FREQUENCY REGULATION POSSIBILITIES OF POWER-TO-GAS PLANTS IN GRIDS INCLUDING HIGH SHARES OF RENEWABLE ENERGY PRODUCTION

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Introduction

In networks where high share of renewable energy sources are used for primary energy production the inertia will become low since the rotating mass of the connected synchronous machine is mainly lost [1],[2]. The lower inertia means that connected regulation reserves must be able to respond faster to a frequency containment control than currently. The requirement for faster regulation have already been recognized by the transmission system operators (TSO) and distribution system operators (DSO). Recognition of the increasing need of balancing reserves has led to higher prices offered by the TSOs for power plants involved in the frequency regulation markets.

Increased and faster frequency variability is solved by using energy storages that enable faster transient performance. These faster solutions include especially the battery energy storage systems (BESS) using different battery technologies [3]. There are also other energy storage technologies such as pumped hydro storages, compressed air storages, flywheels, SMES, and supercapacitors. However, suitability of these energy storages is worse than battery energy storage solutions both technically and economically in most of the cases.

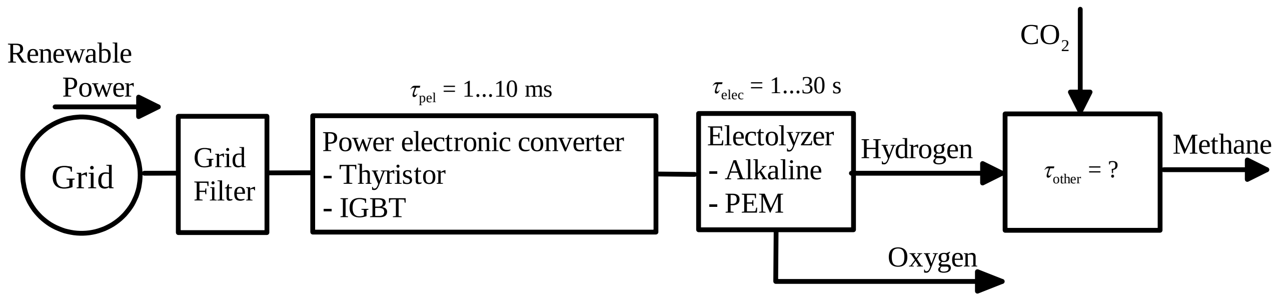
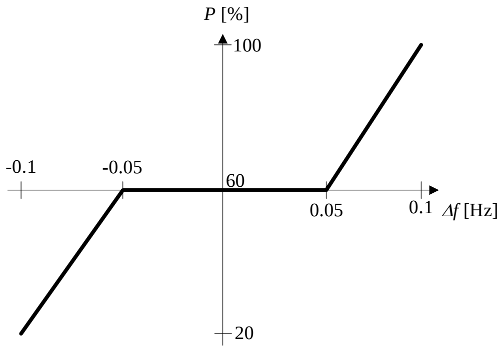


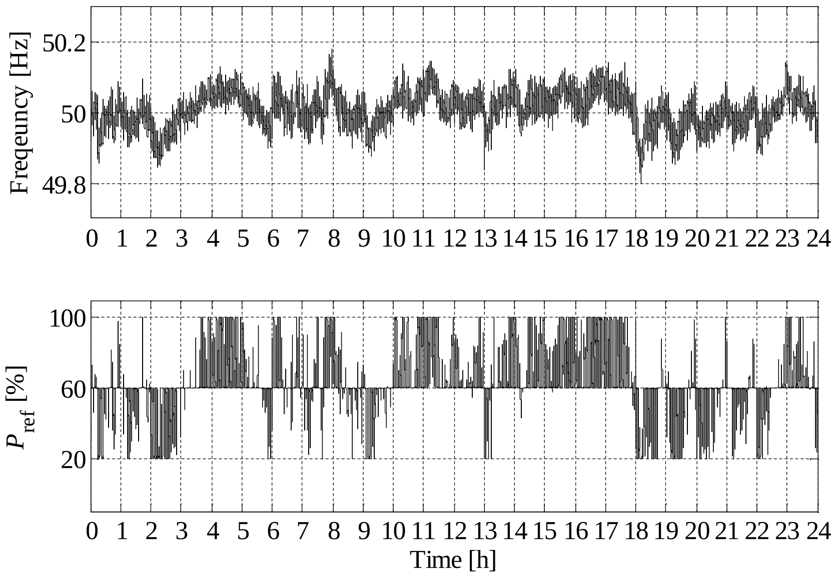
Figure 1. Schematic of the PtG plant grid interface.

In this paper the suitability of power-to-gas (PtG) plants (Fig.1), that have been recognized as a possibility to solve the seasonal storage problem, is investigated for frequency containment control [4]. In frequency containment control market the power plants have offered their available capacity to the TSO. Among the power plants involved with the control so called droop principle is often used.

That is, the change in plant's output power follows the change in grid frequency according to droop characteristic. In Fig.2 the droop characteristics for PtG plant is shown. From the grid point-of-view, the PtG plant operates as a tunable load. To avoid unnecessary control, in the characteristics there is a deadband near the nominal frequency. Typical values for deadband are ±0.01 Hz and ±0.05 Hz. However, according to Finnish grid code power plant operating in the primary frequency control market are supposed to deliver their total capacity for regulation when the frequency deviation crosses ±0.1 Hz.



(a) Droop characteristics.



(b) From frequency to PtG plant's power reference

Figure 2. Principle for power reference for the PtG plant.

Now, the rate of change of frequency (ROCOF) dictates which power plants are able to take part in the primary frequency control market. The ROCOF is governed by the grid's inertia. As noticed by the TSOs, when the amount of renewable energy sources has increased in the power grid, the inertia of the grid has reduced [1]. When the share of renewables in the grid becomes significant the conventional power plants connected to the grid are no longer able to react to the frequency variations as fast as needed. The current dynamic requirements for the power plants involved with regulation are shown in Table 1. To be able to respond fast enough also other options have been considered. The markets have been opened for smaller power plants whereas in the past, the power plants smaller than 10 MW were not considered. Apart from the conventional technologies used for frequency control new technologies have emerged [5]. One technology with the very good properties for primary frequency control is the battery energy storage systems (BESS).

In this paper the ability of PtG plant to take part in the frequency containment control markets is considered. The ability to fulfil these requirements by the PtG plant depend on the dynamics of different processes involved gas production (Fig.1). For different unit processes there are different technologies that can be used and these technologies have different properties that affects the plant's suitability for the frequency containment control. This suitability of different plant topologies is evaluated in the paper. The paper also studies the limit how fast responses are required in grids including high share of renewables using transfer function model of an island grid.

Table 1. Today's requirements for frequency containment control in some European countries.

	Minimum size	Full activation time	Activation principle	Resolution in time	Other
Germany	1 MW	30 s	symmetrical between ±0.2 Hz	Week	Deadband ±0.01 Hz
Finland	0.1 MW	3 min	symmetrical ±0.1 Hz	Day	Deadband ±0.05 Hz
Belgium	1 MW	30 s	symmetrical ±0.2 Hz and asymmetrical	Month	Deadband ±0.01 Hz

Methodology

To reveal the ability of PtG plant to execute frequency containment control the system needs to be modelled. Since the frequency control is a dynamic process, dynamic models of unit processes is required. The main processes of the system are shown in Fig. 1. In this paper 9 MW PtG plant is modelled. In the model there are three parallel connected 3 MWe electrolyzers (Fig. 3) which are connected to the grid via power electronic converters. The differences in dynamics between different power electronic converter technologies is considered in the paper. As an electrolyser, alkaline technology is modelled based on the Ulleberg model including the thermodynamics [6]. The electrolysers' output hydrogen pipes are coupled before the hydrogen storage tank and the size of the storage is determined so that constant hydrogen flow rate to the methanation process would be ensured.

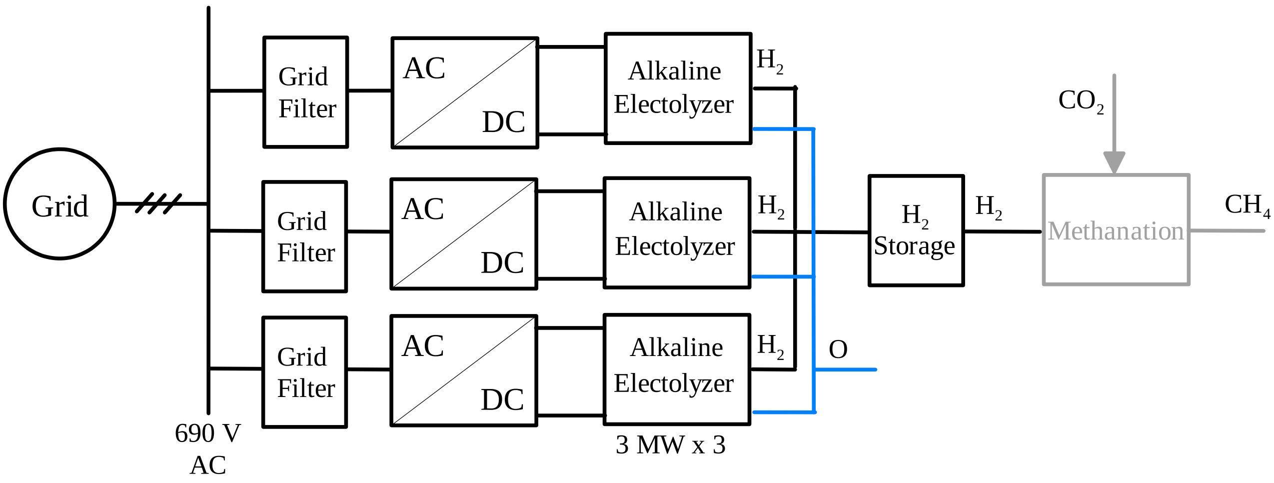


Figure 3. Investigated 9 MW PtG plant.

The modelling work of the PtG plant is carried out using Apros software. The Apros modelling software is suitable for dynamic modelling of chemical processes. Apros model is used as a reference model for the PtG plant. The dynamic properties of the reference PtG plants are then modelled to the power system simulation environment (PSCAD) and also for detailed grid interface models built to Simulink.

In this paper the dynamic limitations of the PtG plant are discovered using Apros model. In other words, the maximum rate of change of input power for PtG plant is determined when process constraints are considered. To find out the performance limits also the grid transfer function model needs to be varied. Especially, the inertia of the grid is varied that directly results in different ROCOF and frequency nadir. Comparison of these dynamics reveal the ability of this specific PtG plant type to operate in frequency regulating markets.

Results

The grid is interfaced with the power electronic unit. Typically the power electronics used is based on thyristor technology. The reason for applying thyristor based solutions is that electrolysers have typically applied low voltage 100-300 V and therefore with high powers the nominal currents become so high that high frequency switching is not an option. Secondly, the output DC voltage of the thyristor bridge can be controlled between 1.35*U_{LL} and zero which makes it suitable for electrolyser application with low voltages. If active rectifier using high switching frequency would be applied the output DC voltage would be constrained by the grid voltage. The minimum DC voltage that could be applied to the electrolyser system would be the peak value of the line-to-line voltage. In the 690 V system as shown in Fig. 2 it would mean that minimum voltage would be 975 VDC. It implies, that each parallel connected electrolyser module should have high enough nominal voltage to match the voltage control range of an active rectifier. Today electrolysers with nominal connection voltage of 400 apply or 690 V are commercially available. However, dynamically there is not much difference between the solutions and therefore not discussed in more detail here. In these simulations an ideal rectifier is used.

Next, the 9 MWe reference power-to-gas plant (Fig. 3) is simulated in Apros. The purpose is to show the behavior of the plant when the speed of power response is changed. When not contributing to the primary frequency response market the plant is operated at 5.4 MWe that corresponds 60 % of the nominal power. The minimum load for the alkaline electrolyser is 20 %. Therefore, the PtG plant has 40 % frequency regulation capacity to decrease or increase frequency.

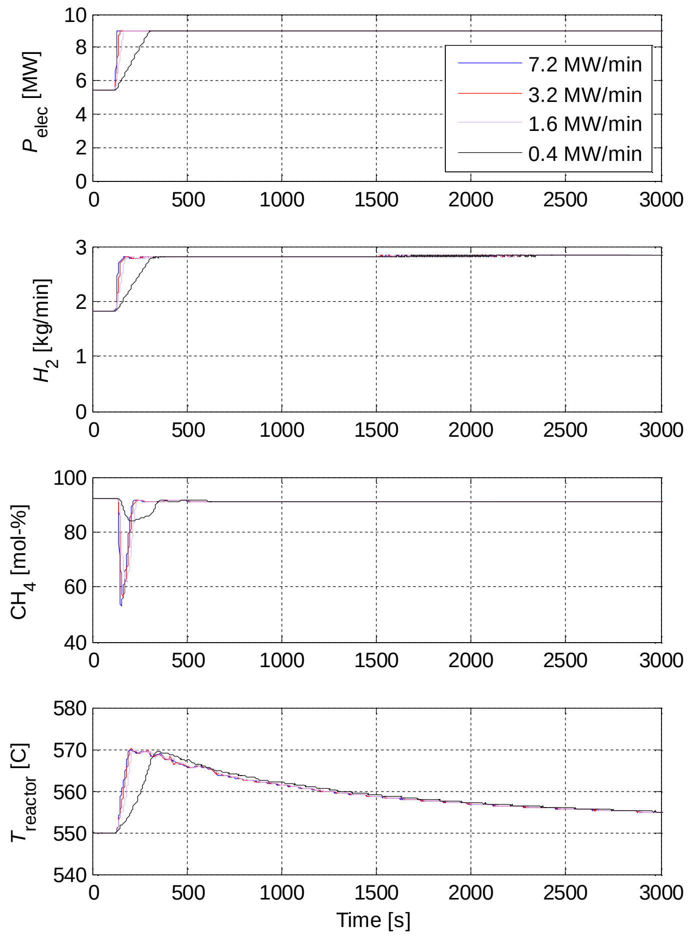


Figure 4. Ramp responses of the reference 9 MWe PtG plant.

In the simulations four different ramp rates are tested: (1) 0.4 MW/min, (2) 1.6 MW/min, (3) 3.2 MW/min, and (4) 7.2 MW/min. These ramp rates correspond that the 40 % input power change from 60 % level is carried out in 10 s, 22.5 s, 45 s or 180 s, respectively. The results of the simulations are gathered in to Fig. 4. The figure shows that responses in electrical power and hydrogen occur almost immediately whereas the methane process suffers a bit longer from the power transient. Interestingly, the peak thermal response does not change much with respect to change in ramp rate.

The ability of PtG plant to be used in the frequency regulation market is studied using a transfer function model [7] of an small island grid of which power production consists of 80 MW connection to main land grid and 22 MW of wind power that is in total of 102 MW. The peak load of the island is approximately 65 MW.

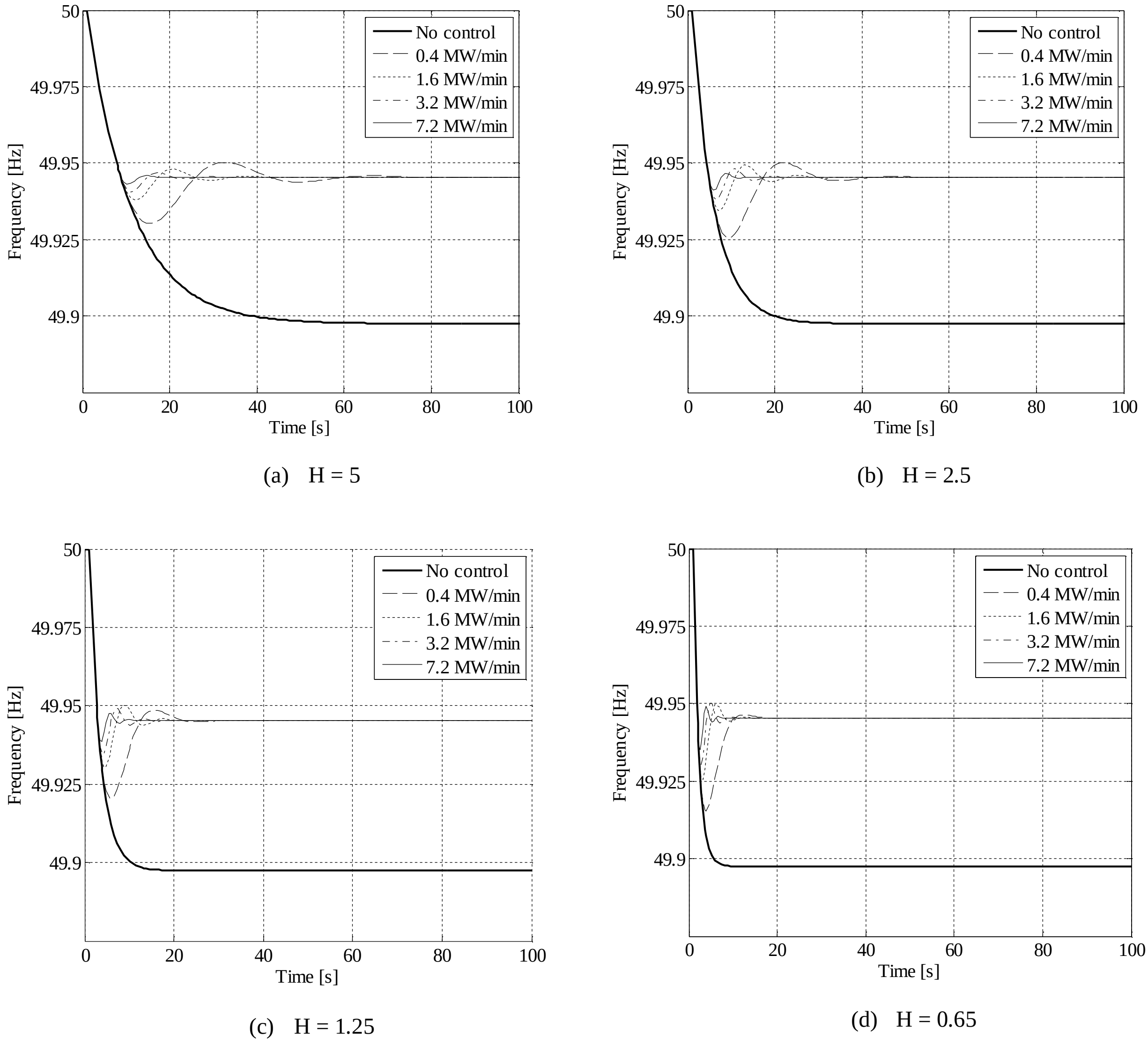


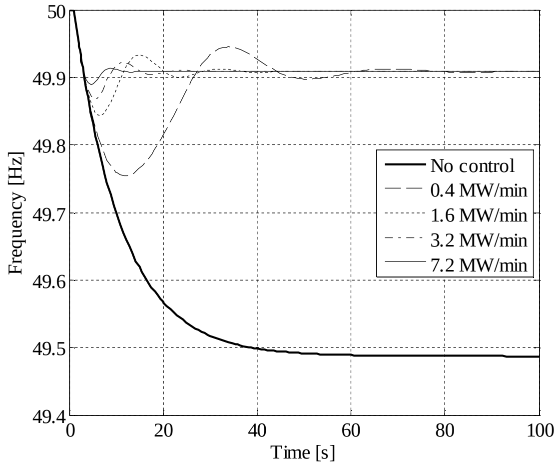
Figure 5. Behavior of primary frequency control when 200 kW load change in the grid. In the responses the inertia of the grid is varied.

The connection to the main land grid is obviously quite rigid and therefore simulations carried out with current network structure would not give results that reveal the potential of PtG to be used in frequency regulation markets. Therefore, a modified numbers are used in the transfer function model in order to really challenge the performance of the PtG. Although, the wind turbines ability to take part in the frequency regulation have been studied quite a lot the literature is still missing the method how the inertia of the turbine should be evaluated as seen from the grid interface of the wind turbine [8-11]. However, it is well known that approximately 10 % of the nominal power could be used for grid balancing. This concept is known as synthetic inertia. Synthetic inertia values for HVDC link have instead been calculated in [12], [13]. In [13] inertia values of H=1 and H=3 have been applied for the link. Therefore, power system inertia values of 5 and lower are used for grid inertia.

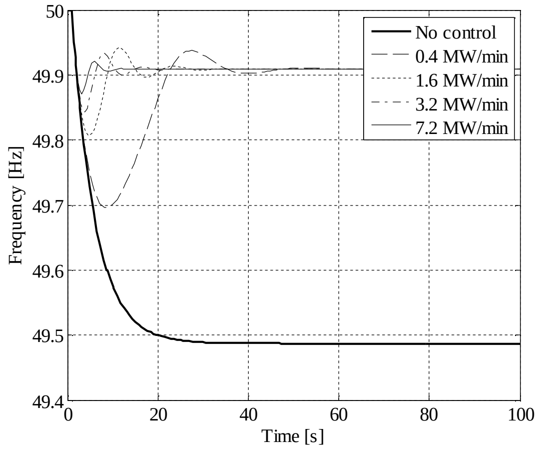
First, in this 100 MW grid small enough load or production change is simulated in order to show the performance in the regular primary frequency control, that is small load or production changes that result in small frequency variations ($\Delta f < \pm 0.1$ Hz). Here, 200 kW load change is applied where without primary frequency control the frequency would settle to 49.9 Hz as shown in Fig.5. The simulation is carried out using different inertia values to reveal the differences in performances between different ramp rates. The smaller inertia values would correspond to the case where more renewable power sources would be used in the grid. It can be noticed from the figure that with all ramp rates the response remains stable and as expected there is difference between the settling times as well as with the frequency nadir. One important thing that may have effect on the performance of PtG plant is that when $\Delta f > \pm 0.1$ Hz all the frequency control capacity ($P_{ctrl} = \pm 0.4 P_n$) would need to be assigned for the grid. This hypothesis is tested next where higher load change is applied in the grid so that it would saturate the power regulation capacity of the PtG plant.

In Fig.6. the results when 1 MW load or production change takes place in the grid. Now, bigger differences in responses can be noticed. The reason is that with lower ramp rates the control saturates and that can be immediately seen in the response. For example, with the lowest ramp rate the settling time of the frequency is approximately 60 seconds. With lower inertia values settling times are shorter but the frequency nadir is lower. Due to the slowness in response next it is considered what happens when there is a constantly variating either load or production. In practice in the real grid the frequency changes all the time and the performance should tested under constant variation.

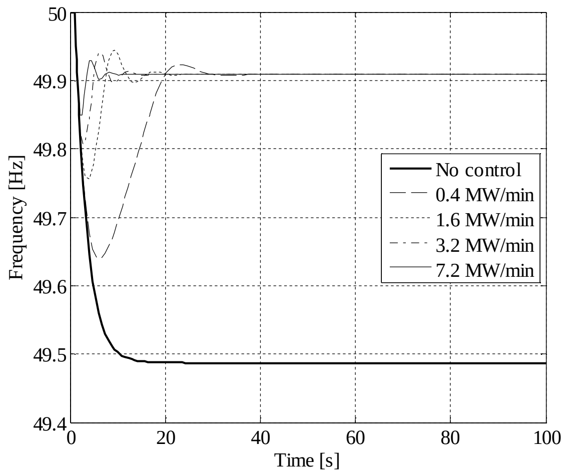
In Fig. 7 results of the simulation where the load and production constantly vary is shown. It can be noticed that with slow ramp rate the frequency variation is significantly higher than with the fastest



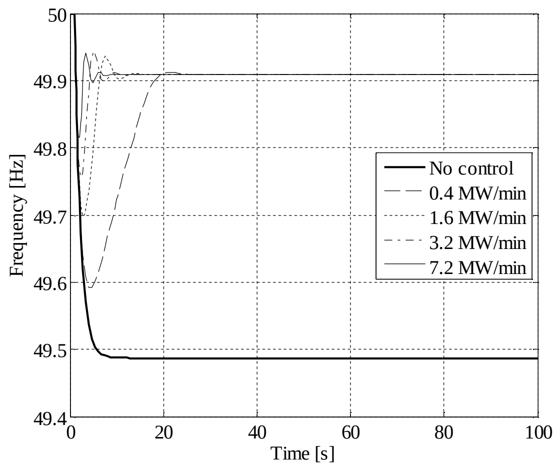
(a) H = 5



(b) H = 2.5



(c) H = 1.25



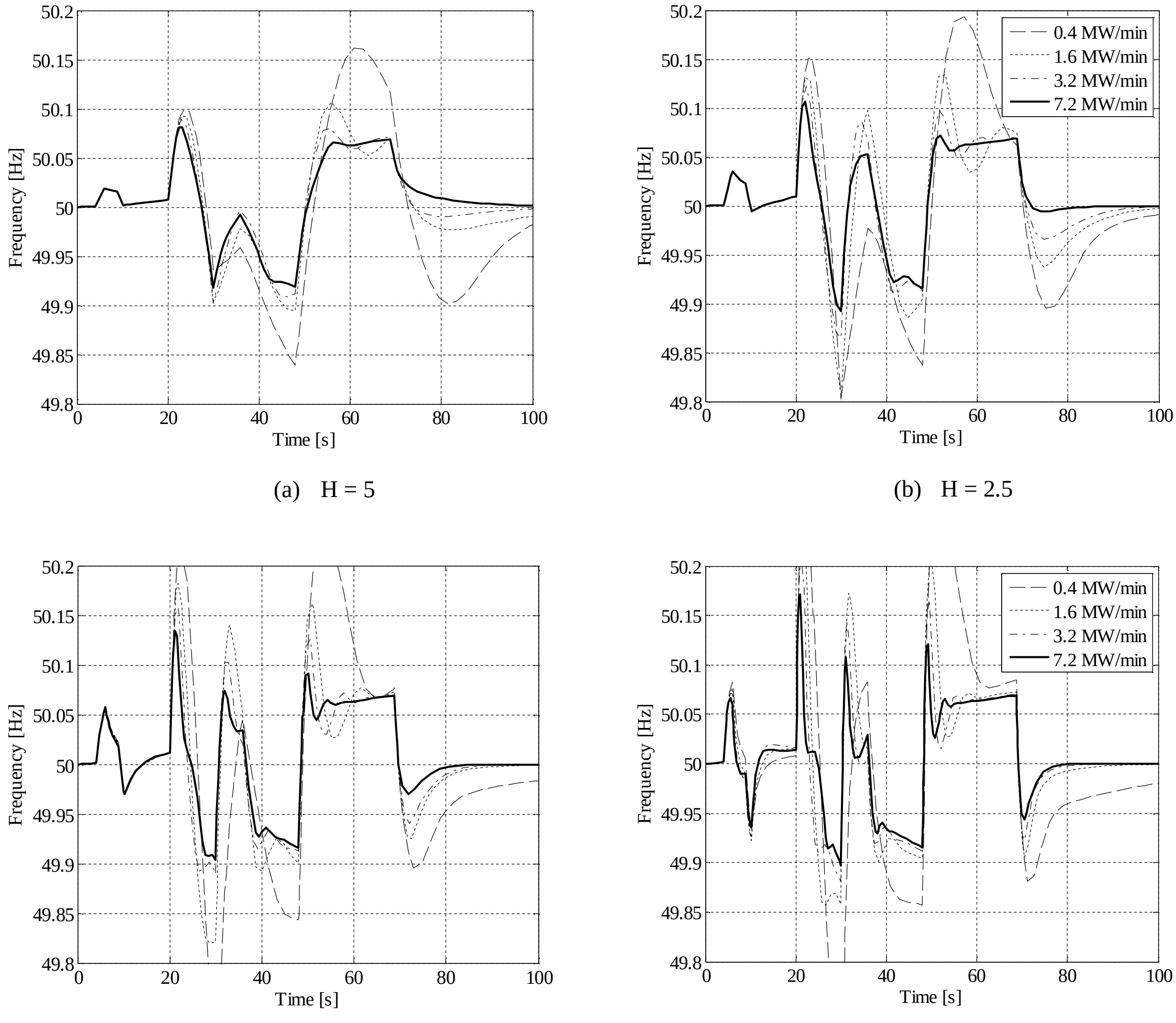
(d) H = 0.65

Figure 6. Behavior of primary frequency control when 1 MW load change in the grid. Responses with different inertias are plotted.

ramp rate. With the smallest inertia the frequency variations are unacceptably high when slow ramp rate is applied and therefore could not be applied in practice. What could be concluded from the figure is that all other rates produce acceptable frequency behavior when frequency nadir and settling times are considered.

Conclusions

In the paper power-to-gas plant's ability to take part on the frequency containment control market was considered. The paper studies a 9 MWe electrolyser performance under different power up ramp rates and noticed that there was not so much difference in the plant's performance whether slow or



(c) H = 1.25 (d) H = 0.65

Figure 7. Behavior of primary frequency control when consecutive load changes occur in the grid. Responses with different inertias are shown.

fast ramp was applied. From the PtG plant simulation guidelines for tuning the grid model were achieved. With the grid mode frequency behavior was studied under different load or production changes. Ultimately was noticed that slow ramp rate was not suitable for real life application since it resulted in too high frequency variations in the grid. Furthermore, it was concluded that three other ramp rate options would result in satisfactory result in frequency and if such performance would be realizable the PtG would easily be fitted for frequency control purposes.

References

[1] Ø. H.R. Chamorro, M. Ghandhari, and R. Eriksson, "Wind Power Impact on Power System Frequency Response," North American Power Symposium (NAPS), 2013, p. 1- 6

[2] Mohammad Seyedi, Math Bollen, The utilization of synthetic inertia from wind farms and its impact on existing speed governors and system performance, elforsk rapport, 2013, 53 p.

[3] Gauthier Delille, Bruno François, and Gilles Malarange, Dynamic Frequency Control Support by Energy Storage to Reduce the Impact of Wind and Solar Generation on Isolated Power System's Inertia, IEEE Tran. On Sustainable Energy, October 2012.

[4] M. Lehner, R. Tichler, H. Steinmüller, and M. Koppe, *Power-to-gas: technology and business models*, Springer International Publishing, New York, 2014.

[5] Sekyung Han, Soohee Han, Kaoru Sezaki, Development of an Optimal Vehicle-to-Grid Aggregator for Frequency Regulation, IEEE Tran. On Smart Grid, Vol. 1, No. 1, june 2010

[6] Ø. Ulleberg, "Modeling of advanced alkaline electrolyzers: a system simulation approach," *Int. J. Hydrogen Energy*, vol. 28, no. 1, pp. 21–33, Jan. 2003.

[7] P.Kundur, *Power System Stability and Control*. New York: McGraw-Hill Professional, 1994.

[8] Johan Morren, Sjoerd W. H. de Haan, Wil L. Kling, and J. A. Ferreira, Wind Turbines Emulating Inertia and Supporting Primary Frequency Control, IEEE Transactions On Power Systems, Vol. 21, No. 1, Feb 2006

[9] F. Gonzalez-Longattl, E. Chikuni, W. Stemmet and K. Folly, "Effects of the Synthetic Inertia from Wind Power on the Total System Inertia after a Frequency Disturbance," IEEE PES PowerAfrica 2012 Conference and Exposition, Johannesburg, South Africa, 9-13 July 2012

[10] M. Kayikç and J. Milanović, Dynamic contribution of DFIG-based wind plants to system frequency disturbances, *IEEE Trans. Power Syst.*, vol. 24, no. 2, pp. 859–867, May 2009.

[11] James F. Conroy, and Rick Watson, Frequency Response Capability of Full Converter Wind Turbine Generators in Comparison to Conventional Generation, IEEE Transactions on Power Systems, 2008.

[12] Markus Imhof, Göran Andersson, Power System Stability Control using Voltage Source Converter Based HVDC in Power Systems with a High Penetration of Renewables. .Power Systems Computation Conference (PSCC), 2014, p.1 - 7, DOI: 10.1109/PSCC.2014.7038493

[13] Jiebei Zhu, Campbell D. Booth, Grain P. Adam, Andrew J. Roscoe, and Chris G. Bright, Inertia Emulation Control Strategy for VSC-HVDC Transmission Systems, IEEE Transactions on Power Systems, 2013.