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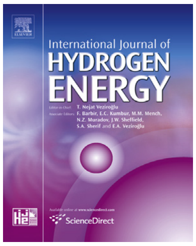

Multi-level optimization approach for directly coupled photovoltaic-electrolyser system

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ABSTRACT

In this study, directly coupled photovoltaic-electrolyser system is designed and optimized and a new method for optimization is given. The accurate electrical models of advanced alkaline electrolyser, photovoltaic system, and hydrogen storage tank are simulated using Matlab. The system is investigated for a day using actual meteorological data of Miami, FL. The purpose of the optimization, which has been performed using genetic algorithm, is to produce maximum hydrogen, minimum excess power, and minimum energy transfer loss. In each iteration of the optimization, due to crucial role of temperature in overall performance of the system, the average operating temperature is optimized using genetic algorithm. The system is optimized in a way that the operating condition is as close as possible to the maximum power point of the photovoltaic array. The operation of the system is discussed in 24 h period and working hours to make the system comparable to other studies with different power sources. The result of the analysis shows that optimal system for a 10 kW electrolyser can produce the average hydrogen of 0.0151 mol/s when the system is operating with 2.2% power loss and 4.7% power transfer loss.

Introduction

The rising demand for new procedures of energy production and storage has been the focus of study in recent years. Among them, due to the environmentally friendly features, abundancy, and reduced costs photovoltaic (PV) systems are one of the most popular power production methods [1,2]. However, due to limited availability of solar irradiation during day and unreliable power production, it can be converted to a reliable fuel. Hydrogen can be a good choice due to high energy density, low energy loss, mature technology, on-site provision capability, and compactness [3–5]. One of the most promising ways of producing hydrogen from the electricity produced by PV systems is water electrolyser because their electrical characteristics match in a way that the overall system is efficient.

For the combined PV electrolyser system, several studies have been done [6–9]. In a study in 2008, the operation of coupled photovoltaic-electrolyser system with controlled DC–DC converter is investigated [10]. The maximum power point of the PV system is chosen by safe optimum searching algorithm and the buck-boost converter, which connects the PV array to electrolyser, is controlled. In some other studies, the power electronic devices are used to ensure optimal power transfer between the systems [11,12]. The advantage of

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using directly coupled system is that the cost and complexity of the overall system is reduced and because in case the system is optimally designed, the electrical characteristics of electrolyser can follow the maximum power point of the PV with appropriate accuracy, the overall economics of renewable-hydrogen systems compared to conventional fuels is improved. In a study in 2009, the direct-coupled PV system with proton exchange membrane (PEM) electrolyser is investigated. The fail-safe operation of electrolyser with multiple levels of safety and operational redundancy is designed [13]. In 2010, the operation of directly coupled PV power regulator for stand-alone power systems with hydrogen generation is evaluated [14]. Few studies have tried to find the optimal operational set points and size of directly coupled PV-electrolyser. In order to obtain optimal performance, several optimization algorithms have been investigated [15–20]. In 2011, optimized method for direct-coupled PV-PEM electrolyser was proposed for relative sizing between components based on simple modelling of both polarization curves [21]. The optimization was based on minimization of energy transfer loss. In 2014, a novel integrated system was proposed that by using energy and exergy methodology, combined photocatalysis, photovoltaics, thermal engine and chemical energy storage for better solar energy harvesting [22]. In 2014, multi-objective optimization of direct coupling of PV-electrolyser systems using imperialistic optimization algorithm is performed [23]. The optimization was based on minimum energy transfer loss, which is equal to the difference of power of maximum power point to the power of system. In another study, hydrogen generation is maximized by optimizing the size and the operating conditions of an electrolyser directly connected to a photovoltaic module at different irradiances using particle swarm optimization (PSO) [24]. In mentioned studies, the objective is to minimize the gap between actual operational points and maximum power points. In another study, Optimization and sensitivity analysis of directly coupled photovoltaic-electrolyser system in Beijing is performed. Parameter of V/V_m as the ratio of actual voltage to voltage of maximum power point was introduced to analyze the efficiency changing point (ECP) which is the working point that distinguishes the variation trends of the system efficiency [25]. In 2015, the optimum analysis of photovoltaic-driven electrolyser system for hydrogen production was studied. The optimization was based on efficiency of hydrogen production with numerical calculation method with considering parameters including solar irradiance, the operating temperature of the electrolyser, and band-gap energy of the electrolyser [26].

In this study, the electrical performance of combined PV-Electrolyser system is evaluated and the electrical production of the PV system is optimized in a way that the output be as much as possible near to maximum power point of the system with maximum hydrogen production and minimized excess power. Beside optimization of the dimensions of the system, the optimal working temperature of the electrolyser is also evaluated. Therefore, a two combined level GA is designed for the optimization process. Also, for optimization of the system, a new index has been proposed. The comparison between the electrical performance of direct-coupled system and the system with DC/DC converter that follows the maximum power point of the PV is assessed. Then, a view of the operation of the system in operating time and in 24 h period is given. Finally, for validation of the results, a comparison with another study is given. The schematic of the proposed system is given in Fig. 1.

Electrolyser

Alkaline electrolysers are one of the most widely used instruments for hydrogen production through water electrolysis. For conduction of ions between the electrodes liquid electrolyte is used. Because of the optimal conductivity and corrosion resistance of the stainless steel, potassium hydroxide (KOH) is widely used as electrolyte. The reactions for the alkaline electrolyser anode and cathode is given by

$$\begin{aligned} &\mathit{Cathode}: 2H_2O_{(l)} + 2e^- \rightarrow H_{2(g)} + 2OH^-{}_{(aq)} \\ &\mathit{Anode}: 2OH^-{}_{(aq)} \rightarrow \frac{1}{2}O_{2(g)} + H_2O_{(l)} + 2e^- \end{aligned} \tag{1}$$

Electricity is needed for the process of hydrogen production. The electrical equivalent of electrolyser can be considered as a nonlinear load that as the input voltage rises, more hydrogen is produced, due to current increase. In addition, the power rises, which is restricted to the power characteristics of power delivery source. The U–I characteristics of an advanced alkaline electrolyser is defined as [27]

$$U_{electrolyser,Cell} = U_{reversible} + \frac{r_1 + r_2 T}{A} I + s \log\left(\frac{t_1 + t_2/T + t_3/T^2}{A} I + 1\right) \tag{2}$$

where $U_{electrolyser,cell}$ is the cell terminal voltage (V), $U_{reversible}$ is reversible cell voltage (V), r_1, r_2 are parameters for ohmic resistance ($\Omega.m^2$, $\Omega.m^2/°C$), as the coefficients for ohmic voltage, s, t_1, t_2, t_3 are parameters for overvoltage (V, m^2/A, $m^2.°C/A$,n $m^2.°C^2/A$), A is the area of cell electrode (m^2), I is electrolyser current (A), and T is cell temperature (°C). $U_{reversible}$ is given by the Gibbs free energy change of the electrical process as

$$U_{reversible} = -\frac{\Delta G}{zF} \tag{3}$$

where, z is the number of molecules transferred per hydrogen molecule which is 2, ΔG is Gibbs free energy, and F is Faraday constant. So, $U_{reversible}$ can be expressed as an empirical equation as

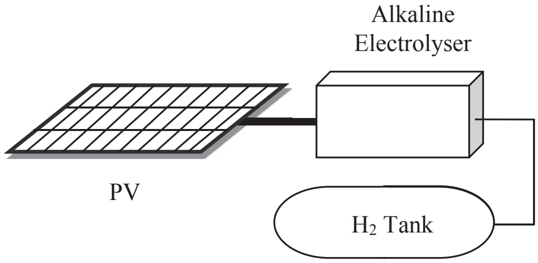

Fig. 1 – Simplified schematic of directly coupled PV-Electrolyser system with hydrogen storage.

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