Energy Conversion and Management 166 (2018) 402–408

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Optimal sizing of a grid-assisted wind-hydrogen system

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ARTICLE INFO

Keywords:
Hydrogen production
Wind energy
Grid assistance
Electrolyzer sizing

ABSTRACT

Hydrogen obtained from water electrolysis in addition to being sustainable becomes commercially competitive when a high degree of purity is sought. Ideally such purity is achieved by keeping the electrolyzer on a constant and rated power. To satisfy this objective the assistance of the electric grid to deal with the variability of the wind resource was proposed. The disadvantage of this alternative is the failure to ensure a 100% carbon-emission-free hydrogen. The surplus wind energy can be delivered to the grid to optimize the trade-off between purity and cleaning degree. This paper presents a study on how the electrolyzer should be sized – according to the turbine and wind resource – to fully compensate these emissions along the year, that is, to cancel the annual power supplied by the grid.

1. Introduction

When renewable energies are used, the hydrogen obtained from water electrolysis is far more sustainable than the hydrogen obtained from steam methane reforming (SMR) [1]. But that is not better regarding the economic viability, even when energy is extracted from wind – one of the most attractive options [2,3]. However, it does become commercially competitive when a high degree of purity is sought. High-pressure and temperature alkaline electrolyzers generate H_2 with a purity better than 99.97%, which is the quality used in the automotive industry [4]. But this purity is achieved for very strict conditions on the electrolyzer operation; and due to the variability of the wind resource such conditions cannot be guaranteed [5]. Ideally such purity could be achieved by keeping the electrolyzer on a constant and rated power.

The electric grid, if available, can be used to assist the system to satisfy the purity objective. That is, the grid connection will provide electricity in the periods of wind resource shortage. In [6] it is remarked that without extra power from grid the intermittently work of the electrolyzer exerts negative influence on its efficiency, lifetime and hydrogen purity. Even with part time electrolyzer operation to avoid intermittency only limited reductions of the average hydrogen production cost are achieve. Additional advantages of grid assistance were pointed out in previous works. In [7] it is presented as the way the electrolyzer may operate all the time at its design point. As the only down-time would be for maintenance, the system may reach capacity factors of 90%. This would improve the economics by significantly reducing hydrogen cost. In [8] is shown that a combined wind and grid connected hydrogen refuel station can served a higher number of customers. In [9] is ensured that electrolyzer efficiency and hydrogen production is maximized as a consequence of keeping constant the electrolyzer power at its rated value. Another benefit of this operation mode is that the electrolyzer is subjected to less stress [10].

The disadvantage of this alternative is the failure to ensure a 100% carbon-emission-free hydrogen. That is, there is a trade-off between purity degree and cleaning degree. One way to compensate CO_2 emissions is to deliver – if possible – the surplus wind energy to the grid. For this aim, the wind turbine should be oversized as suggested in [11]. The difference is that the wind power excess is not sent to the grid but it is stored in batteries in that work. This have the disadvantage that the greater the power excess, the greater the storage system cost. In [12] is reported the inverse case, where the power delivered to the grid is fixed by the demand and the power excess is sent to the electrolyzer. The absorbed energy determined there, which is a function of the oversize or rather the ratio of the turbine and electrolyzer power, is of particular interest here. In that reference the sizing that optimizes the power excess absorbtion is determined through numerical simulations of the system based on large real wind and demand time series considering different electrolyzer sizes.

There exist other more complex methods of optimum sizing which take into account the stochastic nature of multiple renewable energy sources, electric loads profiles, as well as non-linear responses of the system components, costs and life cycles associated. These can be classified as probabilistic, analytical and iterative methods or a combination of all of them [13–17]. As an example of iterative method it

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https://doi.org/10.1016/j.enconman.2018.04.047
Received 12 January 2018; Received in revised form 11 April 2018; Accepted 12 April 2018
Available online 03 May 2018

can be cited the population-based optimization algorithm proposed in [18] to minimize the energy transfer loss and the levelized cost of hydrogen production.

In the present work, a sizing methodology oriented to a grid assisted wind-hydrogen system is provided to the scientific community. The assistance of the grid is controlled to guarantee the rated operation of the electrolyzer independently of the variations of the wind resource. As a consequence the purity and production rate of the hydrogen is maximized. The grid, in turn, can receive excess power from the wind-hydrogen system. The purpose of the sizing procedure is therefore to find an optimum ratio between wind turbine and electrolyzer rated powers, such that the power supplied by the electric grid is balanced with that received from the surplus of the renewable resource along the year. In this way, the carbon emissions associated with the grid would be compensated and then a more sustainable hydrogen could be produced. A simple probabilistic method based on stochastic parameters of the resource at the turbine location is proposed. The results will be compared with that obtained from a proposed iterative method. The disadvantage of this one is the higher degree of difficulty for implementation.

The paper is structured as follows: Section 2 provides a model description of components of the wind-hydrogen system to be sized; Section 3 presents a sizing methodology based on specifications of the wind turbine and stochastic characteristics of the installation site; Section 4 shows numerical results of the sizing methodology based on simulations in order to verify the theoretical results. Finally, Section 5 summarizes the conclusions.

2. System description

The autonomous system under study consists of a three-bladed horizontal axis turbine directly coupled to a permanent magnet synchronous generator which feeds an alkaline electrolyzer for the hydrogen production. Such devices are coupled to a common DC-bus using suitable power converters. Grid assistance can be incorporated into the same bus as shown in the block diagram of Fig. 1.

2.1. Turbine power converter

The mechanical power captured by the wind turbine for a given wind speed v is [19]:

$$P_T = \frac{1}{2}\rho A_T C_P v^3, \tag{1}$$

where ρ is the air density, A_T is the area swept by the blades and C_P is the power coefficient, which can be modeled by the following empiric formula [20]:

$$C_P = c_1\left(\frac{c_2}{\lambda_i} - c_3\beta - c_4\right)\exp\left(-\frac{c_5}{\lambda_i}\right) + c_6\lambda, \tag{2}$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{3}$$

The tip-speed-ratio λ is defined as the ratio between de linear speed

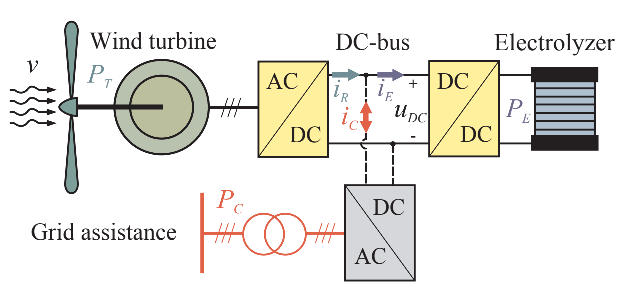

Fig. 1. Scheme of the wind-hydrogen system with assistance of the electric grid.

of the blade tip with respect to the wind speed v,β is the blade pitch angle and the coefficients c_i are $c_1 = 0.5176$, $c_2 = 116$, $c_3 = 0.4$, $c_4 = 5$, $c_5 = 21$, $c_6 = 0.0068$. The dependence of C_P on λ and β is shown in Fig. 2. Note the maximum of the surface at $\lambda = 8.1$ and $\beta = 0$, corresponding to the maximum power coefficient $C_{P,max} = 0.48$. As it was expected, it is less than established by Betz [21]. By substituting $C_{P,max}$ in Eq. (1), the maximum wind power specified by the manufacturer is obtained. The AC-DC converter depicted in Fig. 1 – which couples the wind turbine synchronous generator to the DC-bus – can be used to keep the tip-speed-ratio fixed at λ_0 and ensure the maximum power point. Then the dependence of P_T with v follows a cubic law as it is shown in Fig. 3. The cubic function is valid between the cut-in (v_{min}) and rated wind speed (v_N). From v_N to the cut-out wind speed $v_{\max}$ the power must be kept constant at the rated value P_T^N of design. This can be ensure by rotating the blades to increase the pitch angle β [19].

In this work control strategies applied to the power converter and the pitch actuator are assumed to follow exactly the power curve depicted in Fig. 3. For instance, the minimum projection algorithm proposed for the converter switching in [22] and the proportional controller designed for the pitch servo in [23] can be implemented in order to guarantee the tracking of such reference. For the purpose of the analysis, the electrical, magnetic and mechanical losses of the turbine-generator-converter assembly are neglected and P_T is considered the power delivered to the bus.

2.2. Electrolyzer power converter

The hydrogen production can be characterized by the electrical behavior of the alkaline electrolyzer generating it. The voltage u_E in terminals and the current i_E supplied to such device can be linked by the following empirically expression:

$$u_E(i_E, T_E) = N_S\left[U_{rev} + s\ln\left(\frac{1}{t}i_E + 1\right) + v\ln\left(\frac{1}{w}i_E + 1\right) + \frac{r}{A_E}i_E\right], \tag{4}$$

where N_S is the number of series-connected cells of the electrolyzer stack, A_E is the cell surfacer, U_{rev} is the cell reversible potential and $\{s,t,v,w\}$ models the dependency on the electrolyte temperature T_E of the activation and ohmic irreversibilities or overvoltages as shown in [24].

Since each molecule of hydrogen generated needs two-electron transfer, the hydrogen production rate $\dot{n}_{H_2}$ is proportional to the supplied current i_E, as can be seen in the following expression:

$$\dot{n}_{H_2} = N_S\eta_F 2Fi_E, \tag{5}$$

where F is the Faraday constant and η_F is the Faraday efficiency which increases with i_E according to the formula given in [25]. Furthermore, the electrolyzer current directly affects the quality or purity level Q_{H_2} of the produced hydrogen. This is defined as the ratio between the product gas H_2 and the total volume of the mixture of gases H_2 and O_2. The expression (6) reveals the increase of Q_{H_2} with i_E:

$$Q_{H_2} = 1 - \frac{\dot{n}_{O_2/H_2}}{\dot{n}_{H_2} + \dot{n}_{O_2/H_2}} = 1 - \frac{a_T a_P}{i_E}, \tag{6}$$

where a_T and a_P models the dependency on temperature T_E and pressure P_E respectively as shown in [26].

From the Eqs. (5) and (6) it is inferred that the optimum quantity and quality of the produced H_2 is obtained with the maximum current I_E^N admissible by the electrolyzer. Such rated current can be an assumption or a result of a technical-economic optimization. For instance, high cell areas of the electrolyzer give lower values of I_E^N for the same water utilization factor but with higher investment costs. Here I_E^N is assumed as the maximum current that should be consumed by the electrolyzer to convert all make-up water into hydrogen and oxygen [27].

Consequently, the control objective of the DC-DC converter coupling the electrolyzer to the DC-bus in Fig. 1 is to maintain the current i_E