Modelling of Large-Size Electrolysers for Real-Time Simulation and Study of the Possibility of Frequency Support by Electrolysers

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Abstract: Hydrogen as an energy carrier holds promising potential for future power systems. An excess of electrical power from renewables can be stored as hydrogen, which can be used at a later moment by industries, households or the transportation system. The stability of the power system could also benefit from electrolysers as these have the potential to participate in frequency and voltage support. Although some electrical models of small electrolysers exist, practical models of large electrolysers have not been described in literature yet. In this publication, a generic electrolyser model is developed in RSCAD, to be used in real-time simulations on the Real-Time Digital Simulator (RTDS). This model has been validated against field measurements of a 1-MW pilot electrolyser installed in the northern part of the Netherlands. To study the impact of electrolysers on power system stability, various simulations have been performed. These simulations show that electrolysers have a positive effect on frequency stability, as electrolysers are able to respond faster to frequency deviations than conventional generators.

1. Introduction

In the future energy system, hydrogen as an energy carrier will play a role of increasing importance. Electrical energy can be converted into hydrogen locally by electrolysers and stored for a relatively long period. The hydrogen can then be used by final consumers like the transportation system or industries. The flexibility of electrolysers offers promising opportunities for electrical grid support by the provision of ancillary services like frequency and voltage support. Currently, a 1-MW pilot electrolyser is installed in the northern part of the Netherlands. A larger electrolysis plant of 300 MW is planned to be installed in this area later on. The feasibility of the installation of this large-scale plant, its impact on the stability of the electrical transmission network covering the northern part of the Netherlands, and the possibilities for ancillary services provision are currently being studied in the project TSO2020 [1], [2].

As it is important that the impact of electrolysers on power system dynamics is understood well, suitable generic models of large electrolysers need to be developed as models of large-scale (>1 MW) electrolysers are currently not described in existing literature. This publication describes the development of an electrical model of the 1-MW pilot electrolyser in RSCAD, to be used in real-time simulations on the Real-Time Digital Simulator (RTDS). Real-time simulation offers the possibility to perform Hardware-in-the-Loop (HIL) testing and facilitates the development of real-time controllers for future electrolyser plants. The developed model has been equipped with a control system which enables the electrolyser to respond to grid and market conditions in order to participate in ancillary services provision like frequency support. The developed model has been validated against field measurements from the pilot electrolyser and has been tuned accordingly. The developed model has been used to study the impact of smaller and larger electrolysers on the stability of power systems and to analyse the possibilities to participate in the provision of ancillary services. In this analysis, it is studied whether large-scale electrolysers could be utilised to support power system frequency and how effective this is in comparison with frequency support by conventional generators.

This paper is organised as follows. First, Section 2 describes the modelling of the electrolyser. The validation of the model against field measurements of the 1-MW pilot electrolyser is discussed in Section 3. Section 4 describes several simulations in which the contribution of electrolysers to frequency support is analysed. Finally, general conclusions and future work are discussed in Section 5.

2. Modelling of the Electrolyser

This section describes the modelling of the electrolyser. After introducing the various electrolyser technologies in Section 2.1, a detailed literature review is given in Section 2.2. The electrolyser model which will be used in this research is then presented in Section 2.3.

2.1. Electrolyser Technologies

There are mainly four types of electrolysers: Polymer Electrolyte Membrane (PEM) electrolysers, alkaline electrolysers, Solid Oxide Electrolysers (SOE) and Anion Exchange Membrane (AEM) electrolysers [3]. Currently, both PEM and alkaline electrolysers are commercially available. AEM electrolysis has a limited range of applications, whereas SOE technology is at its early stage of development. Among the cited technologies, alkaline electrolysis is the most mature, while PEM is in its initial commercial phase. Although alkaline technology is well suited for smaller applications, PEM electrolysis is a promising technology for future, large-scale applications [4], [5]. It holds the highest promise in the sense of lowest capital cost along with higher power densities, smaller footprint, larger dynamic range and a scalable design. The models developed in this study are therefore based on PEM electrolyser technology.

An electrolyser plant basically consists of three parts: (i) the electrolyser stack, in which the electrolysis takes place; (ii) the Balance of Plant (BoP) components, which support the operation of the stack (e.g. feedwater and circulation pumps); and (iii) the power conversion system, which connects the stack to the electric power system (e.g. rectifier, DC/DC converter and transformer).

2.2. Electrolyser Models in Literature

Although some electrical models of small electrolysers exist, practical models of large (>1 MW) electrolysers are not available in current literature yet [6]. According to [7], research over the past decade in the field of PEM electrolysers has led to models of increasing complexity and utility. Significant research has been conducted into improving the PEM stack efficiency and reliability, among others, and in line with these objectives, theoretical or/and graphical models have been developed with the aim of enhancing the integration with other systems or improving the device itself. The modelling approaches also vary based on the physical parameters of interest. For example, the models in the electrical domain model voltages and currents, whereas thermal models highlight temperature and entropy flow. According to [8], some models in literature concentrate on the impact of specific parameters (e.g. membrane conductivity, exchange current densities, temperature, pressure, thermal energy) on the device behaviour, while others take into account all phenomena occurring in the device. Despite this variety, simplified electrical and thermal models are mostly used [9].

A steady-state electrical model and linear dynamic thermal model of a PEM electrolyser were developed in [9]. Electrical model parameters were estimated through a nonlinear least square method and thermal model parameters were identified using the properties of a first-order linear model. The focus was to develop a model to aid monitoring of PEM cells, thus the model captures the system at the PEM stack layer. Naturally, this approach excludes the power conversion system and other components and therefore, it is of limited use in the study of interactions with power systems. A similar approach was used in [10]. The developed model can be applied to different sizes of PEM electrolysers as well as to different parallel/series combinations of cells. The model can also be applied to electrical systems in order to analyse the electrical response and performance of PEM electrolyser systems. This model also captures the electrolyser at the stack layer and, therefore, its application is limited as well.

In [11], Electrochemical Impedance Spectroscopy (EIS) was used to develop an electrical equivalent circuit for the PEM electrolyser. The model captures the electrolyser in good detail at the PEM stack layer, but does not capture the power conversion system. In [7], a SIMULINK model of a complete PEM electrolyser cell based on modules describing the behaviour of the anode, cathode, membrane and cell voltage was developed in terms of physical parameters related to the materials of construction. This research concentrated on improving the PEM cell, while excluding other system components such as the BoP and the power conversion system. In [8], a model was developed using Energetic Macroscopic Representation (EMR), a graphical modelling approach which attempts to capture phenomena in different domains. Although the resulting model's output fits well with real data, it does not capture the power conversion system in sufficient detail. The power conversion system plays a significant role in the interactions with the power system and other controllers and it was modelled as an energy source using a black box approach. This limitation prevents the effective use of the model to study the electrical response of the electrolyser within the framework of ancillary services delivery.

Some modelling approaches have expanded the focus to systems to be coupled to renewable sources, however, the scale is small (i.e. <1 MW). For example, a simple model for atmospheric or low-pressure PEM water electrolysers made of three related sub-models was proposed in [12], but this model also captures the electrolysers at the PEM stack layer. In [13], a complete model of a 500-kW electrolyser system was built in PSCAD with the aim of demonstrating the capabilities of electrolysers in voltage support applications. The scale of this model, though under 1 MW, may be the closest to a large-scale model described in literature.

The various modelling approaches reviewed concentrate on different layers of the electrolyser system as a result of different objectives and are mostly for sizes of electrolysers smaller than 1 MW. Most of the models are suitable for the limited scope they are proposed for. However, for purposes of understanding interactions of large-scale electrolysers with the power system, more will be required. To address this gap, a generic model that captures the PEM stack in addition to key subsystems like power conversion and BoP in sufficient detail and at a scale in the order of megawatts, is needed. Such a model should be equipped with a control system which is able to control the active power consumption of the electrolyser based on the grid and market conditions. This is currently missing in the existing literature models.

2.3. Electrolyser Model Development

For this study, a model of the 1-MW pilot electrolyser has been specifically developed in RSCAD (i.e. the simulation software of the RTDS, Real-Time Digital Simulator) [14]-[16], based on existing literature describing the working principles of electrolysers. Fig. 1 shows the components of the electrolyser system, as modelled in this study. The AC/DC and DC/DC converters are implemented in a number of ways by different manufacturers, depending on the application. In this study, the AC/DC conversion is implemented with a 3-phase active rectifier in series with a DC/DC converter. The DC/DC converter is implemented as an interleaved buck converter. The BoP components are modelled by a constant load, as it can be assumed that most of these have a fixed power consumption.

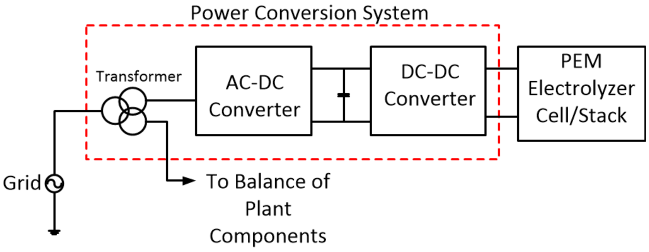

Fig. 1. *Electrolyser system components.*

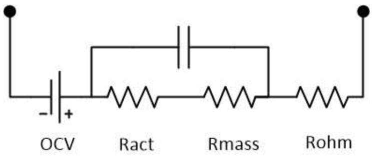

Fig. 2. *PEM stack equivalent.*

Fig. 2 shows the electrical equivalent of the PEM electrolyser stack. Electrolysis requires a Direct Current (DC) source that must overcome a reversible voltage in order to trigger the chemical reaction of water splitting into oxygen and hydrogen. Losses within the PEM stack increase the required voltage and are modelled as overpotentials. The representation by the electrical equivalent is widely used in current literature [17]. The reversible voltage is represented by a fixed DC voltage (OCV). Ract, Rmass and Rohm represent the activation, mass transport and ohmic losses, respectively. The double layer capacitance of the cell is represented by a capacitor. A further simplification of the model can be made by neglecting the activation and mass transport losses and the double layer capacitance. The electrical model then becomes a series connection of the open cell voltage and ohmic losses, which can be estimated from the slope of the I-V curve between the boundaries of the upper and lower operating current densities for a given cell area. As the model developed in this work is intended to be used for grid studies, it does not model the electrochemical reactions and thermal phenomena in detail and the aforementioned simplification is expected to be sufficiently accurate. This will be verified against field measurements in Section 3.

The electrolyser model developed in this project is equipped with a control system [14], [16], which is based on a generic architecture proposed in [18]. Control systems in commercially available electrolysers are primarily designed to support plant automation for the production of hydrogen gas. In order to optimise the electrolyser system to support additional objectives such as the provision of ancillary services, an additional control layer is required. The Front End Controller (FEC) is this additional high-level control and integrates with low-level controls to form a hierarchical control scheme with extended capabilities, such as the capability to simultaneously respond to market price signals, the condition of the power system and internal signals like electrolysis process alarms. Fig. 3 shows the structure of the high-level control. A detailed description of the high- and low-level controls of the electrolyser can be found in [14], [16].

3. Validation of the Developed Model against Field Measurements

The developed electrolyser model has been validated against field measurements of the 1-MW pilot electrolyser installed in the northern part of the Netherlands in Veendam-Zuidwending. The parameters of the electrolyser model have been adjusted to the field measurements, such that the model is able to accurately replicate the behaviour of a real electrolyser. This section discusses the network configuration and measurement setup (Section 3.1), the measurement procedure (Section 3.2), the measurement results (Section 3.3), and the adjustment of the developed electrolyser model to the measurements (Section 3.4).

3.1. Network Configuration and Measurement Setup

The simplified network configuration at Veendam-Zuidwending is illustrated in Fig. 4. A 5-km (double circuit) cable connects the 33-kV substation Veendam-Zuidwending to the 110-kV substation Meeden. At Veendam-Zuidwending, two 110/33-kV transformers are installed.

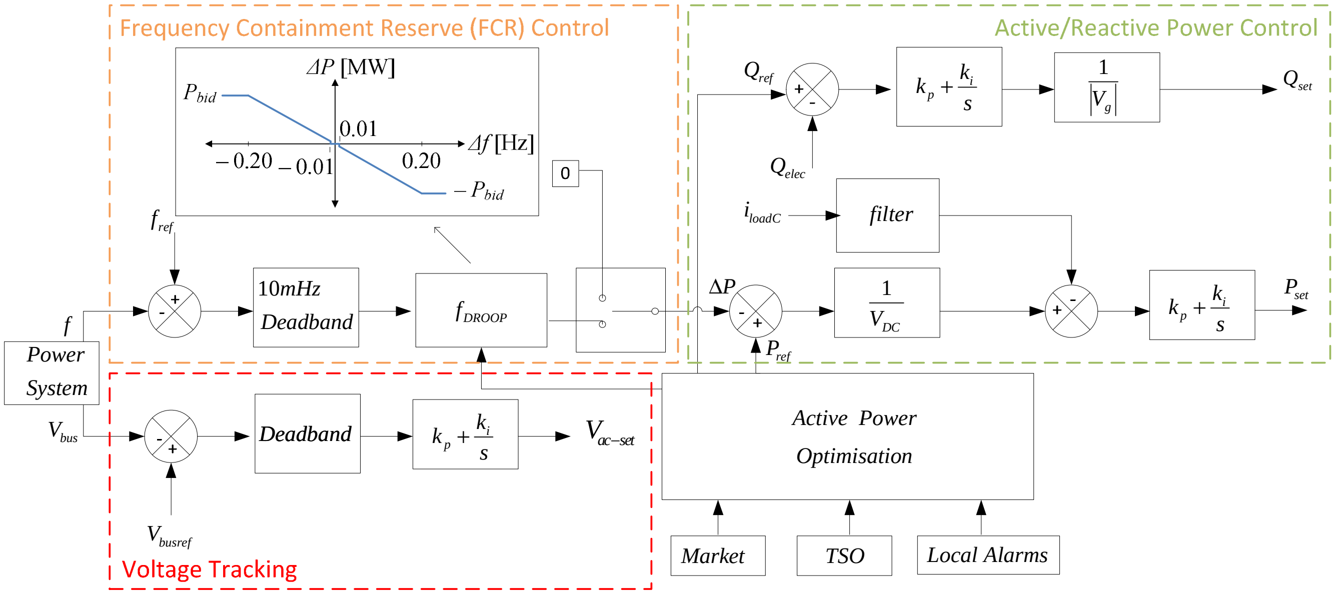

Fig. 3. *Structure of the high-level control (Front End Controller).*

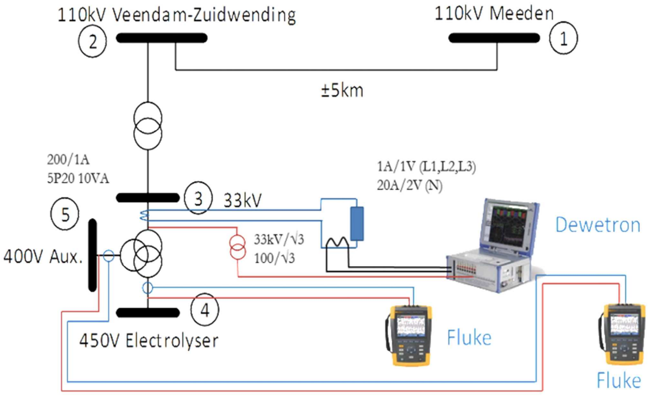

Fig. 4. *Measurement setup at Veendam-Zuidwending.*

The substation contains two busbars and several bays, to which the compressors and other systems of the natural gas storage facility at this location are connected. The electrolyser has its own bay and is connected by a three-winding transformer. The electrolyser itself is linked to the secondary winding of the transformer, while auxiliary systems are connected to the tertiary winding. Measurements have been performed at all three windings of the transformer, i.e. points 3, 4 and 5 in Fig. 4.

The measurements at 33 kV were performed within the substation. The current was measured in the secondary circuit of the 33-kV installation with a current clamp of 1A/1V. The secondary current comes from a (200/1A, 5p20, 10VA) current transformer. The voltage was measured at the secondary side with a (33kV/√3/100V/√3) voltage transformer. The 33-kV measurements were performed using a Dewetron measurement system, equipped with a DAQP-VB measurement card for the current measurements and a DAQP-HV measurement card for the voltage measurements. The current measurements were performed using Universal Technic M1.UB 1A/1V and Chauvin Arnoux 20-200A/2V MN 38 current clamps.

The measurements at 450 V and 400 V were performed directly at the secondary and tertiary windings of the transformer, respectively. For these measurements, Fluke 435 series 2 power quality and energy analysers were used. For the current measurements, I430-FLEXI-TF-II Ragowski coils were used, while the voltages were measured directly.

3.2. Description of the Measurement Procedure

During the test, the operation of the electrolyser was tested in two cycles, as illustrated in Fig. 5. These cycles consisted of starting up the unit, varying its operation setpoint between various levels (i.e. 10/50/70/100%), and shutting down the unit. As the electrolyser needs to build up pressure and perform some safety checks first, the operation level is limited to 50% directly after starting up the unit. After a certain time, the operation level goes to the desired setpoint. This is indicated in the graph by the dashed lines. During the test, measurements were recorded at the three mentioned voltage levels, where the main quantities of interest were: the voltage and current magnitudes, the total active power and the total harmonic distortion of the voltage and current.

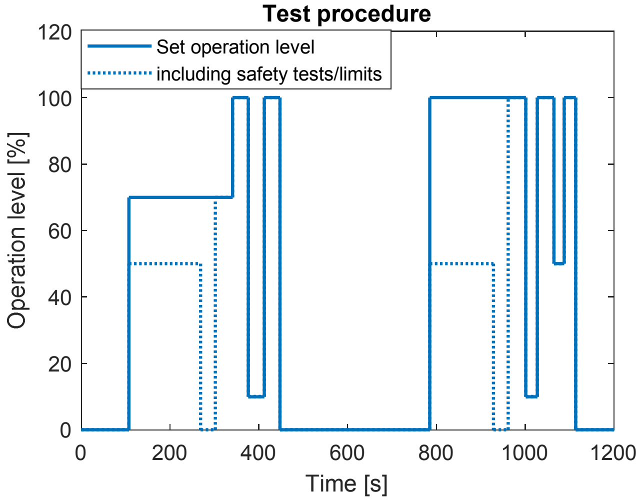

Fig. 5. *Operation cycles during the electrolyser test.*

3.3. Experimental Measurement Results

The active power consumed by the electrolyser, measured at the 450-V side of the transformer, is illustrated in Fig. 6. It can be seen that the active power consumption clearly follows the test cycles shown in Fig. 5, apart from the inrush currents when starting up the unit. The active power consumed deviates somewhat from the operation level setpoints (i.e. 50/70/100% of 1 MW).

The graphs shown in Figs. 7 and 8 zoom in on the active power ramps during the setpoint changes, which are aligned at t = 0. For this graph, the measurements at 33 kV were used, as the Dewetron device has a higher resolution than the Flukes. The graphs show that the active power ramps are linear and quite similar during normal operation (i.e. between 10 and 100%). The active power ramps after starting up the unit are typically slower. From these graphs, the average ramp rate of the electrolyser can be estimated. It can be seen that the average ramp up rate is about 0.5 MW/s (0.5 pu/s) during normal operation, while it is about 0.2 MW/s (0.2 pu/s) during startup of the electrolyser. The average ramp down rate is about 0.4 MW/s (0.4 pu/s).

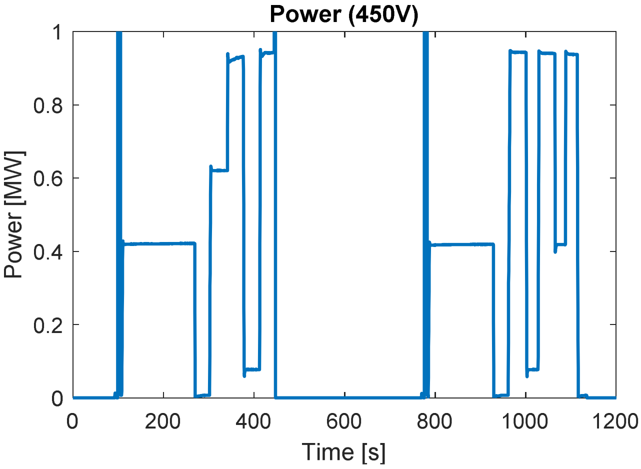

Fig. 6. *Active power of the electrolyser measured at the 450-V bus.*

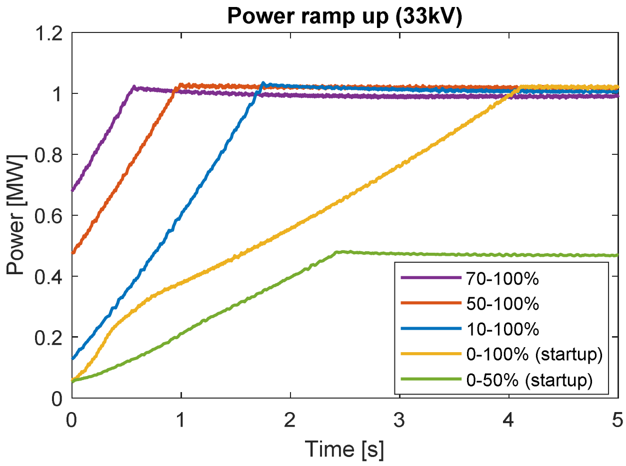

Fig. 7. *Response of the electrolyser to operation level setpoint changes (ramp up).*

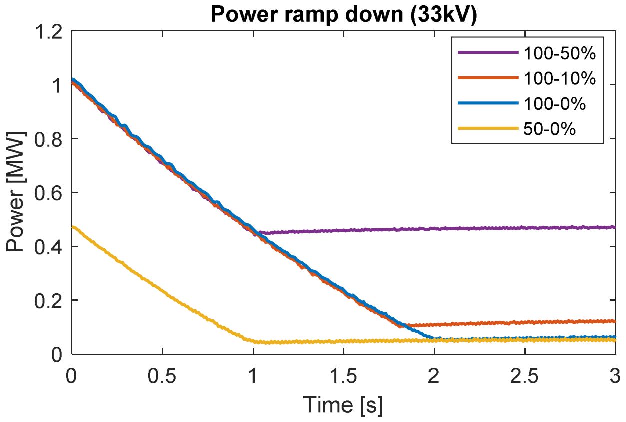

Fig. 8. *Response of the electrolyser to operation level setpoint changes (ramp down).*

3.4. Comparison of the Developed Model with the Field Measurements

Based on the field measurements, it is possible to estimate the ramp rate of a larger electrolyser unit. It was found that the 1-MW pilot electrolyser shows a linear response to setpoint changes, and has a ramp rate of about 0.5 MW/s (0.5 pu/s). Large electrolyser facilities consist of many small electrolysers in parallel. This means that a 300-MW electrolyser plant consisting of 300 units of 1 MW can reach a ramp rate of 150 MW/s (0.5 pu/s). This result can, roughly, be compared with data available in literature. In [19], the response of a 40-kW PEM electrolyser was tested. It was found that this electrolyser shows a non-linear behaviour, where the dependence of the response time on the size of the setpoint change is only small. Ramping up or down is generally completed within 0.2 s. A capacity change of 50% within 0.2 s gives a ramp rate of 20kW/0.2s = 0.1 MW/s (2.5 pu/s). Under the assumption that the response time does not increase significantly for electrolyser capacities in the range up to a MW and the fact that a 300-MW electrolyser plant consists of many smaller units, this would lead to a ramp rate of 750 MW/s (2.5 pu/s) for a 300-MW electrolyser plant. Although this comparison is based on rough assumptions, it still gives an indication of the range of ramp rate to consider in further studies, i.e. 150–750 MW/s (0.5–2.5 pu/s).

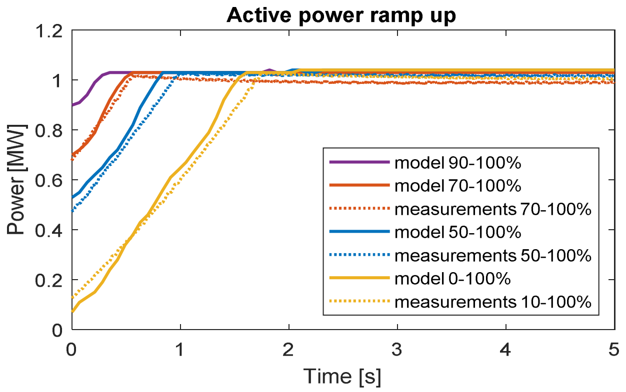

Fig. 9. *Comparison between the detailed electrolyser model and the field measurements (ramp up).*

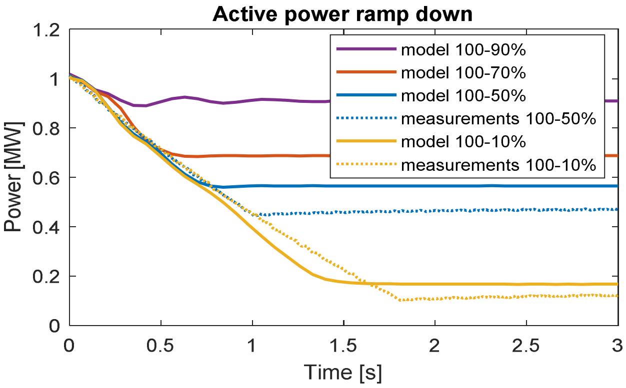

Fig. 10. *Comparison between the detailed electrolyser model and the field measurements (ramp down).*

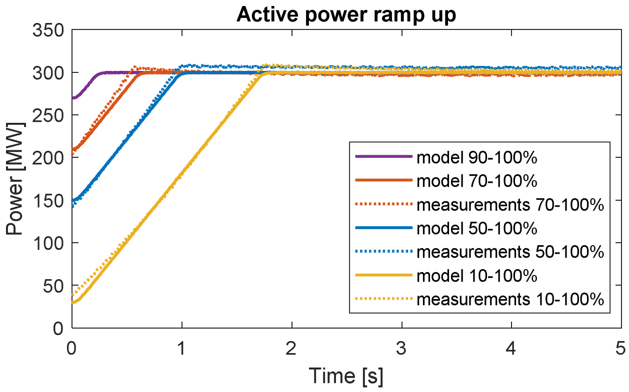

Fig. 11. *Comparison between the simplified, scaled-up electrolyser model and the field measurements (ramp up).*

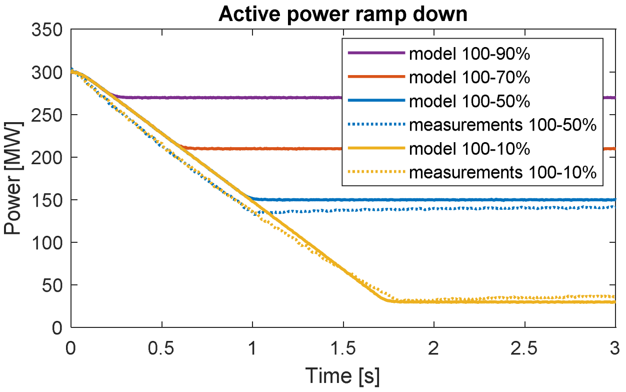

Fig. 12. *Comparison between the simplified, scaled-up electrolyser model and the field measurements (ramp down).*

The parameters of the developed electrolyser model have been adjusted, such that the electrolyser model is able to accurately follow the response of a real electrolyser. The electrolyser has been extended with a ramp rate limiter, which has been empirically tuned to follow the desired response. Figs. 9 and 10 show the response of the 1-MW electrolyser model. It can be seen that the developed model is able to replicate the response of a real electrolyser. The response of a second, simplified and scaled-up, version of the electrolyser model (without DC/DC converter) is shown in Figs. 11 and 12. It can be seen that this scaled-up version is able to follow the measurements accurately as well. As the response of this simplified version was already inherently linear, this scaled-up model follows the measurements somewhat more accurately.

4. Simulation of the Impact of Electrolysers on Power System Stability

The developed electrolyser model is used to study the impact of smaller and larger electrolysers on the stability of the power system. This section discusses the considered network topology and two study cases, namely the loss of generation capacity and the loss of demand.

4.1. Network Topology and Operational Scenarios

For this study, a model of the northern part of the Dutch transmission network has been developed in RSCAD. This part of the transmission network contains several large-scale facilities which interact with electrolysers, namely: the 700-MW HVDC NorNed connection (to Norway), the 700-MW HVDC COBRAcable (to Denmark), the 600-MW GEMINI offshore wind farm, and almost 3 GW conventional generation. The network topology considered in this study is illustrated in Fig. 9. The two operational scenarios considered here are shown in Table 1. The total electricity demand of this area is 2075 MW for the considered scenarios. The demand is divided over the three provinces within this area: Groningen-Drenthe (875 MW), Overijssel (800 MW) and Friesland (400 MW), and distributed over the substations within the network. The demand has been projected based on the demand of 2018 [20], while considering the estimated growth proportion and distribution over the substations.

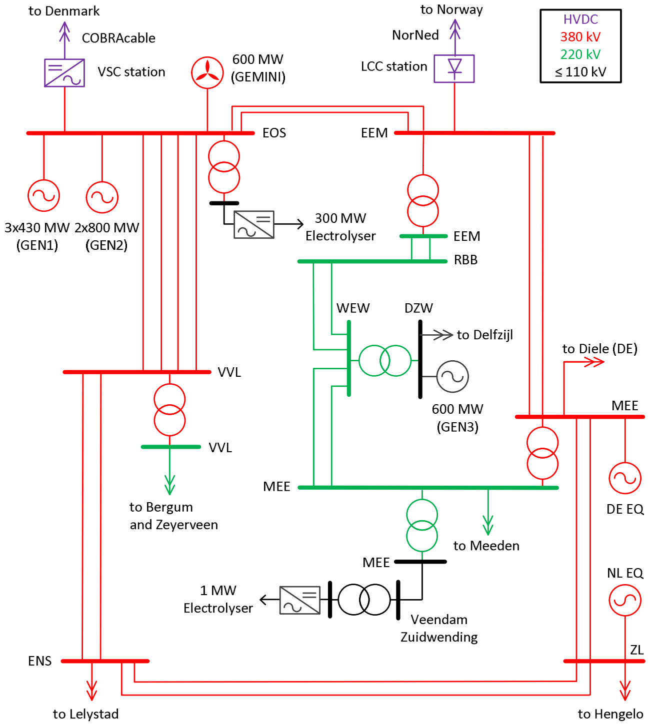

Fig. 9. *Considered network topologies for this study.*

Table 1 Operational scenarios considered in this study

Generator/HVDC link/electrolyser	Case 1: loss of generation [MW]	Case 2: loss of load [MW]
GEMINI wind farm(EOS)	450	450
GEN1 (EOS)	3×430	3×430
GEN2 (EOS)	2×800	2×650
GEN3 (DZW)	233	233
NorNed import (EEM)	700	700
COBRAcable import(EOS)	-700	-500
Electrolyser demand (EOS)	300	190

4.2. Simulation of Case 1: Loss of Generation Capacity

In the first study case, a loss of generation capacity is considered. For this purpose, the generation at EOS substation is reduced by 200 or 50 MW by decreasing the power generated by GEMINI wind farm. The impact on frequency stability of the system is studied considering Frequency Containment Reserve (FCR) support by generators. In this study, there is a total of 300 MW FCR support in the system, divided over the generators in the system (i.e. 190 MW DE EQ, 30 MW for each other generator and NL EQ). To study the impact of electrolysers, the participation of electrolysers in FCR is varied from 0 to 100% by replacing the FCR support of some generators with FCR support by the electrolyser.

The results of these simulations are shown in Fig. 10 (for a loss of 200 MW generation capacity) and Fig. 11 (for a loss of 50 MW generation capacity). An overview of the frequency nadirs is given in Table 2. It can be seen that the replacement of FCR support by the electrolyser has a positive effect on the frequency stability of the system, as the electrolyser has the ability to respond faster to deviations of the frequency. The oscillation of the frequency completely disappears when the electrolyser takes over the full FCR support, as electro-mechanic oscillations of the generators do not occur then. Simulations with different electrolyser ramp rates (i.e. 150 and 750 MW/s; 0.5 and 2.5 pu/s) have been performed, but this did not result in significantly differently results as the Rate-of-Change-of-Frequency (RoCoF) is slow in comparison to the minimum ramp rate of the electrolyser.

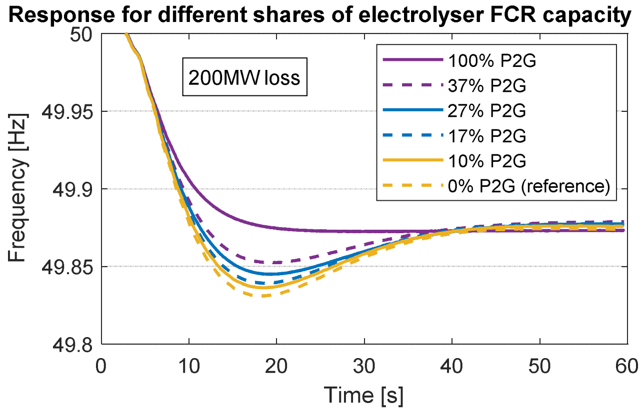

Fig. 10. *Frequency response of the system with different shares of electrolyser FCR capacity for a loss of 200 MW generation capacity.*

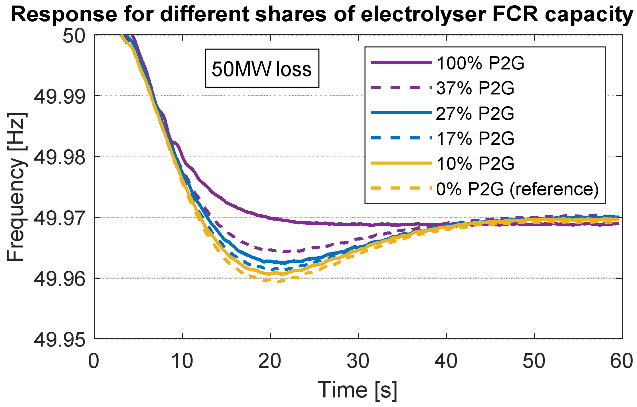

Fig. 11. *Frequency response of the system with different shares of electrolyser FCR capacity for a loss of 50 MW generation capacity.*

Table 2 Frequency nadirs for case 1: loss of generation

Share of electrolyser FCR capacity	Loss of 200 MW nadir [Hz]	Loss of 200 MW difference [mHz]	Loss of 50 MW nadir [Hz]	Loss of 50 MW difference [mHz]
0%	49.831	0	49.959	0
10%	49.836	5	49.961	1
17%	49.839	8	49.961	2
27%	49.845	14	49.963	3
37%	49.852	21	49.964	5
100%	49.872	41	49.969	9

4.3. Simulation of Case 2: Loss of Load

In the second study case, a loss of load is considered. For this purpose, the operational scenario has been changed according to Table 1. The electrolyser operational setpoint has been reduced to 190 MW, to enable upwards regulation of the electrolyser consumption and 37% of electrolyser FCR support. In this case, the loss of load is simulated by reducing the load at MEE380 substation by 200 or 50 MW. The results of these simulations are shown in Figs. 12 and 13. An overview of the frequency nadirs is shown in Table 3. Similar to the loss of generation capacity, it can be concluded that electrolysers have a positive effect on the frequency stability as electrolysers are able to respond faster than generators to deviations of the frequency.

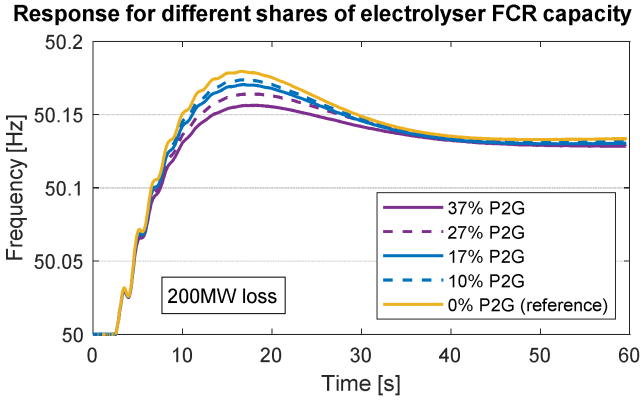

Fig. 12. *Frequency response of the system with different shares of electrolyser FCR capacity for a loss of 200 MW demand.*

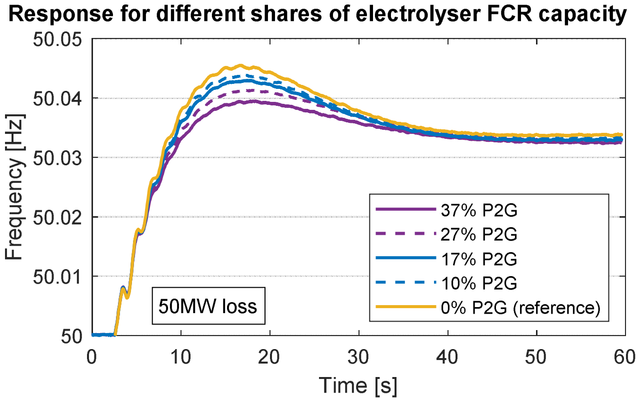

Fig. 13. *Frequency response of the system with different shares of electrolyser FCR capacity for a loss of 50 MW demand.*

Table 3 Frequency nadirs for case 2: loss of load

Share of electrolyser FCR capacity	Loss of 200 MW nadir [Hz]	Loss of 200 MW difference [mHz]	Loss of 50 MW nadir [Hz]	Loss of 50 MW difference [mHz]
0%	50.180	0	50.046	0
10%	50.174	6	50.044	2
17%	50.171	9	50.043	3
27%	50.164	15	50.041	4
37%	50.156	23	50.040	6

5. Conclusions and Future Work

In this paper, a generic electrolyser model was developed in RSCAD, to be used in real-time simulations on the Real-Time Digital Simulator (RTDS). In order to provide frequency support, the electrolyser model has been equipped with a Front End Controller (FEC) that responds to grid and market signals like frequency deviations. The electrolyser has been validated against field measurements of a 1-MW pilot electrolyser installed in the northern part of the Netherlands. After adjustment of the model, it is able to accurately replicate the behaviour of a real electrolyser. Frequency support by electrolysers was then studied in several real-time simulations, considering the northern part of the Dutch transmission network. It was found that electrolysers have a positive effect on frequency stability after losing generation capacity or load, as electrolysers are able to respond faster to frequency deviations than conventional generators. This work is part of a larger project in which the technical and economic viability of power-to-gas solutions is investigated. For the electrical studies, various scenarios for 2030 and 2040 are considered. The contribution of electrolysers to Automatic Frequency Restoration Reserve (aFRR) and voltage support are considered in the studies as well. Generally, the simulations show that electrolysers have the potential to support frequency stability more effectively than conventional generators.

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