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SYSTEMATIC REVIEW ON FAST FREQUENCY ANCILLARY SERVICES PROVIDED BY LARGE-SCALE HYDROGEN ELECTROLYZER PLANTS

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Abstract

The decrease in physical inertia within AC grids may lead to more serious frequency deviations caused by power imbalances. To address these challenges attention has been paid to the potential of converter-connected resources to reduce frequency deviations. Since grid development plans aim to integrate a large capacity of hydrogen electrolyzer plants (HE) into the power grid, the analysis should be extended to include the ability of these loads to reduce frequency deviations.

This paper performs a systematic review to evaluate the state-of-research on the potential of large-scale HE to reduce the rate-of-change-of-frequency and maximum frequency deviation. Current literature states a high potential of HE to counteract frequency deviation. Furthermore, various control approaches for delivering frequency ancillary services have been investigated. However, the paper identifies a research gap concerning applicability of the control approaches to large-scale HE considering resulting fluctuation in the flow rate of hydrogen production.

1. Introduction

The change in electrical power generation, and consumption from directly connected generators or loads towards converter interfaced units, is causing a reduction of physical inertia in the grid. The decreased inertia leads to higher fluctuation of frequency in response to power imbalances. The occurrence of higher rate-of-change-of-frequency (RoCoF) and frequency nadir/zenith (Δf_{max}) may impose challenges for the operation and stability of the electrical power grid. To face these challenges, and to secure the reliability of the grid in the future, studies worldwide have been conducted to evaluate the need for frequency support from converter interfaced units [1, 2]. For grid stability in Germany, which is embedded within the synchronous grid of Continental Europe, it has been stated that the conventional reference case of a generation loss of 3 GW for frequency reserves will not endanger the RoCoF limitation of 1 Hz/s even for the planned converter penetration in 2050 [3]. However, grid stability studies have additionally revealed that there will be a gap of physical inertia to prevent critical frequency deviations in case of severe system split scenarios. A system split is the result of cascaded line outages, which lead to a separation of one synchronous grid area into two or more asynchronous areas[3]. The presented stability study in [4] states that there is a high demand for regionally distributed additional inertia to secure frequency stability in case of the reference system split scenario from 2006 [5] for the expected grid dynamics in the year 2037.

Simultaneously, the German TSOs state an expected power demand of at least 26 GW from hydrogen electrolyzer plants (HE) in the year 2037, whereas the current power consumption of HE in Germany is less than 1 GW [6]. Hence, a huge amount of large-scale HE is expected to be connected to the grid which still needs to be engineered. This offers the opportunity to consider the provision of fast frequency ancillary services in the early design phase of novel HE.

This paper evaluates the state-of-research on frequency support provided by large-scale (HE). The focus is on frequency responses which aim to reduce the RoCoF and improve Δf_{max} to address the predicted frequency stability problem of the German grid. Furthermore, the work discusses open research gaps and challenges related to fast frequency ancillary services provided by electrolyzers. From these objectives, the following research questions are derived for the review:

(i) Can HE reduce the RoCoF and Δf_{max} of frequency deviations and therefore decrease the need for additional inertia in the future grid?

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(ii) What challenges arise from the provision of fast frequency ancillary services by large-scale HE?

To answer these research questions the work conducts a systematic literature review. The paper first reviews the recommendations of the European Union Agency for the Cooperation of Energy Regulators (ACER) on grid codes concerning demand connection to provide a comparative benchmark for the review. The regulators perspective is not covered by the systematic review. In addition, the section clarifies notations which are used throughout the review. Section 3 provides an overview of the applied method for the systematic review, and then section 4 first provides a quantitative overview of the results followed by a more detailed insight. In this work, a special focus is on mapping the power ramp rates in [pu/s] applied to HE due to frequency ancillary services and on the effect of the services on the RoCoF and Δf_{max}. Section 5 discusses the review results with respect to the research questions and section 6 derives a conclusion.

2. Background

This section clarifies notations used throughout the review and provides background knowledge concerning the analysis of the references. Furthermore, the section briefly defines the four main types of fast frequency ancillary services investigated in current literature.

2.1. Grid-frequency studies

ACER released recommendations for a generalized grid code on demand connections in [7]. The document includes functional requirements on future HE units. The requirements are briefly introduced below as a benchmark for the frequency studies considered in this work as result of the review. The focus lies on the requirements which are related to frequency ancillary services of HE.

The grid code recommendations suggest frequency ranges in which HE units are required to stay in continuous operation. These ranges are shown in Table 1. Since the work concentrates on the reduction of RoCoF and Δf_{max}, which results in a time-period of interests of a few seconds, especially the boundary frequencies of 47.5 Hz and 52.2 Hz are particularly relevant compared to the time periods.

Table 1 Frequency operation range for demand units introduced by [7]

Frequency range [Hz]	Time period of operation
47.5 - 48.5	30 min
48.5 – 49.0	30 min
49.0 – 51.0	Unlimited
51 – 51.5	30 min
51.5 – 52.5	10 s

In addition, the document introduced novel RoCoF ride-through requirements which are listed in Table 2. To provide an example of the interpretation of the requirements: HE units are not allowed to disconnect and are requested to provide the required demand response to the occurring frequency deviation, if the RoCoF is not higher than 4.0 Hz/s over a period of 250 ms.

Table 2 RoCoF ride-through requirements introduced by [7]

RoCoF $[\frac{Hz}{s}]$	Time period
± 4.0	0.25 s
± 2.0	0.5 s
± 1.5	1 s
± 1.25	2 s

Furthermore, the authors of [7] state that future HE units should be required to reduce their output power with a frequency droop of 5 % from their operation point if the threshold value of 49.8 Hz is crossed. In a statement paper of the German TSOs, this requirement is repeated as 40 % adjustment from the current operation point per Hz deviation [8]. Considering the maximum deviation from Table 1 of 2.5 Hz that results in 100 % power reduction. For the worst-case RoCoF defined in Table 2 that would require the HE to reduce the power with 1.6 pu/s. However, [7] states that the reaction time must not be higher than 0.5 s which reduces the power ramp rate requirements of HE to 0.8 pu/s.

The conducted review reveals that in current literature four different types of frequency responses are considered to reduce the RoCoF and Δf_{max}. For clarification, these four different types are briefly presented below. It should be noted that the actual realization and implementation of the controls varies between publications and therefore needs to be checked in the relevant publications itself:

- Frequency containment reserve (FCR): The frequency response is controlled by measuring the frequency deviation and adjusting the power reference of the HE proportionally through multiplication with a constant gain. FCR is close to the frequency response defined in [7].

- Fast frequency response (FFR): The frequency response is controlled by measuring the frequency deviation. If a frequency threshold crossing is detected, a defined power reserve volume is activated for a defined time and the power consumption of HE is adjusted accordingly.

- RoCoF based Response (RbR): The frequency response is controlled by measuring the frequency and calculating the derivation (RoCoF). The power reference of HE is adjusted proportionally to the calculated RoCoF. Frequency responses which aim to

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mimic the physical inertia response of synchronous generation but still rely on measuring the frequency first, are grouped under RbR as well. It should be mentioned that for this response there is no consistent naming throughout the literature yet.

- Grid-forming control (GFM): Frequency responses grouped under the notation GFM do not react to a measured frequency deviation. The controls aim to mimic the behaviour of a voltage source. Therefore, a phase-shift caused by a frequency deviation at the Point-of-Connection (PoC) will lead to a change of power consumption instantaneously.

2.2. *Hydrogen Electrolyzer Plant*

In this paper, the large-scale *Hydrogen Electrolyzer plant (HE)* consists of the electrical power supply system including multiple modules, electrolysis stacks, the chemical process technologies and the corresponding auxiliary systems. The *power supply* mainly denotes the transformer, the electrical converter systems and corresponding controls. For the power supply itself it is considered that for each module the electrolysis stack is connected via a voltage-source converter, and a DC/DC-converter if not mentioned differently. For large-scale applications multiple modules are connected in parallel to achieve the desired HE rating. The introduced power supply design is stated as future trend in [9] and is the most investigated one in the studies considered in the review. The *hydrogen process* summarizes the chemical process technologies required for large-scale applications (e.g. hydrogen tank, cooling system, compression units, dryers, circulation pumps, demister etc.) [10].

3. Review Method

For the systematic review, groups of keywords are derived which are logically linked for a database-search to narrow the quantity of considered publications down to less than a hundred references per database. Afterwards, the identified literature is systematically analyzed following the PRISMA structure [11]. The PRISMA structure includes a stepwise review approach to identify relevant literature for the research questions. The review does not consider any publications older than 2009 and released after the 24th of April 2024. Furthermore, the considered publications where limited to English language. The databases which are used for the search are Scopus and Web of Science.

Figure 1 provides an overview of used search-keywords. "Hydrogen electrolyzers" defines the object of the investigation and is therefore considered as one keyword, which needs to be part of the abstract or title of the literature. Furthermore, the following keywords are or-connected with "Hydrogen Electrolyzers" for the search:

- Hydrogen, Electrolyzers, Electrolysis, PEM, Polymer electrolyte membrane

The more specific search has been limited to polymer electrolyte membrane electrolyzers (PEM), since that technology is most promising for flexible operation combined with the readiness of the technology for large-scale applications. [12] [13]

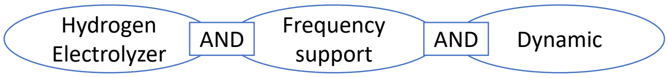

Figure 1 Keywords used for the review

Secondly, keywords summarized with "Frequency support" within Figure 1 sharpen the search to the investigation focus of frequency support provided by HE. The following keywords are or-connected:

- RoCoF damping, Frequency regulation, Fast Frequency*, inertia emulation, grid-forming*, grid forming*, synthetic inertia, control reserve, demand response, virtual inertia, frequency stability, frequency containment*

The last group, summarized with "dynamic", aims to reduce the references to the focus on dynamic operation of HE. As a consequence, literature investigating HE on timeframes above several minutes should be excluded. The following keywords are or-connected with "dynamic":

- Ramp rates, response time, rise time, settling time, reaction time, fluctuating power, rapid, quick

4. Review Results

In total, the search identified a quantity of 166 references (Figure 2). The search indicates an arising interest in the topic, since 76% of the references are published after 2021. Following the PRISMA flow chart 21 references are considered for this review paper. In addition to the literature identified within the database search, six papers are added manually since they are indicated as relevant due to citation within reviewed literature. The main factors concerning the exclusion of search results are that references are either considering non-hydrogen related electrolysis, have a focus on the economic value of ancillary services, or investigate services within a timeframe of more than 30 s and are therefore not relevant for the reduction of RoCoF and frequency Δf_{max}.

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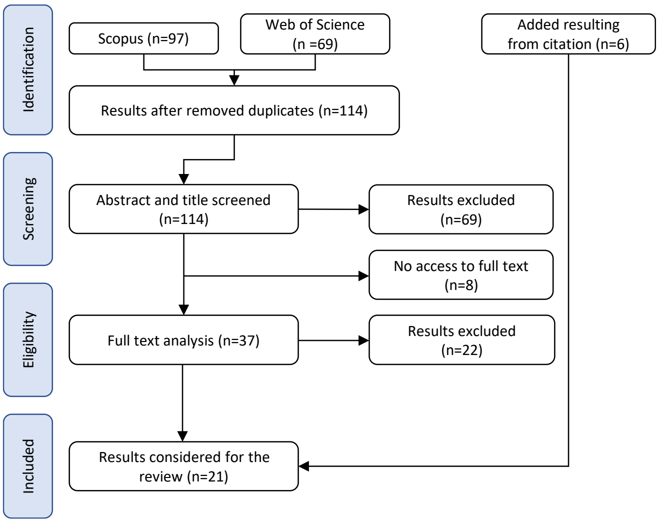

Figure 2 Prisma flow chart of review based on [11]

The references are assigned to four different groups with respect to their main focus (Figure 4). The review results can be sorted into references which are introducing modeling approaches for hydrogen electrolyzers [14–18], focusing on frequency support by control of HE [15, 18–26] or proposing a novel electrical system layout [27–32]. Furthermore, Figure 4 illustrates that only [17, 18, 33, 34] performed parts of their investigation with electrolysis stack hardware and therefore include measurement data within their publication. The rating of the hardware under study is noted in the figure.

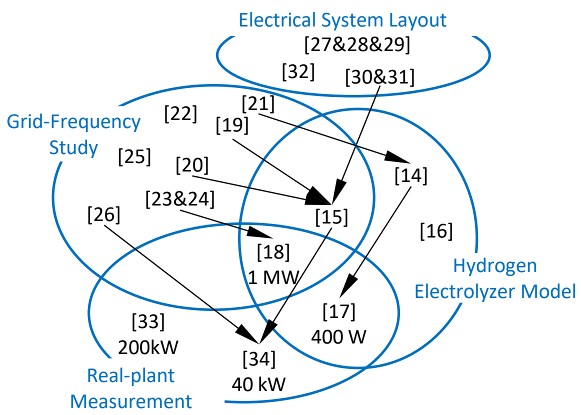

Figure 4 Synthesis of references

In addition, Figure 4 illustrates whether a study references another publication in the matter of modelling of the HE.

The paper aims to address the question, if HE can reduce the need for additional inertia, and which operational constraints need to be considered for the provision of fast frequency ancillary services. Therefore, the main focus of the literature analysis lies on the references concentrating on the modelling of the HE, and especially on the references investigating the potential frequency support of the HE.

4.1. Hydrogen electrolyzer plant model

The electrical characteristic of an electrolysis stack is considered in all the models, whereas non-linear limitations of the hydrogen processing (e.g. pressure limits, filling level of tank) are considered only in [15], and [16] (Table 3). The processing of hydrogen is considered in [16] and partly in [18].

Table 3 Comparison of HE models

References	Electrical dynamics	Hydrogen process non-linear limitations	Hydrogen process dynamics
[14]	✓	×	×
[15]	✓	✓	×
[16]	✓	✓	✓
[17]	✓	×	×
[18]	✓	×	Partly

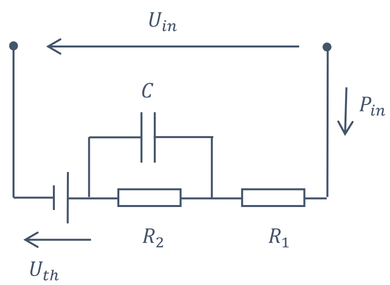

Figure 3 Electrical equivalent circuit of electrolysis cell

In [18] restrictions for the dynamics of the converter controls are derived from measurement data of a 1 MW pilot plant with a ramp rate limit of 0.5 pu/s. However, the impact on the hydrogen process is not evaluated or modelled and the paper does not provide insights about the used hydrogen process related plant.

The work in [16] focusses on the control of the hydrogen process to be used in formic acid synthesis. The author states the importance and challenges to maintain defined process values (e.g. pressure, ratio of CO_2 and H_2, and temperature) through control of the auxiliary systems (e.g. compressors, pumps). Therefore, the formic acid synthesis is affected by a fluctuating hydrogen flow rate, which is directly related to the provision of grid-frequency services by adjusting the operation point of the HE. This challenge is addressed in the paper by introducing a novel control design including the power supply and hydrogen auxiliary systems to enable FCR by simultaneously remaining sufficient operation condition for the formic acid synthesis. The considered power ramp rate for which the hydrogen process remains in optimal working conditions is approximately 0.005 pu/s.

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In [15], the considered system includes a hydrogen buffer stage to decouple fluctuating hydrogen flow rate from the further processing of hydrogen. The correlation between electrolysis current and hydrogen flow rate is derived mathematically to observe the filling level of the hydrogen buffer. It is stated that the frequency ancillary services under study can be provided as long as the storage buffer is within suitable limits.

All of the introduced models replicate the current-to-voltage characteristic of an electrolysis cell with an electrical equivalent circuit consisting of a DC-Voltage source, and a combination of capacities and resistances. An exemplary implementation of the electrical equivalent circuit is illustrated in Figure 3. Only [14] models the voltage dynamics with a mathematical approach. The main objective of the models is to correctly replicate the dynamic voltage to current relationship. The work of [17] derives the delay behaviour of the voltage in response to a current step applied to an experimental setup of an 400 W electrolysis stack. Furthermore, the provided measurement results show the proportional, and close to instantaneous dependency of supplied power and hydrogen flow rate. In [14], the data is reused to define a first-order delay function which describes the electrolysis stack voltage dynamics.

The electrical equivalent model derived in [15] is parameterized based on the measurement data from a 40 kW electrolysis stack provided in [34].

In [34], the current consumption of a PEM electrolysis stack in response to a step in the reference current of the control system is measured over time. The measurement shows that the current of an electrolysis stack is adjusted from a 25 % to a 100 % rated current within less than 100ms, which indicates a power ramp rate of 7.5 pu/s. However, the impact of the ramp rate on the degradation of the stack and the processing of hydrogen are not analysed within the study.

4.2. Grid-Frequency Study

To address the research questions, this section compares the studies with the main focus on the frequency support (Figure 4) with respect to the investigated frequency responses introduced in 2.1, the resulting value for the RoCoF and Δf_{max}, and the power ramp rate applied to the HE. Table 4 provides an overview of which frequency responses are investigated in which publication.

Table 5 maps the occurring RoCoF considered in the study to the resulting power ramp rate of the HE as well as to the improvement in RoCoF and Δf_{max} due to the frequency response of the HE. For the comparison the investigated worst-case scenarios are chosen with respect to frequency deviation. It needs to be noted that the improvements ΔRoCoF and ΔFreq are calculated based on reference cases provided within the studies itself. Hence, the values are not directly comparable since some studies consider alternative frequency responses from other grid units for the reference cases. However, the values still provide an indication whether the frequency response from HE is able to improve the frequency stability or not.

The references [19], [20], and [25] investigate frequency responses based on GFM. In [19], and [20] the frequency response is investigated in grid simulations modeling parts of the Australian transmission grid. Furthermore, [19] is published in collaboration with the author of [15, 20]. As illustrated in Figure 4 they rely on similar HE models.

Table 5 shows that both frequency responses result from high RoCoF values (Table 2). Both studies conclude that a GFM frequency response from HE can improve RoCoF and Δf_{max}, and [19] additionally concludes that HE are able to provide similar improvement compared to Battery Storage Systems. However, in [20] the author stated that a forced stop of GFM control might induce a frequency deviation in the grid. For [19], it is not possible to extract the beneficial effect on the RoCoF from the presented results in case of the worst-case scenario. In [25], the author does not investigate the effect of the HE frequency response on the frequency. The aim of the study is to identify which dynamic flexibility an HE needs to have in order to enable either a GFM response or FFR of a specific volume. The author concludes that the HE ramp rate should be 1.25 pu/s for GFM. The results are derived from a simulation approximating the HE as a controlled voltage source.

Table 4 Frequency responses considered

References	GFM	RbR	FFR	FCR
[19]	✓	×	×	×
[20]	✓	×	×	✓
[15]	×	✓	✓	✓
[21]	×	×	×	✓
[22]	×	✓	×	✓
[23]	×	✓	✓	✓
[24]	×	×	×	✓
[18]	×	×	×	✓
[25]	✓	×	✓	×
ACER	×	×	×	✓

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Table 5 Comparison of grid-frequency studies

References	RoCoF $[\frac{Hz}{s}]$	ΔP_{HE} $[\frac{pu}{s}]$	$\Delta RoCoF$ $[\frac{Hz}{s}]$	$\Delta Freq$ $[Hz]$
[19]	1.7	0.75	×	0.12
[20]	1.1	3.84	0.85	0.29
[21]	0.02	0.3	×	0.02
[22]	0.01	0.2	0.005	0.07
[23]	0.5	2.32	0.33	0.057
[24]	1.24	0.4	0.13	0.07
[18]	0.02	< 0.5	×	0.041
[25]	2	1.25	×	×
ACER	4	0.8	×	×

The references [22], and [23] study the frequency response introduced as RbR in section 2.1. However, in [22] the response is tuned with a 2nd-order transfer function and in [23] with a 1st-order transfer function. In [23], the potential contribution of HE in frequency ancillary services in the Iberian Peninsula 2040 grid is investigated. The study is conducted within a transfer function-based grid model. In [22] the author compares three different frequency response methods provided by a 300 MW electrolyzer to a 9-bus grid model of the Netherlands transmission grid with a base power of 3490 MW. Both studies compare different frequency responses as indicated in Table 4 and conclude that RbR is the most beneficial one to improve RoCoF and Δf_{max} compared to FFR and FCR. Furthermore, [23] states that RbR by HE can reduce the need for physical inertia, if the HE can be operated with fast power ramp rates. The response time is shown to be more crucial than the amount of provided power reserve. In addition, [22] finds that the implementation with a 2nd-transfer function offers more beneficial frequency responses compared to an implementation similar to [23].

FFR is investigated in [15], [23], and [25]. However, as stated earlier, [25] focuses on the power ramp rate requirements for the HE to enable FFR which is concluded to be 0.83 pu/s. In [23] the author discusses that FFR is on one hand able to improve the exploitation of the HE flexibility for the frequency response compared to FCR, but on the other hand in specific cases it is shown that FFR even induce higher RoCoF values than FCR.

Finally, the references [15], [20], [21], [22], [23], [24], and ACER recommendation (section 2.1) consider FCR. To summarize the conclusions, FCR is stated to be less effective in reducing RoCoF and Δf_{max} in comparison to FFR, RbR and GFM. However, [24] states that FCR provided by HE is still able to improve the reduction compared to FCR provided by conventional synchronous machines. The initial point of the investigation is that conventional synchronous machines have a slower power ramp rate compared to HE.

4.3. *Electrical System Layout*

In [30], the authors propose to combine the faster dynamic responses from PEM electrolyzers for frequency support and lower prices of alkaline electrolyzers in a hybrid system, which is coupled at a DC bus. Therefore, control interaction which might be challenging for AC coupling is avoided. The frequency support capability of the proposed system setup is studied with a transfer function-based grid model.

The publications [27], and [28] introduce a system design, which aims to provide the whole timescale of frequency related ancillary services by connecting a super capacity, battery storage system, electrolyzer and fuel cell system. Thereby, the hydrogen related components are considered for secondary power reserves, which reduces the dynamic requirements for the HE significantly. In addition, the operation of the whole plant is compared for AC and DC connection of the components. It is stated that the DC connection allows an improved decoupling of the electrolysis stack and fuel cell from grid disturbances. The control scheme of the plant is patented in [29].

5. **Discussion**

Regarding the research question if HE can decrease the need for additional inertia, the review indicates that HE systems as converter-controlled loads can reduce the maximum frequency deviation Δf_{max}, and the RoCoF. Especially [19], [20], [23], and [24] show promising results for reducing the need for additional inertia by requesting frequency responses from future HE systems. The references state that the crucial factor is a fast response to the frequency disturbance.

Table 5 indicates that a comparable steep power ramp rate can reduce the RoCoF, whereas an RoCoF improvement is minor or not measurable in the publications, if ΔP_{HE} is small. For the reduction of Δf_{max} a positive impact is already observable for less steep power ramp rates.

Especially the publications in [15], [19], and [20] show that the four different frequency responses are applicable to an aggregated HE power supply by control. The control designs are validated in electromagnetic transient simulations and the concept of the developed grid-forming control is additionally studied with Control-Hardware-in-the-Loop simulations by considering the electrical dynamics of a PEM electrolysis stack in [19]. However, none of the studies considered in section 4.2 used a detailed model of a large-scale HE system in detail with multiple modules connected in parallel. In particular for an operation with grid-forming control, the converter interaction is stated to be challenging in [35].

Comparing the power ramp rates in Table 5 indicates that there is a wide range of ramp rates applied to the HE system for enabling the frequency responses under study. The highest ramp rate is around 38 times steeper compared to a ramp rate of 0.1 pu/s, which is advertised by a manufacturer in [36] in

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2021. In addition, the ramp rates caused by the frequency responses are expected to be even higher for the worst-case RoCoF values defined in Table 2, since the response values are proportional either to the RoCoF or to the frequency deviations. The RoCoF value in [20] which results in a ramp rate of 3.84 pu/s is only 27.5 % of the 4 [Hz/s] RoCoF defined as ride-through requirement by ACER. Summarizing the HE models reviewed in section 4.1, the main focus is on investigating the electrical behavior of the electrolysis stack. In particular, applying a voltage-step to the circuit in Figure 3 instantaneously results in a power increase of P_{in}, which is proportional to the hydrogen flow rate of the electrolysis stack [10, 15]. The impact of steep flow rate changes on the hydrogen process or the degradation of the electrolysis stack is not considered in the studies [14], [15], [17], and [18]. Therefore, it is not possible to state based on the references identified if the ramp rates are realistic for large-scale HE. For the study presented in [16], which modelled the hydrogen process, the power ramp rates applied to the electrolysis stack are around 700 times slower compared to ramp rates in [20]. In addition, Figure 4 shows that only four references considered measurement data of HE or electrolysis stacks. The influence of fast ramp rates on degradation as well as the hydrogen processing has been left unstudied. Moreover, compared to the size of the HE systems used for the grid-frequency studies, the size of HE systems used for system identification and modelling can be considered as small- or even laboratory scale applications. From the authors perspective, it needs to be further evaluated which ramp rates will be acceptable for large-scale HE.

Nevertheless, the system design introduced in [27, 28] provides solutions to reduce the ramp rate applied to the electrolysis stack by simultaneously enabling faster power ramp rates as frequency responses. In comparison, the power adjustability considered in [27, 28] is slow compared to 0.1 pu/s from [36]. Therefore, further investigations considering faster ramp rates could reduce the resulting design costs (e.g. battery sizing) of suggested system designs while still providing the same grid-frequency services.

6. Conclusion

Recent grid-integration studies conclude that frequency responses provided by large-scale electrolyzer plants can significantly reduce frequency deviations in the grid. The main factor for reducing the RoCoF is a fast ramp rate of the power consumption. In current literature, control approaches enabling such fast ramp rates of electrolyzer plants have been introduced and are investigated by considering detailed models of the electrical behavior of the electrolysis stack. On the contrary, the review indicates that operational limitations with special focus on the power ramp rates are not sufficiently addressed or even defined for large-scale hydrogen electrolyzer plants. Therefore, the authors derive a need for further investigating the introduced control approaches by considering limited ramp rates. To overcome this challenge, publications already suggested electrical system designs, focusing on the decoupling of frequency responses from the power ramp rates applied to the electrolysis stack. However, including additional energy storages in the electrolyzer plants design increases the design costs and may therefore be unsuitable for the majority of industrial electrolyzer plants. In conclusion, additional research is needed to evaluate the gap between ramp rates needed for the reduction of frequency deviations and ramp rates suitable for large-scale electrolyzer plants.

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