Risk assessment of electrolyser failure: Analysis of grid faults and grid-serving behavior

Executive Summary

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1 Motivation and Objectives

Increasing requests for connection of electrolyser capacity in Germany poses a high risk to grid stability if these loads are disconnected due to grid faults. Furthermore, there are currently no standards regarding the grid-serving behaviour of electrolyser loads, which could be critical in the event of a fault.

The project was undertaken to assess such risks, particulary during critical hours of high wind generation combined with a highly stressed transmission grid, and to evaluate the minimum grid-serving requirements for such electrolyser loads to ensure post-fault grid stability under stressed conditions.

The project considers an additional 7.5 GW of installed capacity of electrolyser loads, concentrated in the north of Germany, in the coastal region near near the North Sea, based on the potential availability of active power from offshore projects and the existing gas infrastructure for hydrogen in this region [1].

The following objectives were identified

- Identify critical fault locations involving disconnection of large capacities of electrolyser loads due to network faults.
- A risk assessment with voltage- and frequency-stability studies in case of such critical disturbances.
- Evaluate the advantages and disadvantages of different technical requirements from the electrolyser loads to ensure grid stability after faults. Active power recovery with ramp-in rather than sudden step-in, reactive current injection (Iq(U)) with different droops and deadbands, and fault ride through (FRT) with constant active current within time-dependent voltage limits are to be investigated.

Detailed results can be found in the final presentation [2] as part of the full documentation of the study.

2 Methodology

The study is based on a grid model of the European transmission system developed in a previous study commissioned by Tennet TSO GmbH [3]. The focus of the study is limited to Germany. A critical hour of operation with high grid utilisation due to a high north-south active power transfer, also identified in [3] was chosen. The grid model was then modified by adding electrolyser loads. An estimate of 80 GW of additional capacity of electrolyser loads in Germany by the year 2045 is made in [4]. However, it was not possible to integrate all of the estimated capacity into the grid under consideration, which is based on projected data for the year 2028. The load flow did not converge due to the limited active power generation and transmission capacity according to the projected data for 2028. A total of 7.5 GW of electrolyser capacity could be integrated into the given grid. The capacity was distributed evenly across five locations in northern Germany, namely Emden, Diele, Garrel, Conneforde and the Wilhelmshaven region. These locations are based on the existing gas infrastructure for hydrogen and the proximity to surplus active power generated by offshore projects in this region [1]. Figure 1 shows the locations of these loads.

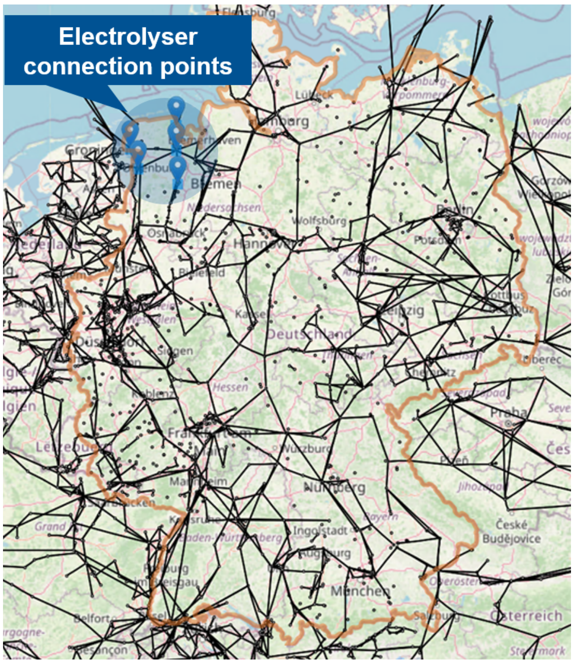

Figure 1 Location of electrolyser loads added in the grid.

The first step is a comprehensive fault analysis to identify critical grid faults. Short-circuits are simulated for various locations in the German transmission grid. The faults are cleared after 150 ms, after which the affected element is taken out of service. The faults considered include (n-1) busbar faults, for which a single system is taken out of service, and in addition (n-2) double line faults, for which the entire corridor is taken out of service. The faults are accompanied by different behaviour of the electrolysers (see Fig. 2). The dynamics of the electrolyser loads are related to the active power as a worst case assumption.

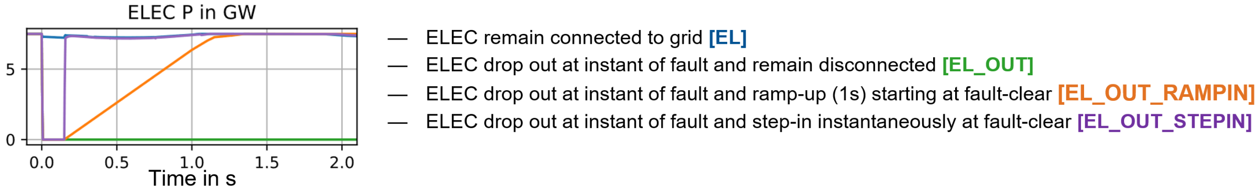

Figure 2 Different electrolyser (ELEC) behaviours after a grid fault, illustrated by the active power demand.

The study examines the cumulative effect of short-circuit faults in the grid and different electrolyser behaviours and how this can adversely affect the dynamic stability of the system. From this, the key stability issues are identified, such as the interactions between short-term voltage stability and transient rotor angle stability. Two fault locations were selected for further analysis, each illustrating one of the dominant stability issues. Different electrolyser responses to the grid faults as shown in Figure 2 are investigated in terms of their impact on dynamic stability. Short-term frequency stability is also analysed for the two fault locations. This is not considered to be critical for the given grid model and study cases, but the effect of different electrolyser responses on frequency stability is still instructive. This is presented in the discussion of ramp-in as a grid-serving behaviour of electrolysers in Section 3.2.1.

Finally, several grid-serving functions of the electrolyser loads, such as ramped active power recovery (RAMPIN) after an outage due to a fault instead of sudden step-in (STEPIN), dynamic Iq(u) injection to support voltage recovery, and fault ride through (FRT) requirement were investigated. For this, a dynamic RMS model is provided by Tennet TSO GmbH. The Iq(u) characteristics with different deadband and droop settings are shown in Figure 3 and the considered FRT characteristics in Figure 4. In this part of the study, both constant current and constant power models of electrolyser loads are tested and the results are similar in the cases considered. However, for consistency with the concept of Iq(u) with reactive current priority as well as the FRT characteristics, the results with the constant current model have been shown in Chapter 3. For the FRT behaviour, the voltage at the electrolyser terminals never fell below the thresholds of region R1 (as shown in Figure 4), within which the electrolyser draws constant active current. Thus, the dynamics observed when electrolysers remain connected to the grid through faults (see [EL] in Figure 2) suggest that requiring FRT from the electrolysers would benefit grid stability (see Section 3.2.2).

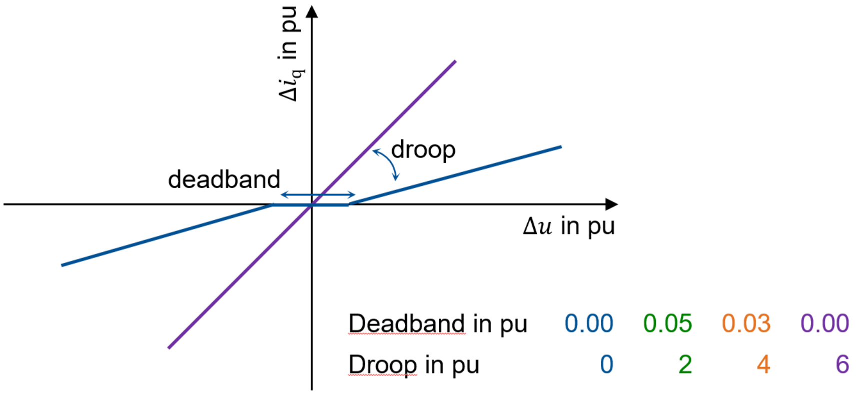

Figure 3 Iq(u) characteristics in per unit for different deadband and droop settings.

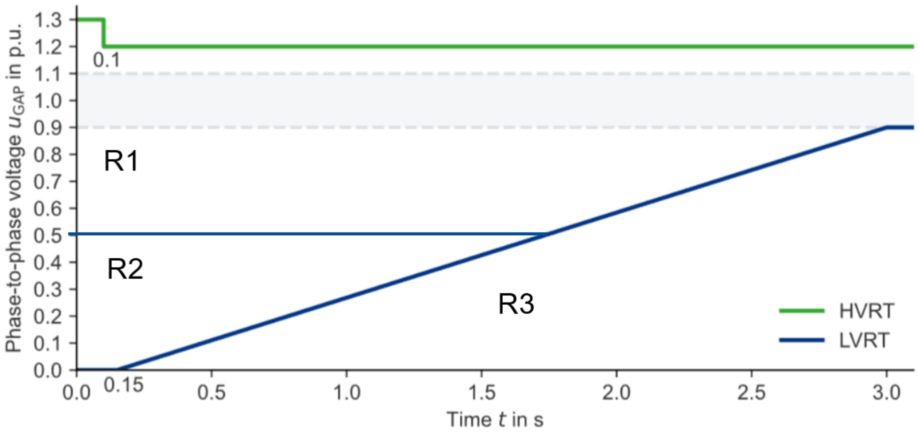

Figure 4 FRT curve implemented. R1: Electrolyser (ELEC) draws constant active current, R2: zero current, but ELEC returns to normal behaviour if voltage eventually improves (>0.5 pu), R3: ELEC falls permanently off.

3 Summary of results

The study was carried out using projected data for the year 2028. In addition, assumptions have been made about electrolyser locations based on what is most probable, as discussed in Chapter 2. It is therefore important to note that while the results of this study provide a good qualitative understanding of the mechanisms at play, they do not indicate a specific situation in the real system.

3.1 The two stability problems

Two critical fault locations, as illustrated in Figure 5, were obtained from the fault analysis described in Chapter 2. Double line faults at fault location A and fault location B were found to be the worst cases in terms of short-term voltage stability (FL-A) and transient rotor angle stability (FL-B) respectively. Figure 5 shows the relative locations of the two faults with respect to the electrolysers. It also shows the voltages in the grid in response to the faults at these locations accompanied by different responses of the electrolysers (see Figure 2). Only the lower envelopes of the voltages across all 380 kV (EHV) busbars in Germany are shown, as these are the most relevant for our observations. This means that at any given point in time, a given curve shows the minimum value of the voltage magnitude encountered at any of the EHV busbars.

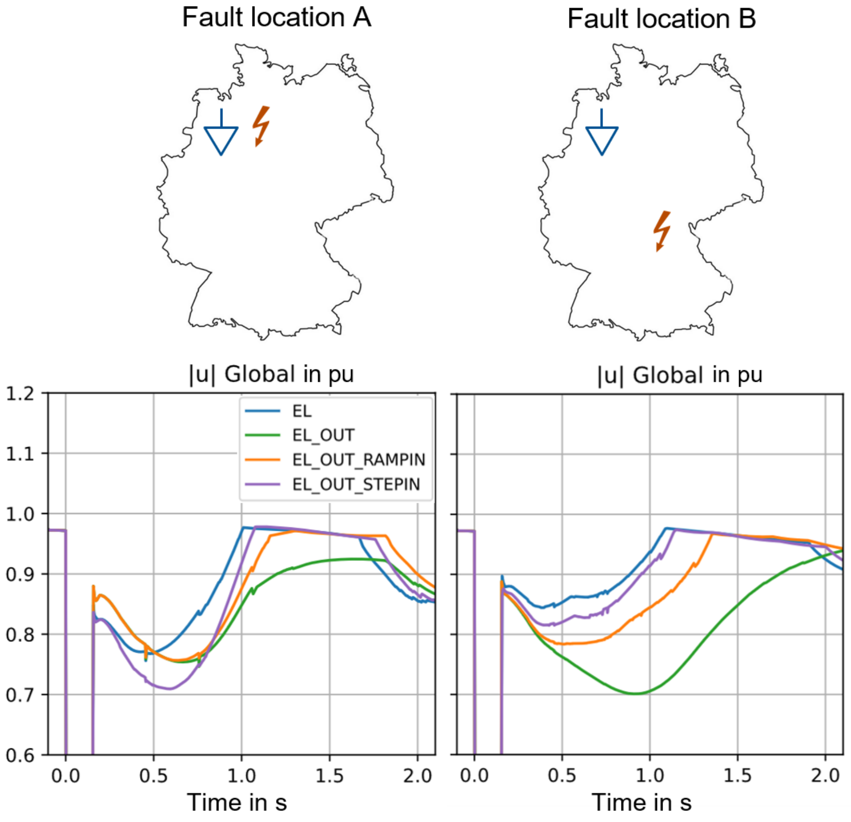

Figure 5 Voltage response to various electrolyser load responses associated with short circuit faults

The following observations are made from the plots of Figure 5.

- The curves **EL** in both plots show the voltage envelopes when the electrolysers remain connected to the grid through the fault. It can be seen that the voltage dip in this case is the smallest, compared to the cases where the electrolysers show some other response along with the short circuit fault. This is discussed again in section 3.2.2 in relation to the FRT requirements of the electrolyser loads.

- The case of **EL_OUT_STEPIN** represents the loss of electrolysers at the moment of the short circuit and the stepwise recovery of the active power after the fault has been cleared. This is considered to be the worst case in terms of voltage recovery for the short circuit at FL-A and is recognised as a short-term voltage stability issue. Voltage stability is a local effect influenced by different electrolyser responses close to the fault location. Subsection 3.1.1 explains this conclusion.
- The case of **EL_OUT** represents the loss of electrolysers at the moment of the short circuit and no recovery at all during the voltage recovery period. This is considered to be the worst response of the electrolysers to the fault on FL-B. Since that in this case the fault is nowhere near the electrolysers and that the worst voltage performance is obtained with the longest lasting active power imbalance in the grid, this is understood as a case where transient rotor angle stability is the main issue. Subsection 3.1.2 explains this conclusion in more detail.
- Finally, **EL_OUT_RAMPIN** shows the case of an electrolyser outage at the moment of the fault and a ramped active power recovery, starting from the moment when the fault is cleared and with a ramp duration of one second. In this case, a ramp-in effectively improves the rotor angle stability problem in FL-B by closing the active power imbalance in the grid, thus reducing the acceleration time of the synchronous machines. Furthermore, a ramp of 1 s (as observed here) avoids the voltage stability problem seen with the sudden step-in of the electrolysers in FL-A (compare EL_OUT_RAMPIN and EL_OUT_STEPIN in FL-A). Section 3.2.1 further discusses the benefits of ramping in the electrolysers in terms of voltage and rotor angle stability as well as short-term frequency stability.

3.1.1 Short-term Voltage Stability

The electrolyser step-in case was observed to be the most critical for the fault at FL-A. Figure 6 compares the cases EL_OUT and EL_OUT_STEPIN (same as in Figure 5) along with further cases of electrolyser step-in at 0.4 s, 0.6 s and 0.7 s. The lower envelopes of the voltages at the electrolyser terminals (|u| ELEC) and the global voltages (|u| Global) over Germany are shown for the different step-in times. The varying responses of the electrolysers can be seen in Figure 6 for ELEC P. In each case, there is a voltage drop at the electrolyser terminals corresponding to the time of electrolyser step-in. This is also reflected in the plot of the global voltages. In this case, this is due to the fact that the lower voltages in the post-fault recovery period are superimposed on the voltage drops associated with the sudden reconnection of the electrolyser loads, both of which occur in a similar region. The voltage stability problem is related to the local substations and only a concern for faults close to the electrolysers. The analysis shows that uncoordinated step-in of electrolysers during the low voltages seen in the post-fault recovery period could be dangerous to the system. It is therefore necessary to prevent an uncoordinated step-in.

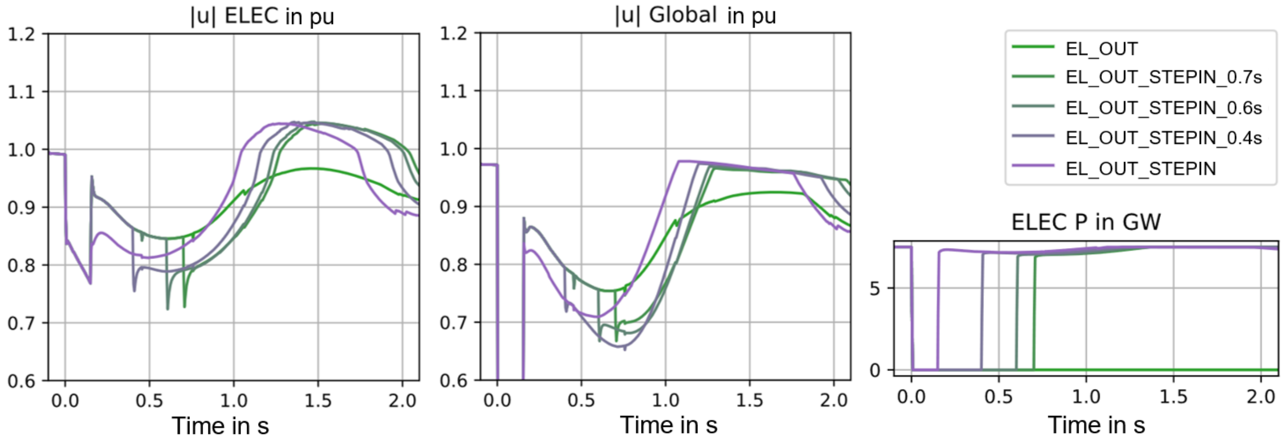

Figure 6 Fault at FL-A (close to electrolysers). Lower envelopes of voltages seen at electrolyser terminals (|u| ELEC) and all EHV buses across Germany (|u| Global) for various step-in times of electrolysers after fault-clear.

3.1.2 Transient Rotor Angle Stability

The case of EL_OUT is the most critical for the fault at FL-B (see Figure 5). Given that the fault, in this case, occurs far from the electrolysers and that the worst voltage recovery is obtained with the longest lasting active power imbalance in the grid, this was understood to be a transient rotor angle stability issue. This is further investigated by comparing different electrolyser step-in times as described in Subsection 3.1.1. Figure 7 compares the cases EL_OUT_STEPIN and EL_OUT (same as in Figure 5) along with further cases of electrolyser step-in at 0.4 s, 0.6 s and 0.7 s. Again, the lower envelopes of the electrolyser terminal voltages (|u| ELEC) and the global voltages (|u| Global) over Germany are shown for the different cases. The voltage drop associated with the electrolyser step-in can again be observed at the electrolyser terminals. However, this is not reflected in the global voltage envelope curves. On the other hand, it can be seen that the global voltages improve significantly with faster electrolyser step-in. This is because earlier step-in reduces the active power imbalance in the system sooner and limits the acceleration of the synchronous machines, thereby reducing the severity of the transient rotor angle problem. It can be concluded that in the event of a fault, the electrolyser loads should be restored as quickly as possible.

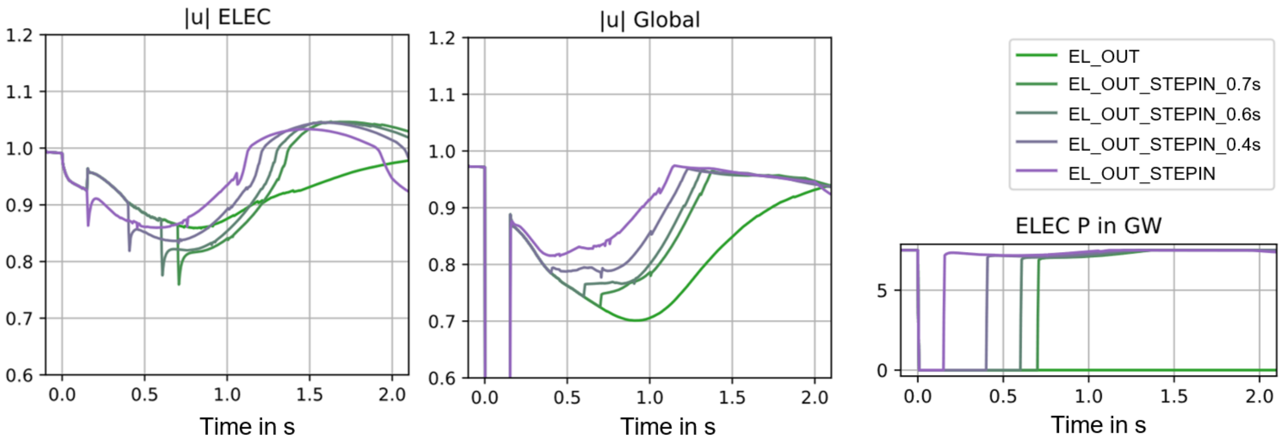

Figure 7 Fault at FL-B (away from electrolysers). Lower envelopes of voltages seen at electrolyser terminals (|u| ELEC) and all EHV buses across Germany (|u| Global) for various step-in times of electrolysers after fault-clear.

3.2 Advantages and disadvantages of grid-serving functions

3.2.1 Ramped active power recovery

Looking at Figure 5, two things can be observed. First, that a fast ramp-in (1s in our case) is better than step-in for short-term voltage stability (compare EL_OUT_RAMPIN and EL_OUT_STEPIN for FL-A). Secondly, that the ramp-in is better for transient rotor angle stability than the case where the electrolysers remain disconnected after fault clearance (compare EL_OUT_RAMPIN and EL_OUT for FL-B). This section discusses in more detail the influence of a ramped active power recovery for both fault locations.

With regard to short-term voltage stability, the fault location FL-A is discussed. Figure 8 shows the cases EL_OUT and EL_OUT_RAMPIN (same as in Figure 5) together with further cases of electrolyser ramp-in starting at 0.4 s, 0.6 s and 0.7 s. The ramp duration is 1 s in each case. The lower envelopes of the voltages at the electrolyser terminals (|u| ELEC) and the global voltages (|u| Global) over Germany are shown for the different cases. The effect of electrolyser ramp-in on the voltages shown in Figure 8 is to be compared with the effect of step-in shown in Figure 6. From this comparison it can be seen that a fast ramp-in (instead of a sudden step-in) of the electrolysers after fault clearance avoids the problem of a sudden voltage drop and reduces the potential risk of voltage collapse.

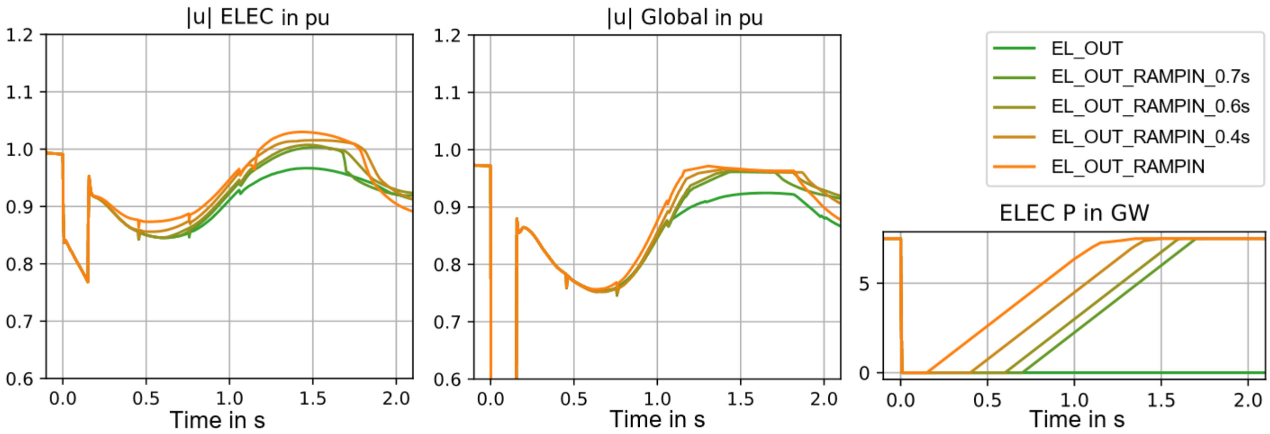

Figure 8 Fault at FL-A (close to electrolysers). Lower envelopes of voltages seen at electrolyser terminals (|u| ELEC) and all EHV buses across Germany (|u| Global) for various ramp-in times of electrolysers after fault-clear.

The influence of ramped active power recovery on the transient rotor angle stability for fault location FL-B is discussed below. Figure 9 shows the global voltages across German EHV substations and at the electrolyser terminals for different ramp-in times. An earlier ramp-in is better for the transient rotor angle stability, as it increases the transferable power faster after the fault. As a result, the excess generation from the pre-disturbance load flow does not lead to over-acceleration of the synchronous machines, which limits the increase of rotor angle differences in the transmission grid. Therefore an early ramped active power recovery is beneficial both for voltage recovery and for ensuring rotor angle synchronism.

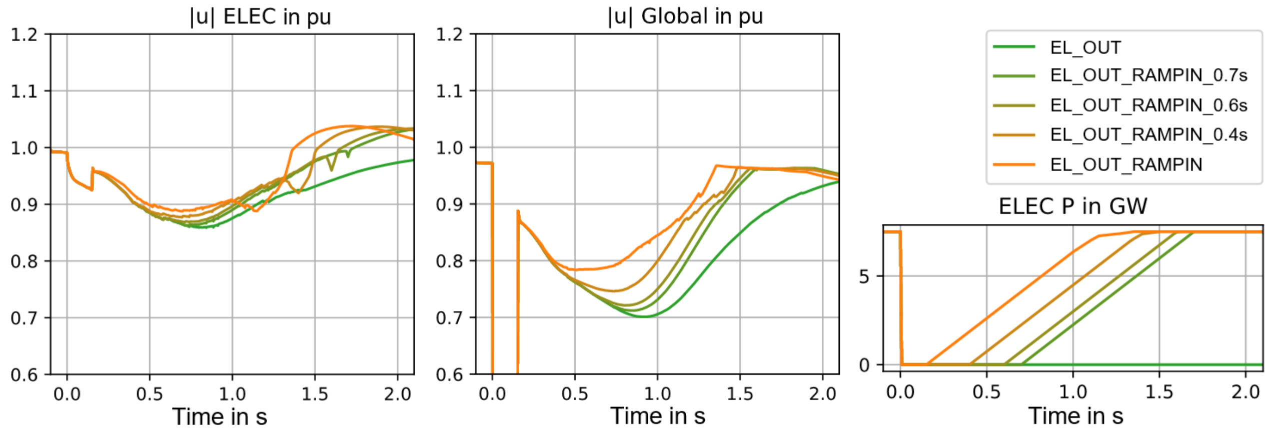

Figure 9 Fault at FL-B (away from electrolysers). Lower envelopes of voltages seen at electrolyser terminals (|u| ELEC) and all EHV buses across Germany (|u| Global) for various ramp-in times of electrolysers after fault-clear.

The effect of faster or slower electrolyser ramp-in for the frequency stability of the system is also evaluated. Figure 10 compares the upper and lower envelopes of the speeds of all the synchronous machines in the grid for different electrolyser responses as described in the legend. The speeds of the synchronous machines are used as an approximation of the system frequency or that of the CoI (Center of Inertia), which would lie between the upper and lower envelopes.

Again, it can be seen that the case where the electrolysers remain in operation is the least severe. If the electrolysers are disconnected at the moment of the fault and are not restarted, there is a steady state frequency deviation due to the persistent active power imbalance. This case also shows the highest zenith of the speeds of the synchronous machines, as the machines have the maximum time for acceleration before the governor response. In all the other cases, representing different ramp-in characteristics of the electrolysers, the frequency returns to the nominal frequency of 50 Hz.

Two variables of the ramp are varied here - the start time and the duration. It can be seen that the small change in the start time of the ramp from the moment when the fault is cleared (0.15 s) to 0.8 s does not make any significant difference to the frequency characteristics on the time scale shown (compare the two 1 s duration curves or the two 60 s duration curves). However, changing the ramp duration from 1 s to 60 s has a significant effect on the frequency response of the system. A slower ramp of 60 s allows the synchronous machines to accelerate for a longer period of time, with the machine speeds reaching a zenith only slightly lower than in the case of EL_OUT. In conclusion, a fast ramp-in of the electrolysers is beneficial in terms of short-term voltage stability, transient rotor angle stability and frequency stability.

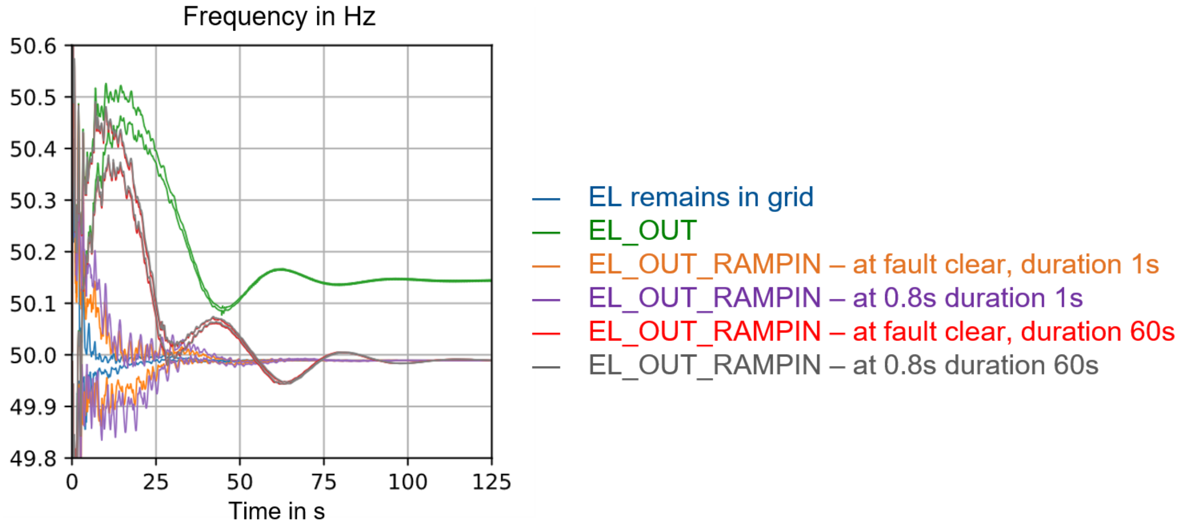

Figure 10 Fault at FL-A. Upper and lower envelopes of speeds of all synchronous machines (in Hz) observed for the fault case of FL-A with different electrolyser (EL) switching behaviours. Frequency of CoI of grid lies between the upper and lower envelopes

3.2.2 Constant current fault ride through (FRT)

The benefit of the constant current fault ride through (FRT) of the electrolysers is evident from the results in Figure 5, which compares the different responses of the electrolysers to the disturbances studied. Considering the two fault locations FL-A and FL-B (identified as the most critical from the fault analysis), it can be observed that the case where the electrolysers remain connected to the grid throughout the fault duration shows the best response both in terms of short-term voltage stability (compare EL and EL_OUT_STEPIN for FL-A), and transient rotor angle stability (compare EL and EL_OUT for FL-B).

To assess the benefits of FRT, the characteristics shown in Figure 4 are defined for the electrolyser loads. However, the voltages in our study cases never crossed the threshold beyond region R1 in the FRT curve. Even so, the FRT behaviour is recommended by the results as it prevents, to the extent possible, the loss of electrolysers during faults, which have the potential to introduce more severe dynamics into the grid (see Section 3.1). Assuming a worst case scenario where the voltages at the electrolyser terminals do fall below the threshold to region R2, the FRT characteristics require the electrolysers to remain ready to return to normal operation as soon as the voltage recovers. This is expected to improve the dynamic stability of the transmission grid by ensuring that active power is recovered as quickly as possible to prevent over-acceleration of the synchronous machines, which is a threat to transient rotor angle stability (see Section 3.1.2). If the electrolysers are shut down and restarted after the fault has been cleared, the study also shows that a fast ramp-in (1 s ramp duration in our case) rather than a sudden step-in could prevent short-term voltage stability problems (see Section 3.2.1).

It is also important to note that since FRT is beneficial in terms of transient rotor angle stability, the effect has a global relevance. This is also true for the ramped active power recovery of the electrolysers (see Section 3.2.1). In contrast, the influence of the reactive current injection (Iq(u)) only has an effect on the local voltages, as discussed in Section 3.2.3.

3.2.3 Dynamic voltage support with Iq(u) injection

The effect of Iq(u) injection from electrolysers is shown using the example of the fault location FL-A in Figure 11. Simulation results are shown for the Iq(u) characteristics according to Figure 3 with a deadband of 0.03 pu and a droop of 4 pu. It is assumed that the electrolysers remain connected to the grid during the fault. The effect of Iq(u) on the voltages at the electrolyser terminals can be observed from the upper and lower voltage envelopes shown in Figure 11 (|u| ELEC). It is clear that Iq(u) injection by electrolysers improves the voltage dip during the post-fault recovery period for the selected study case. It also reduces the overshoot after voltage recovery. However, it should be noted that the effects described are only local, as opposed to the global influence of ramped active power recovery (Section 3.2.1). Additionally, there may be negative interactions in regions where reactive current injection is already high, as discussed below.

Although the example shows an improvement in short-term voltage recovery, a higher Iq injection also carries the risk of overvoltage spikes at the moment of fault clearance. This is also shown in the enlarged voltage plot window in Figure 11, focusing on the moment of fault clearance. The case with Iq injection shows a higher voltage spike than the case without Iq injection. The voltage spike is due to the high reactive current injection from the inverter-based generation during the fault as they go into Iq priority mode as a voltage support measure. Given that the electrolysers are located in northern Germany, which is already rich in dynamic reactive current injected by offshore and onshore inverter-based generation, an additional reactive power injection by electrolyser loads could not only be redundant, but could actually pose a threat in terms of overvoltages. The simulation results do not refer to a real grid situation, which means that higher voltages could occur in system operation. In such situations, additional Iq injection could result in unacceptable voltages. It should be noted that a high voltage spike exceeding 1.3 pu, as shown in the FRT curve of Figure 4, would mean the loss of electrolysers, which worsens the transient rotor angle stability (see Section 3.1.2). For this reason, the use of Iq injection should only be required if the grid connection points do not already incorporate a high level of reactive current injection.

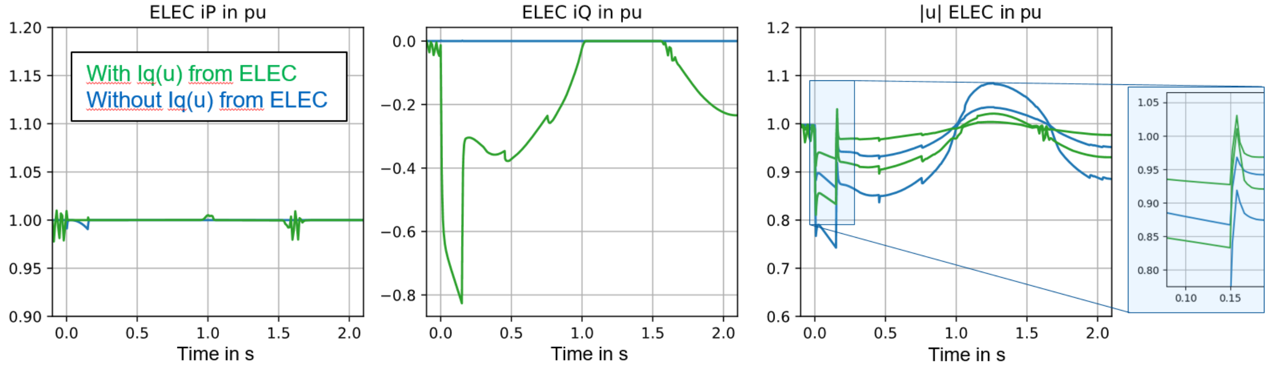

Figure 11 Fault at FL-A. Upper/Lower envelops of electrolyser (ELEC) parameters with and without q-injection from electrolysers during fault and after fault-clear. Shown from left to right: total active current iP drawn by the electrolysers, total reactive current iQ drawn by the electrolysers, and the voltages |u| at electrolyser terminals.

4 Conclusions

The integration of large capacity of electrolysers into the grid poses a risk to the stable system operation. Large voltage surges could be seen when electrolysers suddenly drop out or step in. Combined with grid disturbances, this could lead to short-term voltage or transient angle stability problems.

Short-term voltage stability problems were observed as a local phenomenon for faults closer to the electrolysers. It was also observed that the uncoordinated step in of electrolysers when local voltages are already low could cause a further voltage drop and aggravate the situation. On the other hand, transient rotor angle stability problems were observed for some faults not so close to the electrolysers. This is a global phenomenon influenced by the acceleration of regionally distributed synchronous machines. It is caused by the loss of electrolysers during a fault without active power recovery after the fault has been cleared. A fast ramped active power recovery is considered to be effective against the rotor angle stability problems, as it increases the electrical power that can be transmitted after the fault, thus limiting the acceleration of the synchronous machines. An active power imbalance in the grid also affects the frequency stability. Grid frequencies were studied with different electrolyser ramp characteristics. Faster ramp-in of the electrolysers after a fault limits the frequency zenith by closing the active power gap earlier.

Iq(u) support was seen as having the potential to improve short-term voltage recovery. However, offshore and other inverter-based generation sources prevalent in the region already provide significant Iq(u) during the fault. This leads to overvoltage spikes at the moment of fault clearance. Additional Iq injection from electrolysers during the fault increases the voltage spike. In addition, Iq(u) provides local compensation and is ineffective if the fault is far from the electrolysers, which could be a risk in terms of transient rotor angle stability. In these cases, the injection of Iq would have no benefit and the reactive current priority would actually reduce the active current of the electrolyser loads. The FRT behaviour is considered to be beneficial as it prevents the electrolysers from being disconnected from the grid during faults. It was observed that compared to other electrolyser responses, there is a minimum voltage and frequency dynamic in the grid when the electrolysers remain connected during faults. Even in an adverse case of electrolyser loss due to severe voltage drops, a faster ramp-in as soon as possible after the fault is cleared is seen to have a good effect in preventing transient rotor angle instability by closing the active power imbalance in the grid and limiting machine accelerations. In this study, a fast ramp of 1 s duration started immediately after fault clearance effectively improved transient rotor angle stability and ensured lower frequency zeniths. The fast ramp-in was also found to improve the short-term voltage instability that is threatened by the uncoordinated and sudden step-in of the electrolysers after fault clearance.

From the results of this study, it can be concluded that it is best for the dynamic stability of the transmission system that electrolysers remain connected to the grid for as long as possible during grid disturbances. In this context, fault ride through (FRT) with constant active current is important. In the event of an electrolyser failure, a fast ramped active power recovery as soon as possible after fault clearance is beneficial to improve transient angle stability and to avoid sudden voltage drops in the recovery period. It is also beneficial in terms of frequency stability. In any case, an uncoordinated and sudden step-in of the electrolysers must be avoided.

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