Revis. IEEE Std 4215-1992*, pp. 1–93, Apr. 2006.
[7] J. Rocabert, A. Luna, F. Blaabjerg, and P. Rodríguez, "Control of Power Converters in AC Microgrids," *IEEE Trans. Power Electron.*, vol. 27, no. 11, pp. 4734–4749, Nov. 2012.
[8] C. Jin, M. Gao, X. Lv, and M. Chen, "A seamless transfer strategy of islanded and grid-connected mode switching for microgrid based on droop control," in *2012 IEEE Energy Conversion Congress and Exposition (ECCE)*, 2012, pp. 969–973.