Dynamic control of an electrolyser for voltage quality enhancement

N. Chiesa, M. Korpås, O. E. Kongstein, A. Ødegård

***Abstract*–The aim of this article is to demonstrate the feasibility and the advantages achievable from the integration of an electrolyser system for the production of hydrogen in a renewable energy system (RES). The system chosen for the demonstration is composed by a wind turbine and an electrolyser connected to a relatively weak grid. A model for the generation of stochastic wind speeds and a general wind turbine aerodynamic torque model are used to create realistic fluctuations in wind turbine active and reactive power. A dynamic electrolyser model is used in order to account for the electrolyser efficiency and dynamic response. Fluctuations in active and reactive output power of a wind turbine connected to a weak grid will typically cause voltage fluctuations, therefore reducing the power quality in the grid. The voltage fluctuations at the point of common connection can be reduced by introducing an electrolyser with flexible operating capabilities. Different control strategies are simulated and hydrogen production, system losses, and total energy transfer are compared. In addition, simulations demonstrate how the electrolyser efficiency is only slightly influenced if it is used for voltage quality improvements indicating that fluctuating input power does not cause significant extra losses in the electrolyser.**

***Keywords*: Renewable energy system, wind generation, electrolyser, hydrogen, power quality, voltage fluctuations.**

I. INTRODUCTION

ELECTROCHEMICAL hydrogen production is attractive for integration in a wind turbine system. Hydrogen acts as a storable energy carrier that can be either converted back into electric power by fuel cell during high demand in the grid or little wind, or can be used as a "zero emission" fuel for other applications, such as transport. The re-conversion of hydrogen into electricity is economically challenging for grid-connected systems due to the low electrolyser–fuel-cell system efficiency obtained at present [1]. Studies suggest that unless some improvement in efficiency and cost of such systems are achieved, the installation of an electrolyser makes most sense economically if the hydrogen is used locally e.g. for industrial use or as fuel for land and sea transport [2]. The economical analysis of the integration of hydrogen as a fuel mixed with natural gas for a local ferry transportation is exploited in [3].

Lee, An, Cha and Hur [4] made an analysis of a hydrogen station with wind energy in Korea. In this work it was found that the well to tank cost for hydrogen was almost the same as for gasoline and diesel. Diesel and gasoline was however not competitive when a 50% CO_2 tax was added. The major drawback of such a system was a high investment cost of the hydrogen powered vehicle.

Gutiérrez-Martín, Confente and Guerra [5] studied the possibility of installing a water electrolysis and fuel cell system to a Spanish wind farm. A surplus of 18.4% electricity could be produced during off peak hours, which could be converted to hydrogen and then converted back to electric energy during peak hours. This procedure could raise the total energy output from the hybrid system by 12.3%. In the economic calculations it was estimated a pay back time for the water electrolyser–fuel-cell system of about 20 years.

Ulleberg, Nakken and Eté [6] have reviewed the wind hydrogen system at Utsira in Norway. Among many operational problems the most interesting relataed to this work is the long start up time for the alkaline water electrolyser, and also that this could not operate below 25–50% of the rated capacity. On this basis it was desirable to switch to a PEM electrolyser.

Meibom and Karlsson [7] have analyzed the energy marked in northern Europe for a year 2060 scenario. It was found that by 2060 a significant part of the energy from renewable sources had to be converted to hydrogen by water electrolysis.

Bernal-Agustin and Dufo-Lopez [8] have made a techno-economical optimization of the production of hydrogen from photo voltaic (PV)-wind system connected to the electrical grid in Huesca, Spain. In the calculations, the PV part was found too expensive. In the optimized case the hydrogen cost became 9.25 €/100 km for a fuel cell vehicle, compared to 5 €/100 km for a diesel car when the electricity price was assumed to be 20 c€/kWh and a payback time for the investment of 10 years. It is concluded in the article that the price of electricity sold to the grid is the parameter that mostly influenced the selling price of hydrogen. It also mentioned that the average wind speed is an important factor (3.51 m/s for Huesca, which is very low compared to e.g. typical wind farm sites in Northern Europe).

An electrolyser can be operated in "classical" or "smart" ways in relation to wind power. In a classical way, the electrolyser is set at a fixed (however adjustable) hydrogen production rate. This means that the energy absorbed by the electrolyser is slowly varying or is constant over a relatively long time, e.g. in an hourly time range. Different control strategies for smoothing slow wind variations and for balancing of wind prediction errors have been described and analysed in [1], [2]. Earlier projects at SINTEF Energy Research have exploited the possibility to use an electrolyser dynamically in "smart"

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ways. The connection of the electrolyser to the grid trough a converter allows fast regulation and control of the active and reactive power flows in the system. Improvements of the power quality at the point of common coupling (PCC) and a reduction of system losses have been reported. At the same time, it has been observed experimentally that the electrolyser efficiency is not decreased when using a dynamic control strategy.

The fluctuating power output of RES will influence the operation of an electrolyzer. Large atmospheric alkaline electrolyzers have a long response time of several minutes and are therefore typically designed to operate at a constant operation power. Here, the most severe degradation occurs from current interruptions (unplanned stops) [9]. Pressurized alkaline and PEM electrolyzers have a much faster response time, and are thus more suitable for operation with renewable energy sources like wind mills and solar panels [10]. Here, it is also not primarily the power variation, but rather the current interruptions that lead to the increased degradation rate [10]. Therefore, by maintaining a minimum (protecting) current during operation, the degradation caused by power variation is minimized. By applying a somewhat over dimensioned electrolyzer stack, the efficiency will also be higher, but of course the capital costs increases as well. Polymer electrolyte membrane (PEM) electrolyzers is a promising, but immature technology. Compared to traditional alkaline electrolyzers the energy efficiency is higher [11]. According to Millet et al. [12] and Stucki et al. [13] the life time of PEM electrolysers has already reached nearly 10 years.

In this paper, a “smart” control strategy for an electrolyser-RES system is presented to demonstrate its technological and economical benefits and constraints. The main idea is to demonstrate the tools and the approach for the evaluation of a dynamic control strategy for an electrolyser converter. Fig. 1 shows the output power fluctuation in case of medium and high wind speed conditions. “Smart” control strategies are beneficial at below-rated wind speeds. The output power from the generator is relatively constant at above-rated wind speed, therefore it makes no sense to adopt a dynamic power flow control. The conclusions for the specific case-study analyzed in this paper should not be generalized: parameters such as wind speed and network capacity may greatly influence the final economical results.

II. DESCRIPTION OF THE ELECTRICAL SYSTEM

The case study system of Fig. 2 has been chosen for the analysis of advanced control strategies for the electrolyser converter. This system is a simplified representation of a possible island system. The best wind resources are often found in areas with weak grid connection to the main transmission grid. Typically, the local grid consists of long radial distribution feeders or subsea cables in case of islands. In such cases, voltage variations and thermal limits of network components may put a significant limit on the realizable wind power generation. Full exploitation of wind resources by extensive grid reinforcement projects could be very costly and/or difficult to put forward due to environmental concerns or other planning restrictions [14]. The studied case is of a small island system with one wind turbine connected to the end of a long cable connection. The case study is representative for several locations along the Norwegian coast, with typically high wind speeds and low local demand for electricity. Hydrogen from electrolysis can be considered as fuel for local sea transport as discussed in Section I.

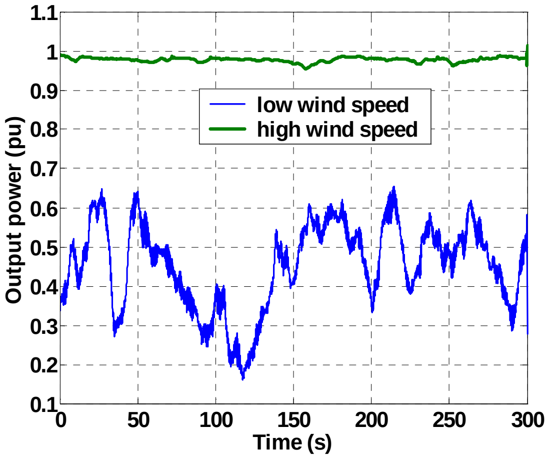

Fig. 1. Simulated output power from a wind turbine below rated wind speed (lower line) and above rated wind speed (upper line).

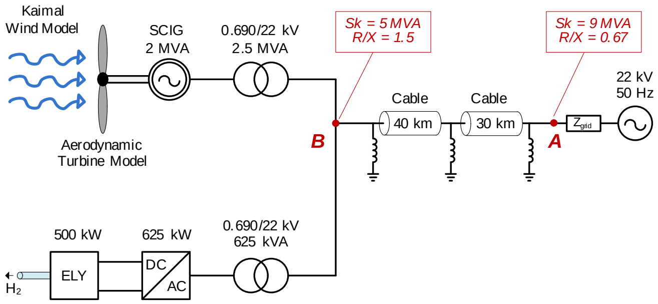

Fig. 2. Electrolyser-RES System.

The electrolyser–RES system is assumed to be connected to a relatively weak grid with short-circuit impedance of 9 MVA and R/X ratio of 0.67 at the point of common coupling (PCC) A. It is assumed that the generation and hydrogen section is located in a remote area connected by a 70 km cable. This results in a short-circuit impedance of 5 MVA and R/X ratio of 1.5 at the PCC B. The system voltage is 22 kV and 50 Hz. The wind generation and electrolyser are assumed at 690 V. The electrolyser power is selected to be 500 kW, however a 25% larger converter is used. The additional converter capacity comes at a low cost and is used for reactive power compensation (STATCOM).

Although only one wind turbine is used in the case study, the developed control strategies for the electrolyser converter are also relevant for larger systems. In other realistic cases, the capacity of the electricity grid may limit the total wind power capacity to some tens of MW (a small wind farm) rather than some MWs as used here. The electrolyser must then be replaced by an electrolyser system of several units in parallel, e.g. with one or two units acting as flexible loads

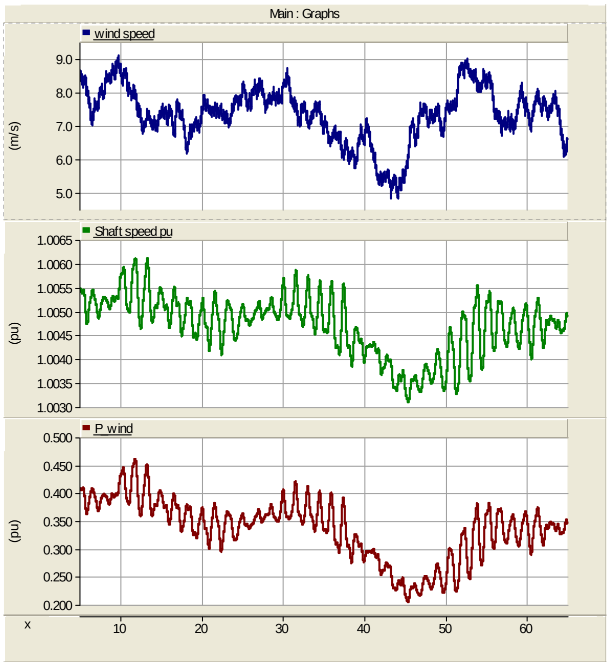

Fig. 3. Synthesized wind profile, shaft speed and generated wind power.

and the others operating at constant hydrogen output. When up-scaling the system, one should be aware of the expected damping of power fluctuations that will occur in a larger wind farm due to the different wind conditions at the different wind turbines. Regarding the “smart” electrolyser control strategies, one might adjust the control parameters in order to smooth out somewhat slower variations than shown in the example used here.

III. SIMULATION MODEL

The Electrolyser-RES system defined in Fig. 2 has been simulated in PSCAD/EMTDC. The use of a dynamic electrolyser model allows to evaluate the energy efficiency of the hydrogen production.

A model for the generation of stochastic wind speeds (Kaimal model, [15]) and a general wind turbine aerodynamic torque model are used to generate the input torque for a squirrel cage induction generator (SCIG). These models can produce representative active and reactive power fluctuation from a wind turbine. The 3P power pulsation due to the tower shadow effect is taken into account by the aerodynamic torque model.

Fig. 3 shows the synthesized 60 s windows wind speed, the generator shaft speed and the active power of the generator. The wind speed is based on an average wind speed of 7.5 m/s and a standard deviation of 1 m/s. These curves are used in all the case studies of this report.

The electrolyser model used in the simulation is shown in Fig. 4 and is based on [16], [17]. This model allows the modeling of the dynamic response of the electrolyser and the intrinsic conversion losses. The modeling methodology is general and can be used on any type of electrolyser technology; however the model parameters are component specific. The parameters required by the model are:

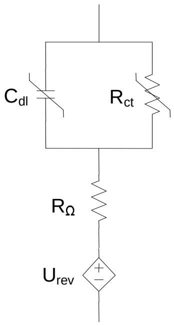

Fig. 4. Dynamic electrical equivalent model of the electrolyser.

- U_{rev} : reversible potential of the water splitting reaction. The potential depends both on temperature and pressure. It is assumed constant.
- R_Ω : ohmic resistance of the cell. This parameter is little dependent from the pressure and operating current. It is assumed constant.
- R_{ct} : charge transfer resistance. It is nonlinear and strongly depends both on pressure and operating current. It is modeled as a nonlinear current dependent resistance.
- C_{dl} : double layer capacitance. It is nonlinear and strongly depends both on pressure and operating current. It is modeled as a nonlinear current dependent resistance.

The parameters used in the model are based on in-house measurements on an alkaline electrolyser at 15 bars operating pressure. A 22-cells stack requires 5.15 kW power. A 500 kW electrolyser is build with 3 parallel sections of 33 stacks to meet the voltage level of the converter used in the simulation. The time constant $\tau = R_{ct} \cdot C_{dl}$ is in the order of 10 to 40 ms for an alkaline electrolyser.

The electrolyser converter is modeled with an average model. The average model performs as a three-phase, two-level, PWM converter, except that switching frequency phenomenas are averaged over the switching period. The principle is to make a continuous model that averaged over one switching period has the same terminal v-i relationship as a full, switched, model. The model makes it possible to run simulation with much larger time-step, resulting therefore in a much faster and larger time span simulations.

The cable in Fig. 2 is modeled with Pi-sections since no high-frequency phenomena needs to be investigated. The 30 km cable section is fully compensated with shunt reactances at each cable end. The 40 km section is not fully compensated on the side of PCC B as some capacitive reactive energy is used for the compensation of the SCIG.

IV. DYNAMIC REGULATION OF THE HYDROGEN PRODUCTION

The block diagram of the converter controller is shown in Fig. 5. The three-phase current reference of the converter is generated based on active and reactive power references. In case of a constant power regulation, the reference signals are kept constant.

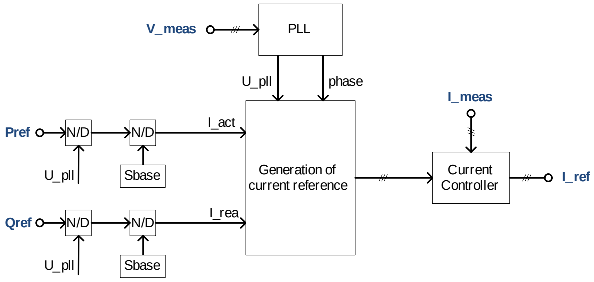

Fig. 5. Block diagram of the converter controller.

The block diagram for the generation of the dynamic reactive power reference signal is shown in Fig. 6. The electrolyser converter is used to compensate the reactive power fluctuation of the generator. The reactive power measured at the generator terminals is used as input for the control. A constant offset Q_{off} can be subtracted from the input signal. In this case the generator reactive power will not be fully compensated, but the remaining reactive power is constant.

The block diagram of Fig. 6 provides a mean of indirect control the bus voltage through a direct compensation of measured reactive power fluctuation. A direct voltage control can be obtain with the block diagram of Fig. 7. This may further improve the voltage quality. The control of Fig. 7 is greatly simplified. A droop function may be included to allow for shearing of reactive power load. A load compensation unit can be added for the control of a different voltage than the measured voltage at the converter terminals.

The same control strategy used for the reactive power regulation can be adopted for the active power regulation as well. However, this is not a very flexible control strategy as a constant offset has to be decided in advance. A new, more advanced, and more flexible control strategy has been developed in this project and the block diagram is shown in Fig. 8.

The target of the control loop of Fig. 8 is to compensate the active power fluctuations, but allow for slow variations in the active power transfer. This is achieved by using a high-pass filter on the input signal P_{gen}. The two feedback loops of the dynamic active power reference signal control are used to smooth the power transferred to the grid, as well as maximize the hydrogen production. The outer (green) loop is used for the automatic calculation of the offset reference signal. The target is to produce an average power defined by P_{set}. The distance in pu of the reference signal from P_{set} is calculated and used in an integral regulator. No proportional regulator is used as the changes in the offset reference signal need to be smooth. The rate or change is reduced by a low gain. The inner (red) loop is used to increase the regulator dynamic response after the maximum allowed regulation ranges are exceeded. The rated electrolyser power P_{ely} is added to P_{gen} to ensure to initialize the control from the maximum hydrogen production. The input parameters P_{min} and P_{set} define the minimum allowed absorbed active power and the desired average power, respectively.

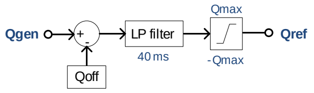

Fig. 6. Block diagram for the generation of the dynamic reactive power reference signal.

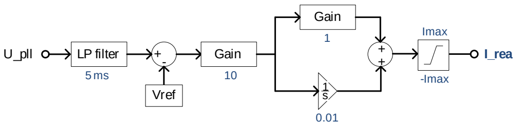

Fig. 7. Block diagram for the generation of the dynamic reactive current reference signal. Control of ac voltage by reactive current.

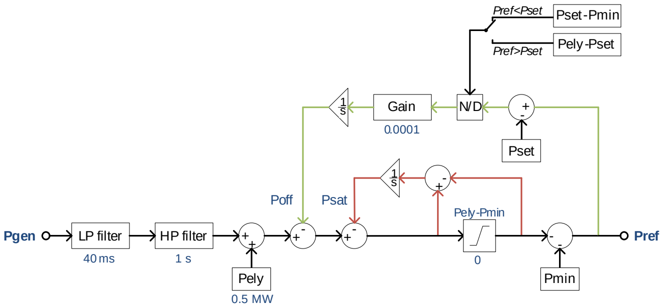

Fig. 8. Block diagram for the generation of the dynamic active power reference signal.

V. CASE STUDIES

Nine different case studies are analyzed and compared. The simulation time is 65 s where the first 5 s are used for the initialization of the generator. The data collected between 5 s and 65 s are used for the analysis. The control strategy for the production of hydrogen is modified in every case. Tab. I summarizes the simulation results obtained from PSCAD simulations. Each case is further described below.

TABLE I
RESULTS FROM PSCAD SIMULATIONS, 60 SECOND WINDOW

Case	E wind [kWh]	E grid [kWh]	E ely [kWh]	E loss line [kWh]	E loss Ely [kWh]	Kg H2 [kg]	Nm3 H2 [Nm3]	E H2 [kWh]
1: No Ely	12.3	10.5	0.00	1.78	0.00	0.00	0.00	0.00
2: Ely Max	12.3	3.08	8.23	0.998	3.04	0.16	1.74	5.2
3: Ely Max, Q comp	12.3	3.17	8.15	0.997	3.00	0.16	1.72	5.15
4.1: 100% reserve	12.3	6.33	4.82	1.16	1.58	0.1	1.08	3.24
4.2: 50% reserve	12.3	5.01	6.22	1.08	2.13	0.12	1.37	4.09
4.3: 20% reserve	12.3	3.78	7.53	1.01	2.71	0.14	1.61	4.82
5.1: Const Ely at E_H2 of 4.1	12.3	6.28	4.82	1.21	1.53	0.1	1.10	3.29
5.2: Const Ely at E_H2 of 4.2	12.3	5.02	6.22	1.08	2.12	0.12	1.37	4.09
6: 50% reserve, V control	12.3	4.98	6.2	1.14	2.13	0.12	1.36	4.07

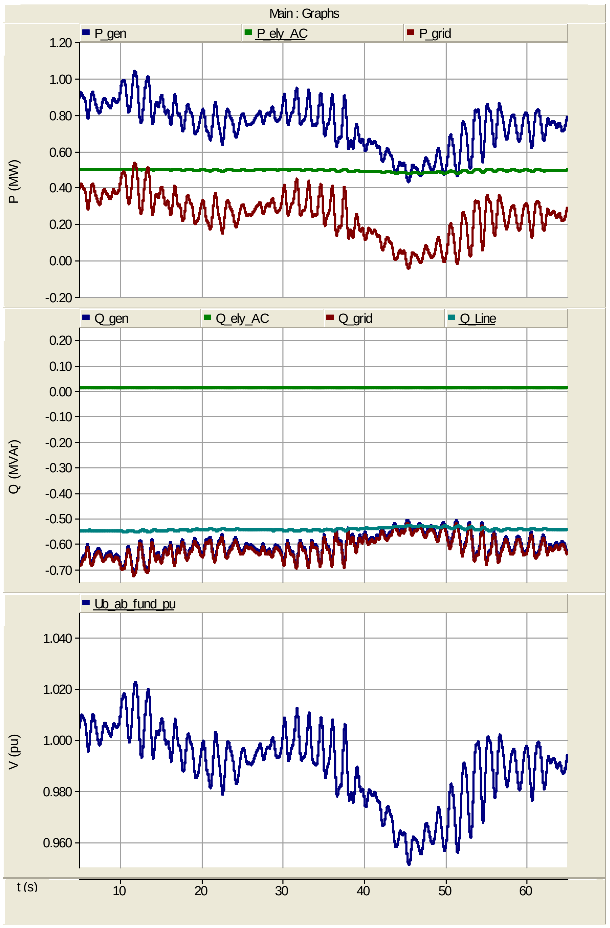

Fig. 9. Case 2: Constant electrolyser at max H2 production.

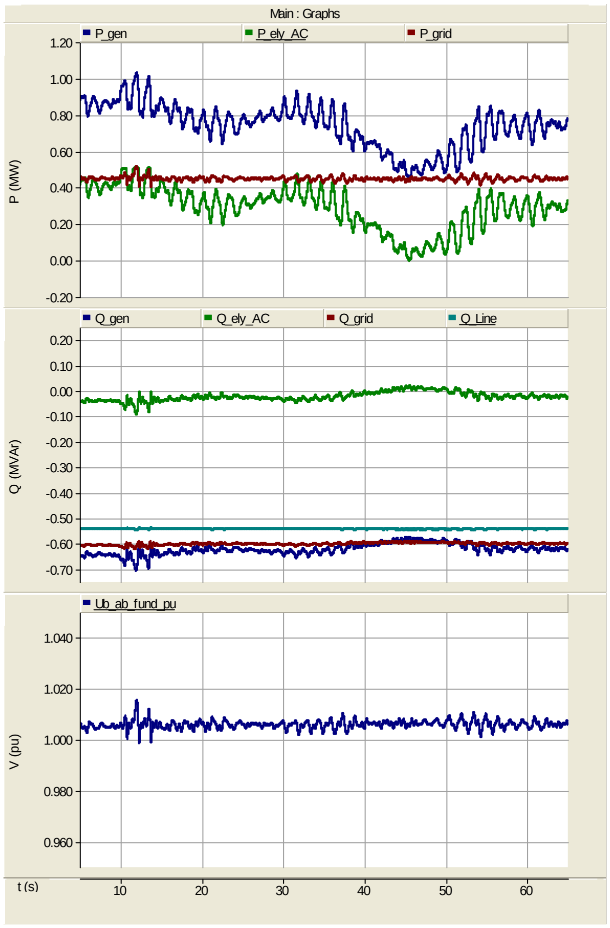

Fig. 10. Case 4.1: Reserve electrolyser and converter capacity for PQ control. 100% as reserve, fix offset.

A. Case 1

The system functions with no electrolyser connected. All the active and reactive energy produced by the wind generator is transferred directly to the network. There is no production of hydrogen. This results in voltage oscillations of approximately ±3% with a frequency slightly below 1 Hz. The fluctuations are well inside acceptable steady state values, however they may cause light flicker problems. It is not straight-forward to assess if these fluctuations are in conflict with the requirements of [18]. It is, however, clear that fluctuation with amplitudes up to ±3% with 1 Hz frequency might be large enough to cause flicker problems.

B. Case 2

The electrolyser is used in a “classical” way: it constantly works at its rated power, therefore the production of hydrogen is maximized. The main difference from case 1 is that lower energy is transferred to the grid. However, this does not have any mitigation effect on the voltage oscillations that result similar to those of case 1. The simulation results are shown in Fig. 9.

C. Case 3

This case is similar to case 2, in addition the surplus converter capacity is used for reactive power compensation. The converter can contribute with ±375 kVAr. This is enough to compensate for the fast reactive power variation, while the average reactive power of the generator is compensated by part of the cable capacitance (≈550 kVAr). The fast reactive power compensation does not contribute to an improvement of the power quality, quite on the contrary the voltage oscillation are slightly increased.

D. Case 4.1

In this case the full electrolyser capacity is used to absorb active power variations. The additional converter capacity is also used for reactive power compensation as in case 3. The simulation results are shown in Fig. 10. The voltage fluctuations are clearly attenuated here, with variation below ±1%. The electrolyser can clearly absorb all the active power variation and the energy transferred to the grid is constant at 0.5 MW. A constant active power transfer has also a positive effect in further damping the reactive power oscillations. The drawback of this control strategy is the low load of the electrolyser. Being an expensive system, it is desired to employ the electrolyser nearly at full capacity to maximize the hydrogen production. In this case, the average load of the electrolyser is 289 kW, only 58% of its capacity.

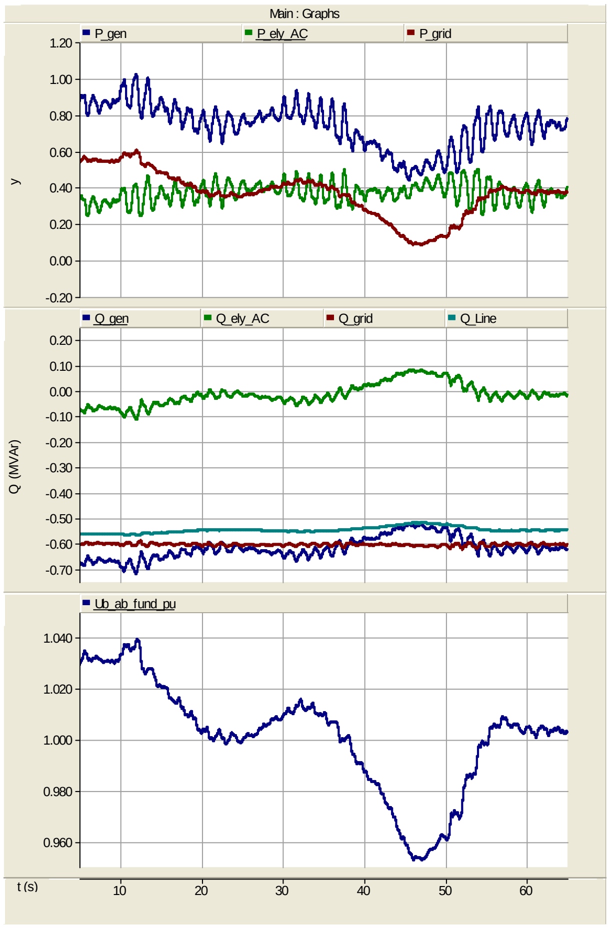

Fig. 11. Case 4.2: Reserve electrolyser and converter capacity for PQ control. 50% as reserve, dynamic offset.

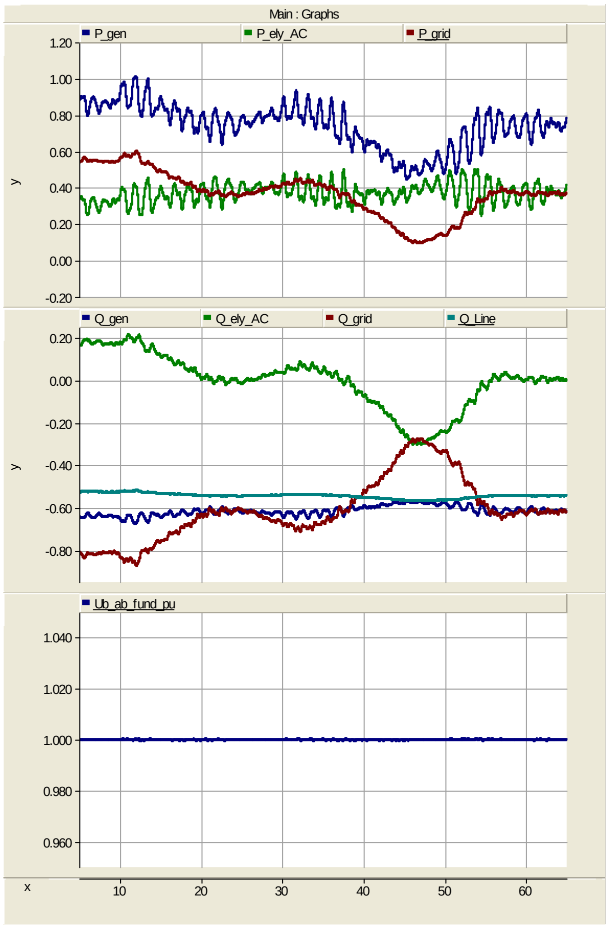

Fig. 12. Case 6: Reserve electrolyser and converter capacity for voltage control. 50% as reserve, dynamic offset.

E. *Case 4.2*

It is clear from the result of case 4.1 that in order to smooth the active power transferred to the grid only the fast oscillations need to be absorbed by the electrolyser. In addition, a completely flat voltage profile is not required. Slow active power and voltage variation can be allowed. This enables the use of a dynamic offset to maximize the hydrogen production. In this case, the minimum load of the electrolyser is set to 250 kW (50%) and the target average set point to 400 kW (80%). This gives a regulation range between +20% and -30% of the electrolyser capacity.

The simulation results are shown in Fig. 11. It is possible to note how the active power transferred to the grid is slowly varying, while remaining smooth, due to the effect of the dynamic offset. The voltage now varies within acceptable steady state values ($< \pm 5\%$) but in comparison to the case 1 and 2 there are no more fast voltage oscillations. The average load of the electrolyser is also much increased compared to case 4.1. It is now 373 kW, or 75% of the electrolyser capacity.

F. *Case 4.3*

This case is similar to the case 4.2, however the regulation margins are reduced in order to further increase the hydrogen production. In this case the minimum load is set to 80% with ±10% regulation range. It is observed that the electrolyser can efficiently smooth the active power fluctuation only in certain instants but fails when the magnitude of the oscillations exceeds the reserved regulation capacity. This is an example of poorly tuned parameters.

G. *Case 5.1 and 5.2*

These two cases are used for comparison with case 4.1 and 4.2 as they have the same electrolyser average load. Here the electrolyser is set to a constant power. The total hydrogen production is equal for case 4.1 and 5.1 (P_{mean} = 289 kW), and for 4.2 and 5.2 (P_{mean} = 373 kW). Thus, it is easier to evaluate the effect of variable versus constant hydrogen production on the losses and the system efficiency. The results reported in Tab. I clearly show that a dynamic control of the electrolyser does not reduce the electrolyser efficiency (seen as the total amount of hydrogen produced vs. total consumed power).

H. *Case 6*

This case is based on case 4.2, however the voltage profile is further improved using the direct voltage control of Fig. 7. The simulation results are shown in Fig. 12. The voltage profile is completely flat with no observable oscillation. On the other side, the reactive power absorbed by the grid is not constant as in case 4.2, but varies to compensate for the voltage oscillations. This does not affect the hydrogen production, however it results in a 5% increase of the line losses.

VI. CONCLUSION

The study performed in this paper demonstrates the possible use of an electrolyser for power quality improvement. The system chosen for the demonstration is an electrolyser for hydrogen production installed in a relatively weak system with wind energy production. The voltage quality at the point of common coupling is improved by introducing an electrolyser with flexible operating capabilities. The principle of the operating strategy is to control dynamically the electrolyser power consumption in such a way that fluctuations in power flow between the central grid and the remote PCC is minimized. The power absorbed by the electrolyser is increased when wind power increases and vice versa. The electrolyser converter used in this study is also able to level out reactive power fluctuations.

The modeling approach and analysis tools demonstrated in this paper are valuable instruments for the investigation, planning and evaluation of future possibilities for the integration of hydrogen and wind energy technologies. The conclusions for the specific case-study analyzed in this work should however not be generalized. Parameters such as wind speed and network capacity may greatly influence the final result regarding power quality improvements.

In future work, it is desired to replace the alkaline electrolyser model with a PEM one in order to evaluate the impact of the higher PEM electrolyser efficiency. It is also encouraged to verify the simulation models with real measurements on an integrated hydrogen-wind system. In addition, the effect of dynamic vs. constant load of the electrolyser on the aging rate of the stack should be investigated as well.

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