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The first and second law analysis of a grid connected photovoltaic plant equipped with a compressed air energy storage unit

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ABSTRACT

PV (Photovoltaic) plants are widely used to produce power in either large or small scales all around the world. In addition, CAES (compressed air energy storage) system has attracted considerable attention as one of the most efficient candidates for large scales energy storage applications in the recent years. In this work, detailed energy and exergy analysis of a 100 MWp (megawatt peak) grid connected PV plant equipped with a CAES system is carried out. The PV plant is assumed to be located in Brazil. The formulations related to the first and the second laws of thermodynamic for all components as well as detailed solar engineering formulations for both the PV farm and the solar heating unit are presented. The performance of the power plant is comprehensively investigated for one entire year in real circumstances. The results revealed that the energy and exergy efficiencies of the CAES system are very close and vary from 35% up to 65% during the year. Also, the annual average exergy and energy efficiencies of the power plant are calculated to be 17.9% and 16.2%, respectively.

1. Introduction

PV (Photovoltaic) panels generate electric power directly employing only solar energy, thus, PV is an absolute environmentally friendly technology. Nowadays, PV panels are used in order to produce power in a wide range from only few kilowatts up to hundreds of megawatts. As the power producible by a single PV cell is extremely trifle, depending on the amount of power that is supposed to be produced, from a few to millions of PV cells are connected together to make solar panels-solar modules [1]. Small scale PV technologies are most suitable for the areas without access to the electrical energy distribution grids for which the PV system is installed on the houses roofs. Also, these systems are even, sometimes, used in grid connected areas for reducing electricity bills. In large scale, on the other hand, PV farms are built to provide the required power of cities or industrial parts [2]. The PV farms are also built in a wide range from 1 MWp up to hundreds of MWp. The largest PV plant in the world is located in Arizona and has a capacity of 290 MWp [3].

The main problem with PV farms is the sharp ramps in their power production which is clearly because of solar irradiation intensity fluctuations. As power distribution grids always need to make a balance between the power required and the power produced, the amount of power that the power plant sells to the grid should be defined in advance based on a mutual contract between the grid and the power plant. In case of any ramp in the power delivered to the grid relative to the value defined in the contract, the PV plant will be penalized financially. Therefore, the solar energy fluctuations must be predicted and offset to minimize these fines. As accurate long term forecast of solar energy fluctuations is not applicable yet, a second measure should be taken. In this regards, the only effective measure seems to be the use of energy storage systems [4]. Battery, flywheel, capacitor, PHES (pumped hydroelectric energy storage), SMES (super conducting magnetic energy storage), CES (cryogenic energy storage) and CAES (compressed air energy storage) are the most efficient energy storage systems proposed ever [5]. Among all these candidates, the CAES is the most promising technology for large scale applications due to being environmentally friendly and its lower capital cost [6].

The CAES technology was proposed and extensively investigated in the 1970s and it is still in development stage. The first CAES plant was built for a gas turbine plant in Germany in 1978. This CAES

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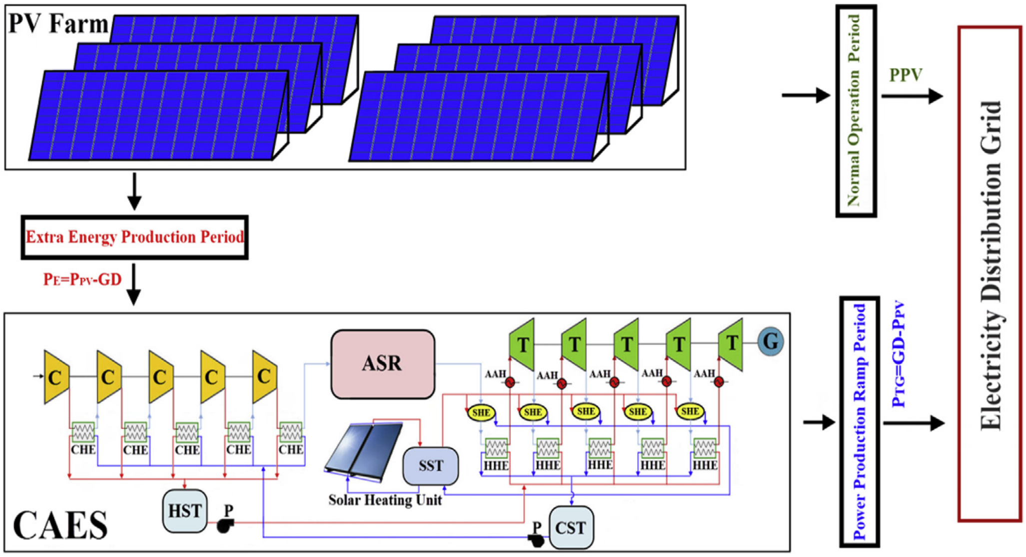

Fig. 1. The proposed system schematic; C: compressor, CHE: cooling heat exchanger, HHE: heating heat exchanger, HST: hot storage tank, CST: cold storage tank, ASR: air storage reservoir, T: turbine, SCS: solar collector series, SST: solar storage tank, AAA: auxiliary air heater, P: pump, G: generator.

system is able to store 310,000 m^3 compressed air with the pressure of 44–70 bar and produces up to 290 MW power [7]. The next CAES system was built in 1991 for McIntosh power plant with the power production capacity of 110 MW for 26 h by storing up to 540,000 m^3 compressed air at a pressure range of 45–74 bar [8]. Thereafter, although extensive studies were accomplished to develop the CAES system design and efficiency, no more CAES system came into operation practically.

Also, despite the extensive research carried out on the PV and CAES technologies individually, no detailed thermodynamic assessment on a PV farm accompanying with a CAES system in real conditions has been reported yet. In one of the most recent works in this area, the authors of this work presented a comprehensive thermo-economic study on a large scale grid connected PV plant equipped with a CAES system and an ancillary solar heating system in Brazil. In this work, first, the best location for building the power plant was selected based on the maximum receivable solar irradiation throughout the country. Then, selecting the most efficient tracking mode for the PV cells, sizing of all components in the CAES system and finding the best power sales strategy for the power plant were carried out by emphasizing on energy-economic considerations [9]. In the current work, a comprehensive thermodynamic analysis (both the first and the second laws of thermodynamic) on the PV plant is presented. For this objective, the performance of the power plant over an entire year (as a sample year of operation) is assessed and detailed energy-exergy performance is presented. In fact, the aim of the current study is to investigate the technical performance of the CAES system in a PV plant in real circumstances. This enables us to evaluate suitability of employing CAES energy storage system for such a power plant. Also, the energy and exergy audit on the understudy configuration could reveal the origins of losses and energy/exergy destructions and this would open new gates for further investigations and research in this area.

2. System configuration

Fig. 1 illustrates the understudy system configuration. According to the figure, the power plant comprises two main subsystems, i.e. the PV farm and the CAES system. The PV farm including thousands of connected PV cells is supposed to produce power. Depending on the amount of power that is to be sold to the grid in every moment, there may be extra produced power or electricity shortage in the system. In case of the existence of any PE (extra power) in the system, the CAES unit can hire it to produce compressed air. In this case, as it can be seen, the compression part of the CAES system, including a multiple-stage compressor (C) with CHE (inter-cooling heat exchangers) and the HST (hot storage tank), is in operation state. In this state, the multiple-stage compressor is used to produce compressed air employing the extra power produced by the power plant during off peak periods. This air is stored in the ASR (air storage reservoir). The cooling heat exchangers are also used as intercoolers between the compressor stages. In this way, not only the harvested heat from the hot air is stored and could be used when required, but also the compressor efficiencies can increase significantly. The compressed air remains in the cavern until producing extra electricity is required. This is mainly by the time that intensive solar ramps occur and as a result, the PV farm is not able to cover the GD (grid demand). At this time, the compressed air is reclaimed to be expanded through the multiple-stage turbine (T). Before each step of expansion, the air stream should be heated up to the required temperature. The heating process is done in three stages. The first stage is employing SHE (solar heat exchangers) supported by hot water provided by the flat plate collectors. The heat harvested from the compressed air during compression process is used in the next stage by employing the HHE (heating heat exchangers). Finally, the warmed high pressure air is heated up to the desired temperature by AAH (auxiliary air heaters). Note that the cooled working fluid outgoing from the heating heat exchangers is then kept in the CST (cold storage tank).

At the end of the day, if there is still extra compressed air in the air reservoir, specific amount of air remains in the reservoir to offset the possible PV farm power slumps during the early daily hours of the next day and the remaining portion is used to produce power at peak power consumption hours (from 8 pm to 12 pm).

It should be mentioned that, as it was explained, the configuration shown in Fig. 1 has been proposed and analyzed thermo-economically in our previous study [9]. In that work, the payback period of the system, with conservative economic consideration, was found to be less than 9 years that is a very satisfactory result, considering the normal efficient lifetime of PV systems which is