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Operation analysis of a photovoltaic plant integrated with a compressed air energy storage system and a city gate station

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ABSTRACT

The use of compressed air energy storage (CAES) systems instead of conventional energy storage systems in large scale grid connected photovoltaic (PV) plants has already been proposed and investigated thermo-economically, resulting to very satisfactory outcomes. On the other hand, CGS (city gate stations), in which high pressure natural gas is expanded to much lower presser levels, has been proved to be a very suitable place for producing free electricity by employing turbo-expanders instead of conventional throttling valves. In this work, the feasibility of employing a CGS power output for improving the performance of a grid connected PV plant accompanied with a CAES system and enhancing its power output stability is studied. Comprehensive energy analysis and economic assessment on the proposed configuration is carried out and the results are discussed thoroughly. Finally, the performance of this hybrid configuration is compared with the PV plant and the CGS station while working individually. IRR (Internal rate of return) method as an authentic economic evaluation approach is used for comparing the considered systems economically.

1. Introduction

Among all renewable energy sources, the sun is the most plentiful and available. The radiated energy from the sun is 3.8×10^{23} kW out of which almost 1.8×10^{14} kW is received by the earth. This amount of energy is almost well over 7500 times the world's total energy demand [1]. PV panels can generate electricity employing the sun clean energy; therefore, they are environmentally friendly. Furthermore, low restriction in installation location and low maintenance costs are other advantages of such panels [2]. PV panels can be employed to generate power in either small or large scales. Extensive research has been carried out, during the last decades, on PV technology experimentally and theoretically. Mendez et al. [3] studied the use of standalone PV systems in places far from electricity distribution grids. Economic and environmental impact aspects of this work were later assessed by Wies et al. [4]. In another work, King et al. [5] developed an electrical simulation model for PV cell modules for analyzing the performance of PV cell arrays. Chenni et al. [6] also developed a computer simulation model that revealed the PV system features by changing solar irradiation intensity and ambient temperature. Rehman et al. [7] studied the potential of Saudi Arabia in terms of solar irradiation amount and the proposed constructing a grid connected PV farm with 5 MWp capacity. In a similar work, in order to improve the electricity demand strategy of Kuwait, constructing grid connected PV farms was studied [8]. Ito et al. [9] proposed installing a 100 MWp PV plant in the Gobi desert and evaluated the economic and environmental aspect of this proposal. Today, in addition to the huge capacity of power production by standalone PV systems, there are numerous grid connected PV farms with capacities from below 1 MWp up to hundreds of MWp all around the world.

The negative point of grid connected PV plants is that the source of energy is intermittent and as a result, instantaneous variations of electricity demand in the grid could not be accurately responded [10]. For overcoming this problem, employing energy storage systems seems to be the best measure by now. Among various energy storage systems, for large scale applications, the CAES has attracted more attention over the recent years due to its lower capital cost, flexibility in the required size and also being environmentally friendly [11]. After introducing the CAES technology for the first time in the 1970s, many studies have been carried out to improve its efficiency and configuration. In terms of novel applications of CAES technology, numerous works have been addressed in the

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literature focusing on renewable energy source power generation systems. For example, Denholm [12] proposed combining a wind farm with a CAES unit and biofuels. In another work, in order to compensate the power output fluctuations of a wind farm, Cavallo [13] suggested a hybrid wind-CAES configuration. Then, Greenblatt et al. [14] compared the cost of power produced by this configuration with other methods of electricity generation and found this system extremely economical. Also, Zafirakis et al. [15] presented an algorithm for sizing the CAES system of stand-alone PV systems. In one of the last works in this area, Arabkoohsar et al. [16] proposed a new configuration of a large scale grid connected PV plant accompanying with a CAES unit. In this work, which was the first study on dynamic modeling of a CAES system in a grid connected renewable energy source power plant, they indicated the size of all components in the CAES system and specified the best power sales strategy for the whole power plant. They found a time dependent pattern as the best mode of selling power to the grid and in order for maximizing the earnable revenue from the power plant; they had to reduce the direct vendible electricity much lower than the average producible power by the PV farm. Also, in another work, they analyzed their proposed configuration energetically and exergetically and indicated the sources of energy waste and exergy destruction in the system [17].

On the other hand, CGS is a place in natural gas transmission system in which the pressure of natural gas from a very high level is reduced to a much lower value [18]. In fact, considering the long distance that the natural gas stream must pass from the refinery to the consumption points like cities and factories, its pressure should be so high that can overcome the losses along the path. This is why, not only the natural gas pressure at the transmission pipeline inlet is at much higher levels than consumption values, but also there are numerous attenuator and booster pressure stations along this way [19]. Near the consumption points, CGSs are located to regulate the natural gas pressure to much lower levels. Therefore, before the expansion process at CGSs, there is considerable amount of exergy along the natural gas stream due to its high mass flow rate and high pressure. In the conventional configuration of CGS, a throttling value accomplished the pressure drop mission and as a result, all the exergy along with the natural gas flow was destructed [20]. However, replacing the throttling valve by a turbo-expander and an electricity generator, in order to hire the natural gas exergy and produce free power, has recently been proposed and studied [21,22].

In this work, the feasibility of employing the power output of a CGS equipped with a turbo-generator set for stabilizing the power output and enhancing the power generation efficiency of a grid connected PV plant accompanied with a CAES system is investigated. In this way, the power sales strategy of the PV plant can be optimized and consequently, the revenue of the power plant increases significantly. Also, the intermittent power produced by the PV farm can be stabilized considerably. In order to prove the effect of utilizing this power source as the stabilizer and auxiliary power production unit of the power plant, the performance of the hybrid configuration proposed in this work is compared with the performance of its two separate power generation units, i.e. a PV plant equipped with a CAES system and a power productive CGS, while working individually. Note that, in order to facilitate addressing the three considered systems in the text, the power plant equipped with a CAES system, the CGS station and the hybrid system proposed in this work are named as systems “A”, “B” and “C”, respectively. It is also noteworthy that the IRR approach is employed as an authentic method for economic evaluation purposes. Besides, in order to have a detailed performance database for the system, a CGS station in Natal city in Brazil, where the previous configuration (system “A”) had been proposed to be built, with 400,000 Sm^3/h (standard cubic meter per hour) maximum capacity has been selected as the case study of this work.

2. The proposed system

Fig. 1 illustrates the schematic diagram of the proposed system. According to the figure, the PV farm produces power employing solar irradiation. Based on the amount of power that is supposed to be sold to the grid, there may be either extra produced electricity or lack of electricity in the system. Note that the amount of power that is going to be sold to grid by the PV plant should be specified in advance. Therefore, one should find the best power sales strategy of the power plant based on energy-economic considerations. In case

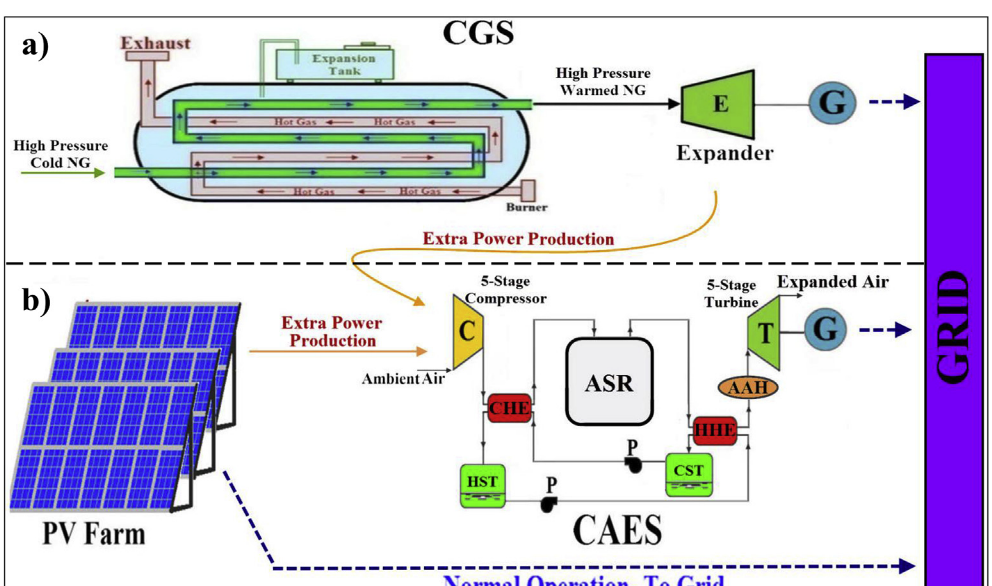

Fig. 1. The schematic of the proposed system; C: compressor set, CHE: cooling heat exchanger set, HST: hot storage tank, ASR: air storage reservoir, T: turbine set, HHE: cooling heat exchanger set, CST: cold storage tank, G: generator; E: expander.