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Hydrogen generator characteristics for storage of renewably-generated energy

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ABSTRACT

The paper presents a methodology for determining the efficiency of a hydrogen generator taking the power requirements of its auxiliary systems into account. Authors present results of laboratory experiments conducted on a hydrogen generator containing a PEM water electrolyzer for a wide range of device loads. On the basis of measurements, the efficiency characteristics of electrolyzers were determined, including that of an entire hydrogen generator using a monitored power supply for its auxiliary devices. Based on the results of the experimental tests, the authors have proposed generalized characteristics of hydrogen generator efficiency. These characteristics were used for analyses of a Power-to-Gas system cooperating with a 40 MW wind farm with a known yearly power distribution. It was assumed that nightly-produced hydrogen is injected into the natural gas transmission system. An algorithm for determining the thermodynamic and economic characteristics of a Power-to-Gas installation is proposed. These characteristics were determined as a function of the degree of storage of the energy produced in a Renewable Energy Sources (RES) installation, defined as the ratio of the amount of electricity directed to storage to the annual amount of electricity generated in the RES installation. Depending on the degree of storage, several quantities were determined.

1. Introduction

It is forecast that the share of renewable energy sources in the world's electricity production structure will increase [1,2]. In Poland, wind turbines and photovoltaic cells are among the most dynamically developing RES technologies [3,4]. The most important advantage of use these sources is lack of emission of harmful substances. In contrast to use of carbon sources the use of renewable energy does not contribute to the emission of dust, sulfur compounds, nitrogen oxides, mercury and carbon dioxide. Commonness of occurrence and renewability of energy potential make that these energy sources are safe and most commonly cheap in exploitation. The popularity of RES is stimulated by support mechanisms regulated by national laws [5,6]. The environmentally-friendly nature of these technologies is a feature that deserves rational support. The basic mechanism of this support, in addition to a system of tradable certificates, is guaranteed priority access to the electricity grid. This mechanism creates a situation in which the large, un-adapted coal-fired units working in the largest centrally organized systems take on a role of regulation system. The Polish energy system has a relatively low level of elasticity. In addition, various renewable energy sources are characterized by considerably differing potentials for electricity generation, which rarely correlate with end-user electricity demand, particularly in the case of wind energy [7–12]. Mentioned features and the necessity to ensure energy security causes that the development of renewable energy sources is limited by the operator of the electricity system.

A further increase in installed wind farm capacity can lead to a situation in which coal-fired units will reach the limits of their regulatory capabilities, and the power system will become unstable [13,14]. Therefore further increase in installed capacity of wind farms will be possible by improving operational features of coal-fired power plants [15–17]. This will be the result of the startup of new units with supercritical parameters [18,19]. It is also important that the increase of installed capacity in power plants will be based on gas turbines [20–22]. However, experts from the Polskie Sieci Elektroenergetyczne S.A. predict that the dynamic of startups of new wind farms will contribute to insecurity of the system by 2025. In addition to the investment in modern power plant units, it is also very important to implement energy storage

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systems to avoid this scenario [23–27]. Energy storage systems would draw power during off-peak demand periods and produce during peak periods [28,29].

Energy storage is important for a wide range of potential beneficiaries of technology - from individual users of electric equipment, automotive users, and industry to network operators. Depending on the scale, energy storage can be classified into five groups by storage method: mechanical, electrical, chemical, electrochemical and thermal. In the case of cooperation with the large power system, the most favorable characteristics have chemical and mechanical solutions, including pumped storage and compressed air energy storage (CAES) [30,31]. A significant development potential have also electrochemical systems. Wide discussion on the potential of the various solutions were carried out in Refs. [32,33]. This article presents the results of analyses for Power-to-Gas technology, which is classified in the chemical group. According to authors' assumptions, the analyzed system is used in a daily cycle and enables the production of hydrogen during the so-called night valleys, i.e., at night. The hydrogen produced is accumulated in buffer tanks and directed to the gas transmission grid.

2. Power-to-Gas technology

The Power-to-Gas technology allows to produce the gas of high potential energy using electricity taken directly from a generation system or the network. The transformation process within a Power-to-Gas installation of electricity to the chemical energy of gas fuel can be justified during periods of higher electricity production and lower electricity demand. This overproduction occurs mainly in systems based on renewable sources (mainly solar and wind sources). A positive economic effect for investments in energy storage systems may occur in a situation in which the price of energy in a period of overproduction is very low [34,35]. The overproduction usually occurs during low demand periods (the night valley, the weekend valley). Such scenarios commonly occur in countries where the share of renewable energy is significant (e.g., Denmark, Spain, and Germany). This is also a justified investment from the point of view of the power system operator. In this case, the Power-to-Gas installation can adopt a function of regulator and adapt the available capacity of the system to the demand [36–38]. The strong interest in energy storage systems, due to their ability to regulate supply to accommodate demand, is observed particularly in countries where a growing share of RES is accompanied by a significant share of coal-fired power plants [12,39–42]. In Poland for example, increasing installed wind farm capacity with priority access to the grid is in force, resulting in an increase in forced shutdowns of power units. Shutdowns of power units are required by the system operator's instructions; they may result from high outputs from wind-power sources and low electricity demand [43,44]. Increased coal-fired power in off-peak periods could be directed to storage; this could contribute to a decrease of the number of the forced shutdowns of units, and thus reduce the related cost [45–47].

The criterion for classifying Power-to-Gas technology can be based on the type of gas produced. The basic element of the system, irrespective of the type of gas, is the electrolyzer, whose function is to produce hydrogen. If the installation contains no additional gas conversion equipment, hydrogen is the final product of the process. In this case, the hydrogen can be injected into the natural gas grid, forming part of the gas transportation infrastructure. Additionally, the product of the electrolysis process can be delivered by tank trucks to industry (e.g., chemical, metallurgical, electronic, refining and fats industries). It can also be used for energy purposes at the place of production (Power-to-Gas-to-Power). It should be remembered, however, that hydrogen is difficult to transport or use for energy generation [48,49]. The literature often emphasizes the problems connected with the use of hydrogen-rich fuels in gas turbines and piston engines [50,51]. Synthetic Natural Gas (SNG) can be a more convenient fuel for these purposes. Synthetic Natural Gas can be produced from carbon dioxide and hydrogen and can be the end-product of a Power-to-Gas installation; however, it requires installing a methanation reactor. A Power-to-Gas installation can be of interest in power plants whose emission of carbon dioxide generates higher operations cost. Carbon dioxide can be a product of gasification of biomass [52,53]. The advantage of these systems is the possibility of efficient use of oxygen, which is the by-product of the electrolysis process. Optional ways of the use of oxygen, and their potential has been described in Ref. [54]. Worldwide, pilot installations currently use methanation reactors based both on biological and chemical processes. The Power-to-Gas technology can be also implemented successfully in other sectors of the industry e.g. in pulp mill, which is a large producer of wood-based CO_2, so the hydrogen can be used for the methanation process and the oxygen in the pulp and paper mill, replacing the existing O_2 production facility [55]. Fig. 1 shows possible connections in a Power-to-Gas system.

3. Production of hydrogen

Hydrogen is a product of an electrolysis installation, constituting of battery of currently available compact electrolyzers. The most popular types of electrolyzers for pilot installations worldwide are electrolyzers with a polymer electrolyte membrane (PEM) [45,56,57] and alkaline electrolyzers (AEL) with aqueous alkaline solutions as electrolytes (KOH or NaOH) [58–60]. Other types of electrolyzers include devices with a ceramic membrane (SOECs) [61–66]. PEM and alkaline electrolyzers operate at a process temperature between 70 and 100 °C. SOEC electrolyzers operate between 700 and 1000 °C. These types of electrolyzers require a supply of heat in the form of steam generated in an external process [67]. This limits the potential points of use. Because of the high process temperature, the efficiency of SOEC electrolyzers (defined as the ratio of the chemical energy of fuel obtained to input electric energy) may exceed 100%. SOEC electrolyzers are rarely considered in installation planning; this may serve to regulate power systems because of the long heating and cooling periods of system elements. In this respect, the PEM and alkaline electrolyzers are more favorable. In addition, the times required to change their loads are from 10% to 100% of the nominal power per second and from 10% to 25% of the nominal power per second, respectively. The PEM electrolyzers, despite lower technological maturity, are a perfect alternative to alkaline electrolyzers because of their wide load range (5%–100% of nominal power), very high purity of produced hydrogen (>99.999%) and lower operating cost. Unfortunately, the lower technological maturity of PEM electrolyzers is reflected in lower membrane lifetime and higher restoration costs [68,69]. An important aspect of the installation, irrespective of the type of electrolyzer, is that the water used for electrolysis must comply with the strictest standards; therefore, it is necessary to install water treatment in Power-to-Gas systems. Especially, the removal of minerals and ions is required before begin electrolysis process [70,71].

The efficiency of the hydrogen generators used is important for the efficiency of the entire Power-to-Gas storage system. There are highly diverse methods to determine this quantity. Knowledge of the efficiency characteristics as a function of electrolyzer load is the basis for a correct analysis of an energy storage system cooperating with a generation system.