The Role of Hydrogen Electrolysers in the Frequency Containment Reserve: A Case Study in the Iberian Peninsula up to 2040

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***Abstract*—This paper investigates the contribution of hydrogen electrolysers (HEs) as highly controllable loads in the context of the Frequency Containment Reserve (FCR), in future operation scenarios on the Iberian Peninsula (IP). The research question is whether HEs can mitigate system insecurity regarding frequency or Rate of Change of Frequency (RoCoF) in critical periods of high renewable energy penetration (i.e. low system inertia), due to the fact that these periods will coincide with high volume of green hydrogen production. The proposed simulation platform for analysis consists of a simplified dynamic model developed in MATLAB/Simulink. The results obtained illustrate how HEs can outperform conventional generators on the provision of FCR. It is seen that the reference incident of 1GW loss in the IP in a 2040 low inertia scenario does not lead to insecure values of either frequency or Rate of Change of Frequency (RoCoF). On the other hand, an instantaneous loss of inverter-based resources (IBR) generation following a short-circuit may result in RoCoF violating security thresholds. The obtained results suggest that the HEs expected to be installed in the IP in 2040 may contribute to reduce RoCoF in this case, although this mitigation may be insufficient. The existing FCR mechanism does not fully exploit the fast-ramping capability of HEs; reducing measurement acquisiton delay would not improve results.**

***Index Terms*—dynamic modelling, frequency containment reserve, hydrogen electrolyser, nadir, RoCoF**

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I. Introduction

The ongoing transition towards a decarbonized energy sector is motivated by several policies aimed at mitigating climate change. Following the European Green Deal, in 2020 the European Commission published its "hydrogen strategy for a climate-neutral Europe" [1] where hydrogen is presented as "a vector for renewable energy storage" that "will play a role, alongside renewable electrification". The document also defines "electricity-based hydrogen", produced in grid-connected hydrogen electrolysers (HEs). These are in fact controllable loads and as such can participate in markets open to demand response. In this paper the focus is on the Frequency Containment Reserve (FCR) market. The aim of the FCR (also known as primary frequency control) is to maintain the balance between generation and demand within the synchronous area, such that, after a disturbance, the system frequency is stabilized within ±200mHz from the nominal frequency, 50Hz [2]. Every control area within the synchronous area has its allocated FCR volume such that the sum equals 3GW; in IP the FCR volume is 430MW [3].

The key idea about electricity-based hydrogen is that its production will be maximized at times of higher renewable energy penetration. For the power grid system operators, maximum renewable energy penetration implies system fragility because inertia is reduced as a result of synchronous machines being displaced by inverter-based resources (IBR); on the other hand, HEs are controllable loads and the more they are present in the grid, the larger the potential of demand response.

The research motivation of this paper regards the expected

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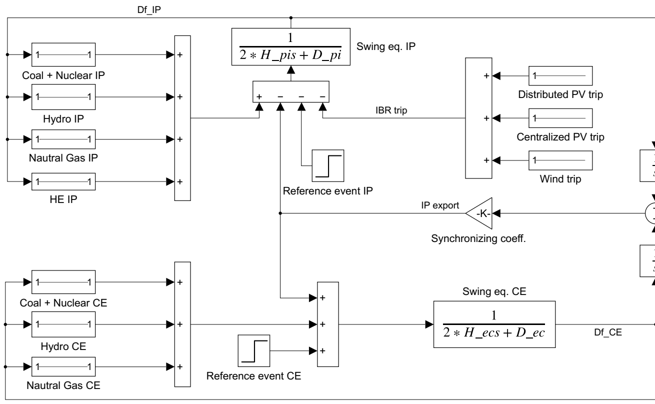

Fig. 1. MATLAB/Simulink simulation platform

performance the HEs connected to the IP grid by 2040 may bring to mitigating unacceptable values of frequency and RoCoF via participation on the FCR. The main innovation of the paper is the impact analysis of HEs on the FCR, taking into account the range of HEs' ramping capabilities described in the literature [4] and influence of measurement acquisition time delays. The two analysed contingencies are more severe than found in the literature (i.e. [4]), but are either in line with the standard practice of ENTSO-e (reference incident) in one case, or with future threats due to large renewable energy generation in the other case as per Section II-C2.

The remainder of the paper is as follows: Section II addresses the simulation platform, HE model and parameters, Section III presents the results, Section IV discusses the results and Section V draws conclusions.

II. Methodology

A simulation platform was developed in MATLAB / Simulink (Fig. 1) to perform simulations related to the system dynamics following a disturbance, from where RoCoF and frequency nadir values are extracted. For this work the time-frame of interest is the first 30s after the incident as per FCR requirements.

A. Simulation Platform

The power system is modelled up to the year 2040. The proposed grid model consists of two equivalent nodes, corresponding to the IP and to Continental Europe (CE), connected via a transmission line here modelled as a synchronizing torque coefficient. The balance in the equilibrium model is disturbed by the contingencies described in section II-C; frequency behavior in each area is modelled using the well known swing equation [5], which causes the active power response of the generators participating in the FCR controlled by a typical speed droop, such that a new equilibrium is met. The nuclear and coal power plants have been grouped in a single unit; these, like combined cycle gas turbine (CCGT), i.e. natural gas plants have been represented by the dynamic model TGOV1 [6]. The hydro plants include an additional transient droop compensation as in [5].

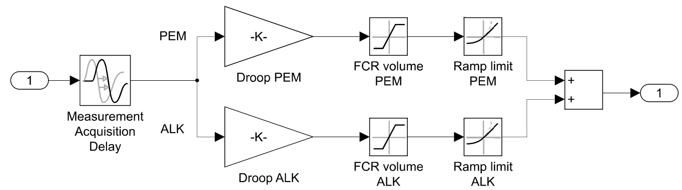

Fig. 2. HE model

Model parameters were estimated, when calibrating the model response regarding real system, as follows: (1) frequency measurements were obtained in both IP and CE, following a real incident in 2011 where a nuclear power unit of 1GW was lost in IP [7], (2) model is run several times varying the following parameters using particle swarm optimization: inertia constant (H_{IP} and H_{CE}), load self-regulating characteristic (D_{IP} and D_{CE}), speed droop of thermal and nuclear, hydro and CCGT plants (respectively: $R_{T\&N,IP}$, $R_{T\&N,CE}$, $R_{H,IP}$, $R_{H,CE}$, $R_{CCGT,IP}$, $R_{CCGT,CE}$), transient droop of hydro plants ($TR_{H,IP}$, $TR_{H,CE}$) and synchronizing torque coefficient (T), so that (3) frequency in IP and CE obtained by the model matches closely the observed frequency measurements. [1]

1) Hydrogen electrolyser model: Tuinema et al. [4] have performed a series of field measurements showing that HEs follow a linear response to set point changes, hence the HE response is practically only limited by a ramp rate. Fig. 2 presents the HEs' model adopted in this work.

In this study both alkaline and polymer electrolyte membrane (PEM) are FCR providers. The HEs receive a frequency deviation measurement after an acquisition time delay. The set point is dictated by the controller, which follows a classical speed droop approach, i.e. responds proportionally ($-1/R$) to the frequency deviation, and R is calculated such that full activation of FCR service volume contracted to HEs is achieved when frequency is below 49.8Hz [8]. A saturation is imposed on the FCR contracted volume. A ramp limit is imposed on the response, such that realistic HE ramp rates are respected.

The HE model represents an aggregation at two levels: firstly because of its modular nature, large HEs will consist of many units in parallel [4], and secondly because the whole IP network is modelled in this work as a single node, so all HE facilities in this region are modelled as a single equivalent unit.

It should be noted that a HE is a load and as a result an energy consumption decrease is equivalent to a generation increase in a conventional generator (i.e. upward reserve provision). In this study, it is assumed that the HEs are working at nominal power when the contingency happens, so that the HEs are only able to provide upward reserve. It is also assumed that the downward reserve (also same volume as upward reserve) could easily be provided by solar and/or wind farms in a market scheme such as FCR Cooperation [9], i.e. a

[1] Additional model details can be provided upon request.

market that allows the aggregation of distinct resources (which would conceptually behave like a Virtual Power Plant (VPP) [10]) so that the resulting FCR market bids of VPP (HEs + solar + wind) are symmetric. In the present study, since only a loss of generation is simulated, only the need for upward reserve from HEs is considered, so for the sake of simplicity the downward reserve is disregarded.

FCR ancillary service provision is presently a mandatory service in the Iberian Peninsula. However in this research it is assumed that a FCR reserve market will be in operation.

B. Parameters in 2040

As a result of inertia decrease, it is expected that concerns with stability issues increase as time passes; the year chosen for the simulations in this paper is 2040, so that a worst-case scenario can be addressed.

The value of inertia is computed as follows: from [11] it is assumed that in 2010 20% of the inertia comes from the demand side, therefore 3.9pu.s[2] of the H_{IP} in 2011. In [11] it is stated that by 2010 10% of the motors had power electronic interface and in 2040 this figure will increase to 50%. Even disregarding further electrification, in 2040 the demand side will contribute with at least 0.78pu.s for inertia. Biomass will correspond to 1.4GW in IP [12] and are supposed to operate at nominal power with an inertia constant of 1s [13]). Additional contribution of inertia will come from hydro run-of-river power plants (4GW in IP [12] and assuming 3s of inertia constant [13]). For this latter case it is assumed to run only one third of its turbines considering dry summer conditions, and therefore the expected inertia of generation is 1.07pu.s. Adding demand and generation inertia, the minimum H_{IP} in 2040 is 1.85pu.s. It is assumed that H_{CE} in the period 2011-2040 drops in the same proportion as in IP (i.e. value in 2040 is 9.5% of value in 2011).

The decommissioning of power plants has an impact in the power plants participating in the FCR. It should be noted that in the IP it is considered that after 2035 all the coal and nuclear power plants have been decommissioned, and their participation is replaced by natural gas and hydro power, whereas in CE only coal is decommissioned.

Regarding HEs, the value of installed power in 2040 in IP will be 12GW. This value is found using the conservative scenario found in [14], which forecasts for 2040 240GW of HEs in the European Union; in this paper it is considered that 50% of these HEs to be grid-connected and 10% of them installed in the IP. Moreover, taking into account that PEM will likely be the dominant technology in the 2030's [15], it is assumed that the installed capacity will be divided into 8GW of PEM and 4GW of alkaline HEs. The ramping capability of alkaline HEs is assumed 0.15pu/s [16] (more conservative than [17]). For PEM HEs, ramps are of 2.5pu/s (*fast HEs*) and 0.5pu/s (*slow HEs*) as per [4]. The minimum load that that HEs need to operate (20-40% for alkaline HEs and 3-10% for PEM [18]) is inherently respected because the FCR volume

[2]System base is 10GW

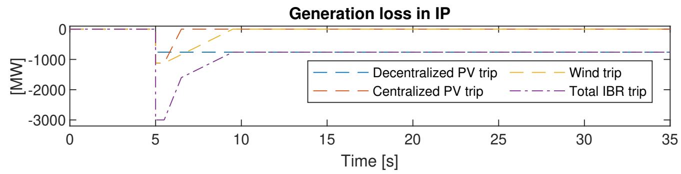

Fig. 3. IBR trip components

is small compared to the HEs' nominal power (430MW vs 12GW). FCR volume is divided into PEM and alkaline HEs propotionally to their installed power, i.e. 2/3 for PEM and 1/3 for alkaline HEs.

PV and wind power projections in Portugal for 2040 are as follows: 17GW of PV (9.6GW centralized, 7.4GW decentralized) and 10.75GW of wind (10GW onshore, 750MW offshore) [19], whereas in Spain around 180GW of renewables are expected. This data is of interest for the IBR contingency presented below.

C. Contingencies

Two types of contingencies are analyzed: the reference incident and the IBR trip.

1) Reference incident: The reference incident is defined by ENTSO-e as the largest credible loss of generation in the synchronous area; in CE this equals the installed power of the two largest power plants (3GW) and in IP the largest unit power plant (1GW). In fact, the volume of FCR required at any instant is defined with regards to the CE reference incident, meaning that 3GW of FCR volume must be available in every instant in the synchronous area to respond to a possible loss of generation of this size.

2) Inverter-based resources trip: The IBR trip considered in this paper is defined as an instantaneous loss of IBR production (e.g. PV, wind) in IP, following a short-circuit, which induces voltage sags that instantly disconnects part of IBR production. As per Fig. 3 there are three components in IBR production loss (a) 760MW of decentralized PV that is assumed to be lost and not reconnected in the following 30s, (b) 1120MW of centralized ("utility-scale") PV are lost during 500ms, and then this power is fully recovered linearly 1s later; (c) 1120MW of wind power are lost during 500ms, then this power is recovered linearly after 4s [20]. This kind of IBR trip (undervoltage disturbances) have been identified as a threat in Australia, where AEMO states that a severe but credible fault could cause the disconnection of up to half of the distributed PV in South Australia [21]. In this paper an IBR trip is considered in the Portuguese area (i.e. part of the Iberian Peninsula) causing an instantaneous disconnection of 3GW of installed IBR generation (i.e. 11% of the installed solar and wind power in the Portuguese control area or 1.4% of total solar and wind power within the whole IP).

D. Frequency thresholds

The metrics presented in Table I are assessed in each simulation. RoCoF violation threshold is considered the same as in Ireland since 2013 [22].

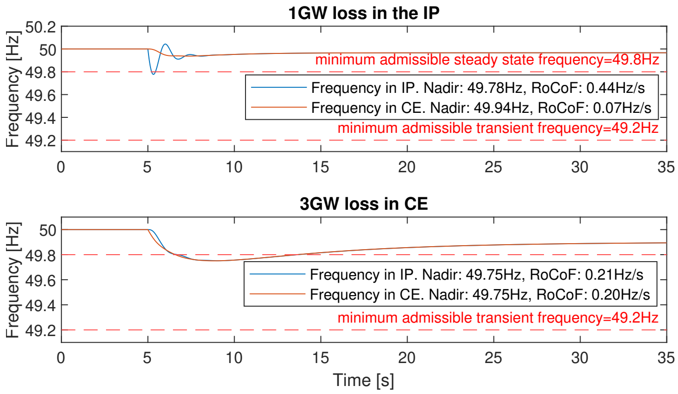

Fig. 4. Frequency in IP and CE after reference incident in IP and CE. FCR provided by conventional technologies.

III. Results

In Fig.4 both the reference incident in the IP and CE are analyzed, with FCR provided by conventional power plants. All limits (quasi-steady-state frequency, dynamic frequency and RoCoF) are respected in both IP and CE. Also, it is noted that although the reference incident in IP is much smaller than the CE reference incident (1GW *vs* 3GW), it causes a much higher RoCoF in IP. The rest of the paper omits the simulations within the CE, where all limits are always respected, and focuses on IP instead.

In Fig. 5 there are four simulations: two scenarios of generation loss in IP, which represent the IP reference incident and IBR trip; for each of those scenarios, two simulations were done, where FCR is provided by either conventional sources (hydro and CCGT) or HEs (*slow* PEM and alkaline). Regarding the reference incident, the metrics improve with HEs' FCR provision, although all these metrics are well within the security margin in any case (see Fig. 5 label). Regarding the IBR trip and considering frequency values, it can be observed that a satisfactory quasi-steady-state frequency (49.8Hz) is respected whether FCR is provided by conventional sources or HEs. The minimum dynamic frequency (49.2Hz) is also respected in both cases, however more severe for conventional sources than for HEs. However, regarding RoCoF, the IBR trip in both cases clearly exceeds the security 1Hz/s threshold but the participation of HEs in the FCR contributes to lower significantly the RoCoF value (1.24Hz/s *vs* 1.38Hz/s).

Fig.6 shows in detail what happens in both PEM and alkaline HEs (see Fig. 2) after the IBR trip. The PEM HEs for this simulation are *slow*. Firstly, the measurement acquisition time delay is relatively "small" if compared with the time

TABLE I
Metrics and Violation Thresholds

Metrics	Value	Source
Dynamic frequency deviation / nadir [Hz]	<49.2Hz	[2]
Quasi-steady-state frequency deviation	<49.8Hz	[2]
Rate of change of frequency (RoCoF)	>1Hz/s	[22]

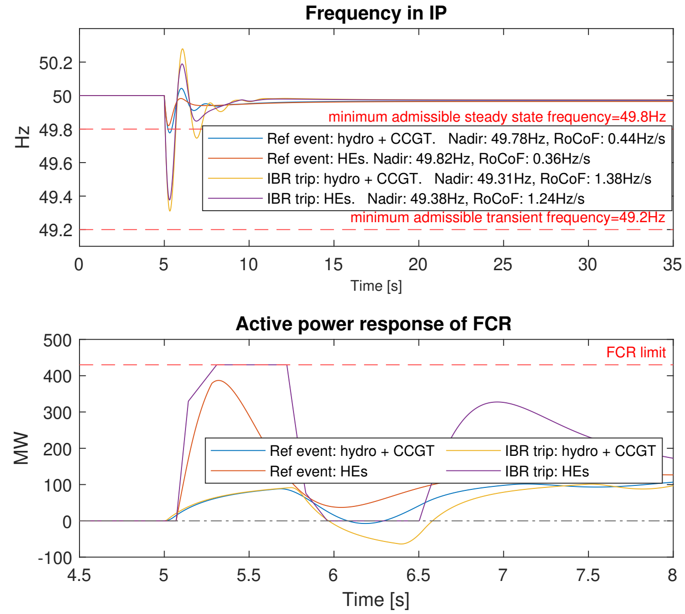

Fig. 5. Frequency in IP after reference incident and IBR trip, FCR in IP provided either by conventional technologies orHEs

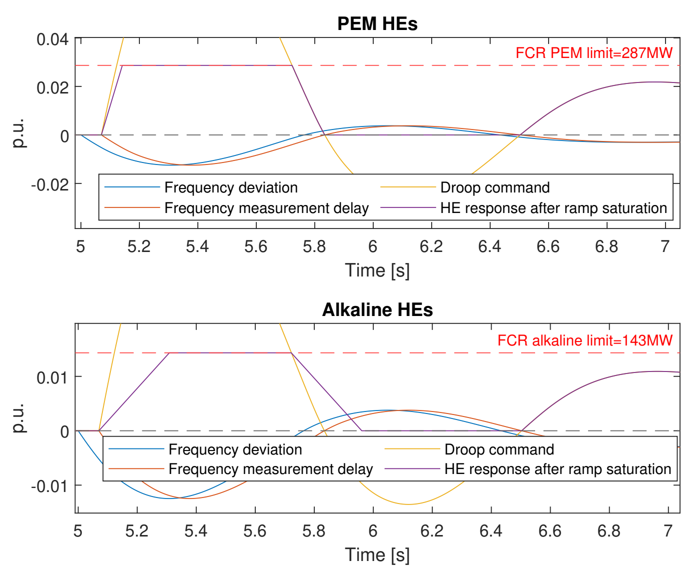

Fig. 6. Frequency measurement, droop command and HEs response

scale of the relevant incidents: this delay is 70ms and the nadir occurs around 320ms. When the HEs receive the first indication of frequency drop, in reality the frequency is already below the threshold at which FCR must be fully activated (i.e. 49.8Hz). Secondly, the droop command, inversely proportional to the frequency deviation, very soon reaches the maximum FCR response because the frequency drops fast below 49.8Hz (<100ms). Thirdly and most importantly, note that PEM HEs' active power output almost overlaps the "droop command", which means that the ramping capability practically allows for the optimal response. Alkaline HEs perform worse than PEM as they do not follow the droop command as closely. In

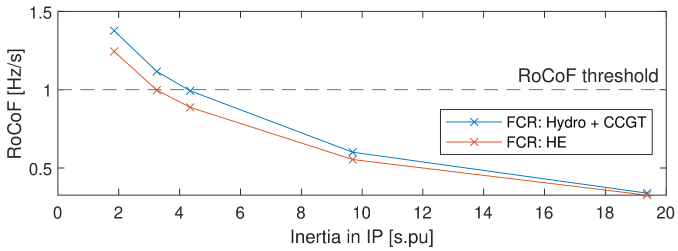

Fig. 7. Influence of system inertia on RoCoF, depending on FCR providers

any case, both *slow* PEM and alkaline HEs are capable of fully exploiting the FCR volume after an IBR incident, as opposed to conventional generation (as addressed in Fig. 5).

It is interesting to note that using *fast* HEs would yield the same nadir and RoCoF, as per Table II. This conclusion needs to be framed as follows: the amount of PEM HEs installed power considered in 2040 (8GW) is roughly 20 times the FCR volume (430MW) and therefore the *fast* HEs would be able to achieve variations of 2,5*8 GW/s which is higher than required by the speed droop controller.

Regarding measurement acquisiton time, besides the original 70ms, further simulations were performed, reducing this value to 40ms (two wavelengths), which is the theoretical minimum time for accurately measuring the frequency as detailed in [23]). As per Table II, simulations suggest an almost negligible nadir and RoCoF improvement regarding this parameter.

In Fig. 7 the RoCoF is analyzed for different system inertia values while FCR is being provided by either conventional technologies or HEs. The HEs contribution for minimizing RoCoF is more visible as system inertia diminishes. Namely, the RoCoF threshold is reached for 4.35pu.s system inertia if FCR is provided by hydro and CCGT, and at 3.25pu.s if FCR is provided by HEs. This means that even if HEs do not contribute to increase the system inertia, having the FCR provided by HEs has the same effect on RoCoF that if 1.20pu.s of inertia (10.2GW.s) is added to the system when FCR is provided by hydro and CCGT.

TABLE II
INFLUENCE OF HEs' RAMPING CAPABILITY AND MEASUREMENT ACQUISITON DELAY ON PERFORMANCE

FCR provider	Nadir (Hz)	RoCoF (Hz/s)
Hydro + CCGT	49.3103	1.3765
Slow PEM and alkaline HEs 70ms measurement acquisiton delay	49.3766	1.2443
Fast PEM and alkaline HEs 70ms measurement acquisiton delay	49.3783	1.2409
Slow PEM and alkaline HEs 40ms measurement acquisiton delay	49.3843	1.2289
Fast PEM and alkaline HEs 40ms measurement acquisiton delay	49.3855	1.2265

IV. Discussion

When low values of frequency in the power system are achieved, under frequency relays are triggered and load shedding mechanisms activated, disconnecting load as quick as possible to re-balance generation and demand. When in this paper it is mentioned that the HEs inject active power in the grid what happens is in fact the temporary diminishing of energy consumption by the HEs, very much like a load shedding, but activated before dangerous frequency values are achieved. This underlines the potential of demand response in the context of HEs, as it is proven that in case of a contingency, when aggregated, HEs effectively have the technical capability of providing the benefits of load shedding to system operators without the inconvenience of totally interrupting their main service (i.e. electrolysis for hydrogen production), as is the case of load shedding programs. Although in the simulations performed the 49.2Hz threshold is not attained, the violation of this limit is less likely when HEs participate in the FCR.

Even if the total mitigation of insecure RoCoF values is not achieved, HEs participating in FCR can effectively complement other technical solutions for future low inertia power systems. It has been seen that an IBR trip with participation of conventional technologies in FCR can achieve very high RoCoF (1.38Hz/s) whereas if FCR is provided HEs this value can drop significantly (1.24Hz/s). This could effectively reduce the need of complementary solutions for lowering RoCoF, such as synchronous compensators.

Regarding the performance of conventional technologies and HEs: in Fig.5 (bottom) it is observed that the hydro and CCGT and start to respond immediately when frequency starts dropping due to the fact that they are synchronous machines and have inertia, i.e. they release the energy stored in their rotors; HEs start to respond later than the conventional units, after a measurement acquisition time delay. This quick response can be seen as an advantage of conventional synchronous technologies over the power electronics interfaced units, but on the other hand, and taking into account that the active power response of the FCR can theoretically reach 430MW, it can be observed that if FCR is provided by hydro and CCGT, in the critical moment before reaching the nadir not even 100MW of FCR are activated. Therefore, it can be concluded that hydro and CCGT do not fully take advantage of this service, as they are not fast enough to deal with the frequency drop in very low inertia situations; in contrast, note that in the IBR case, the HEs are fast enough to respond with the contracted 430MW. These simulations were done using *slow* PEM and alkaline HEs, hence this is a conservative approach. It has been shown that if *fast* PEM are utilized instead, the improvement of RoCoF is marginal. In any case, this suggests that the traditional FCR is unable to unlock HEs' full potential as a fast-responding dynamic load.

Obviously, if the FCR was not limited to 430MW in the IP, the HEs would be able to inject more active power in the grid and contribute to attenuate the RoCoF. But again, the main aim of the FCR is to guarantee a quasi-steady-state frequency above 49.8Hz in the whole synchronous area, and this condition is observed after a severe IBR trip due to the existing FCR mechanism (3GW in the whole synchronous area, 430MW of which in the IP).

The simulations done in this study were performed using the minimum theoretical inertia in the future IP power system. Only a more thoroughly analysis would identify which percentage of the year the RoCoF would exceed the threshold and how to address this question. Fig. 7 allows to conclude the following: during critical hours, if the existing FCR mechanism is dominated by HEs there is indeed a decrease of RoCoF, and therefore less need for complementary services to address it.

V. Conclusions

The Iberian Peninsula will see a progressive decommissioning of conventional power plants (namely coal and nuclear) up to 2040, which will have a decisive impact by diminishing system inertia. This paper simulates contingencies where the impact of the minimum theoretical inertia is analyzed with regards to frequency and RoCoF, while comparing the response of conventional power plants with HEs in the context of FCR. The results indicate that whether the contingency is the conventional reference incident (3GW loss in CE or 1GW in IP) or an IBR generation loss following a short circuit, both conventional plants (CCGT, hydro) and HEs achieve the main FCR objective. Regarding RoCoF in the context of the IBR trip, simulations show that FCR provided by either both conventional plants and HEs may lead to the violation of the maximum acceptable value (1Hz/s). However, the RoCoF mitigation in the HEs case is more marked, which implies that, although additional mechanisms will be necessary to deal with this issue (such as additional fast frequency markets and synchronous compensators), HEs may minimize the need for these mechanisms. Future work will address aditional frequency services, such as fast frequency response or synthetic inertia.

References

[1] European Commission, "A hydrogen strategy for a climate-neutral europe," https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0301&from=EN, 2020, [Online; accessed 2022/03/23].

[2] UCTE, "Appendix 1: Load-frequency-control and performance," https://eepublicdownloads.entsoe.eu/clean-documents/pre2015/publications/entsoe/Operation_Handbook/Policy_1_Appendix%20_final.pdf, 2004, [Online; accessed 2022/03/23].

[3] ENTSO-E, "Continental Europe Synchronous Area Separation on 24 July 2021 - technical report." https://eepublicdownloads.azureedge.net/clean-documents/SOC%20documents/SOC%20Reports/entso-e_CESysSep_210724_211112.pdf, 2021, [Online; accessed 2022/04/04].

[4] B. W. Tuinema, E. Adabi, P. K. Ayivor, V. G. Suárez, L. Liu, A. Perilla, Z. Ahmad, J. L. R. Torres, M. A. van der Meijden, and P. Palensky, "Modelling of large-sized electrolysers for real-time simulation and study of the possibility of frequency support by electrolysers," *IET Generation, Transmission & Distribution*, vol. 14, no. 10, pp. 1985–1992, 2020.

[5] P. Kundur, '*Power system analysis and control*. McGraw-Hill Book Company, New York, 1994.

[6] Power System Dynamic Performance Committee, "Dynamic models for turbine-governors in power system studies," https://site.ieee.org/fw-pes/files/2013/01/PES_TR1.pdf, 2013, [Online; accessed 2022/03/23].

[7] A. Semerow, S. Höhn, M. Luther, W. Sattinger, H. Abildgaard, A. D. Garcia, and G. Giannuzzi, "Dynamic study model for the interconnected power system of continental europe in different simulation tools," in *2015 IEEE Eindhoven PowerTech*. IEEE, 2015, pp. 1–6.

[8] E. Commission, "Commission regulation (eu) 2017/1485 of 2 august 2017, establishing a guideline on electricity transmission system operation," http://data.europa.eu/eli/reg/2017/1485/2021-03-15, 2017, [Online; accessed 2022/03/23].

[9] FCR Cooperation, "TSOs' proposal for the establishment of common and harmonised rules and processes for the exchange and procurement of Balancing Capacity for Frequency Containment Reserves (FCR) in accordance with Article 33 of Commission Regulation (EU) 2017/2195 establishing a guideline on electricity balancing." https://eepublicdownloads.entsoe.eu/clean-documents/Network%20codes%20documents/NC%20EB/FCR_Proposal-Article_33_1%20EBGL_20181018_FV.PDF, 2018, [Online; accessed 2022/03/23].

[10] N. Naval and J. M. Yusta, "Virtual power plant models and electricity markets-a review," *Renewable and Sustainable Energy Reviews*, vol. 149, p. 111393, 2021.

[11] Y. Bian, H. Wyman-Pain, F. Li, R. Bhakar, S. Mishra, and N. P. Padhy, "Demand side contributions for system inertia in the gb power system," *IEEE Transactions on Power Systems*, vol. 33, no. 4, pp. 3521–3530, 2017.

[12] ENTSO-E, "ENTSO-E Transparency Platform: 'Installed Capacity per Production Type." https://transparency.entsoe.eu, 2022, [Online; accessed 2022/03/23].

[13] ENTSO-E, "Future system inertia." https://docs.entsoe.eu/dataset/nordic-report-future-system-inertia, 2018, [Online; accessed 2022/03/23].

[14] S. Deloitte Finance, IFPEN, "Hydrogen4EU - Charting pathways to enable net zero," https://www.hydrogen4eu.com, 2021, [Online; accessed 2022/03/23].

[15] O. Schmidt, A. Gambhir, I. Staffell, A. Hawkes, J. Nelson, and S. Few, "Future cost and performance of water electrolysis: An expert elicitation study," *International journal of hydrogen energy*, vol. 42, no. 52, pp. 30 470–30 492, 2017.

[16] IRENA, "Green hydrogen supply: a guide to policy making." https://irena.org/-/media/Files/IRENA/Agency/Publication/2021/May/IRENA_Green_Hydrogen_Supply_2021.pdf, 2021, [Online; accessed 2022/04/04].

[17] M. Kiaee, A. Cruden, D. Infield, and P. Chladek, "Utilisation of alkaline electrolysers to improve power system frequency stability with a high penetration of wind power," *IET Renewable Power Generation*, vol. 8, no. 5, pp. 529–536, 2014.

[18] Clean Energy Manufacturing Analysis Center, "Manufacturing Competitiveness Analysis for PEM and Alkaline Water Electrolysis Systems." https://www.nrel.gov/docs/fy19osti/70380.pdf, 2017, [Online; accessed 2022/04/04].

[19] República Portuguesa, Fundo ambiental and Agência portuguesa do ambiente, "Roteiro para a neutralidade carbónica 2050 (RNC2050)." https://www.portugal.gov.pt/download-ficheiros/ficheiro.aspx?v=%3d%3dBAAAAB%2bLCAAAAAAABACzMDexAAAut9emBAAAAA%3d%3d, 2019, [Online; accessed 2022/03/23].

[20] J. O'Sullivan, A. Rogers, D. Flynn, P. Smith, A. Mullane, and M. O'Malley, "Studying the maximum instantaneous non-synchronous generation in an island system—frequency stability challenges in ireland," *IEEE Transactions on Power Systems*, vol. 29, no. 6, pp. 2943–2951, 2014.

[21] AEMO (Australian Energy Market Operator), "Minimum Operational Demand Thresholds in South Australia Review." https://www.aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/sa_advisory/2020/minimum-operational-demand-thresholds-in-south-australia-review.pdf?la=en&hash=BBB27149A93B9259C63B47A8ECDB0B6E, 2020, [Online; accessed 2022/03/23].

[22] B. Hartmann, I. Vokony, and I. Táczi, "Effects of decreasing synchronous inertia on power system dynamics—overview of recent experiences and marketisation of services," *International Transactions on Electrical Energy Systems*, vol. 29, no. 12, p. e12128, 2019.

[23] DNV GL, "RoCoF Alternative Solutions Technology Assessment." http://www.eirgridgroup.com/site-files/library/EirGrid/RoCoF-Alternative-Solutions-Technology-Assessment-Phase-1-DNV-GL-Report_.pdf, 2015, [Online; accessed 2022/03/23].