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Development of performance model and optimization strategy for standalone operation of CPV-hydrogen system utilizing multi-junction solar cell

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ABSTRACT

Despite highest energy potential, solar energy is only available during diurnal period with varying intensity. Therefore, owing to solar intermittency, solar energy systems need to operate in standalone configuration for steady power supply which requires reliable and sustainable energy storage. Hydrogen production has proved to be the most reliable and sustainable energy storage option for medium and long term operation. However, at the first priority, solar energy must be captured with high efficiency, in order to reduce the overall size of the system and energy storage. Multi-junction solar cells (MJCs) provide highest energy efficiency among all of the photovoltaic technologies and the concentrated photovoltaic (CPV) system concept makes their use cost effective. However, literature is lacking the performance model and optimization strategy for standalone operation of the CPV-hydrogen system. In addition, there is no commercial tool available that can analyze CPV performance, utilizing multi-junction solar cell. This paper proposes the performance model for the CPV-hydrogen systems and the multi-objective optimization strategy for its standalone operation and techno-economic analysis, using micro genetic algorithm (micro-GA). The electrolytic hydrogen production with compression storage and fuel cell, is used as energy storage system. The CPV model is verified for the experimental data of InGaP/InGaAs/Ge triple junction solar cell. An optimal CPV system design is provided for uninterrupted power supply, even under seasonal weather variations. Such approach can be easily integrated with commercial tools and the presented performance data can be used for the design of individual components of the system.

Introduction

Owing to solar intermittency [1] and prime requirement of the power supplying setups, solar energy systems need to operate in standalone configuration for steady power supply. In addition, it must be able to meet the consumer demand at any time. Current global warming situation requires the renewable energy resources to take over the conventional fossil fuels, as

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primary energy supply [2–4]. However, despite being the highest potential energy source [5], solar energy is intermittent in nature, which demands sustainable and sufficient energy storage for continuous power supply. Hydrogen production has proved to be the most reliable and sustainable energy storage option [6] for medium and long term operation as the conventional electrochemical energy storage i.e. batteries are only suitable for short term and small capacity systems [7].

In addition, energy conversion efficiency of the system is another important parameter that defines its overall size for specific load demand, especially in case of renewable energy resources. Concentrated photovoltaic (CPV) system, utilizing multi-junction solar cells (MJC), provides highest solar energy conversion efficiency among all of the photovoltaic technologies [8–10]. On the other hand, the entire photovoltaic market is dominated by the conventional flat plate panels with single junction solar cells [11]. In addition, all of the theoretical studies are also focused on utilization and performance investigation of conventional flat plate panels, utilizing single junction solar cells. Despite being at the top of the solar cell efficiency chart [12], MJC based CPV systems are still lacking in the interest of customers and researchers. Moreover, none of the commercial renewable energy system simulation and optimization tools e.g. HOMER [13], iHOGA [14], TRNSYS + HYDROGEMS, HYBRIDS2, INSEL, ARES, RAPSIM, SOMES and SOLSIM [15], have provision of performance model and simulation/optimization strategy for CPV systems.

So far, the maximum efficiency of 24% has been reported [16] for Hydrogen production using CPV generated electricity at Standard Testing Conditions (STC), which is almost two to three folds higher than the efficiency of electricity production by conventional PV system alone, with 50–80% performance ratio [17]. Therefore, not only based upon the highest efficiency of CPV system alone but also CPV-hydrogen system, it can provide the most compact and efficient standalone solar energy system with steady power supply. However, the literature is lacking the detailed performance and optimization strategy of CPV-hydrogen system for standalone operation. A performance model and optimization for CPV has been reported first time in our previous publication [18]. However, in this paper, a revised performance model and optimization strategy for CPV-hydrogen system is proposed and analyzed in detail by incorporating all possible aspects of CPV concentrating assembly. Firstly, by using the characteristics of multi-junction solar cell and optical arrangement of concentrating assembly, the model of CPV system is presented for its performance simulation. Due to different optical arrangements of CPV concentrating assembly and its effect on CPV output, it is very important to consider every parameter that can affect the system performance. Commercial CPV systems design has well defined optical parameters which are included in the updated model with revised optimization strategy. In addition, for the first time, the proposed model has been experimentally validated within 2% error range. Secondly, based upon the presented performance model of each of the component of CPV-hydrogen system, the overall size of the system is optimized for standalone operation, with appropriate energy storage level but at minimum system cost, by using micro genetic algorithm (micro-GA).

Standalone CPV-hydrogen system

Fig. 1 shows the schematic of proposed standalone solar energy system, based upon CPV system, utilizing hydrogen production as energy storage. The main power producing unit is the concentrated photovoltaic (CPV) system that can either use lenses or reflectors as concentrators to concentrated solar radiations onto small area of multi-junction solar cell (MJC). The CPV modules are mounted onto two axis solar tracker as solar concentrators can only respond to beam part of solar radiations. Depending upon the requirement and configuration, the concentrating assembly of CPV system can be either consisting of single stage concentration, based upon Fresnel lens and homogeniser, or double stage concentration using cassegrain configuration of reflectors and homogeniser. In order to ensure the maximum output from the CPV system, the maximum power point tracking (MPPT) device is connected across it, before supplying its power output to the main DC line connection through DC/DC converter. The main DC line accepts power from all of the sources and supplies it to the main consumer load through DC/AC converter. It also supplies power to all of the power consuming components of CPV-hydrogen system i.e. solar tracker and gas compressor. The power converter is necessary to match the difference between voltages of generated and the required power.

After covering the consumer and the system load demand, the excess produced electricity is supplied to the electrolyser to produce hydrogen and oxygen as energy storage, from electrolysis of water. However, in case of less power production by the CPV system or power supply at night time, the stored hydrogen and oxygen or ambient air, are supplied to the fuel cell to generate deficient electricity, which is then supplied to consumer load, with water production as by product. In order to lower the footprint of the energy storage, hydrogen is compressed and stored in cylinders using mechanical compressors. However, oxygen is stored at the production pressure, to lower the cost and power consumption as it can also be obtained from ambient air, in case of deficiency. In the proposed standalone operation, all of the components operate in a cycle, without any need of external supply. Assuming zero leak loss, the water that is used for electrolysis is replenished back through hydrogen and oxygen reaction in fuel cell, during electricity is generated. Therefore, the proposed configuration is also ideal to be used in remote applications.

CPV-hydrogen system performance model

In order to optimize the overall size of the CPV-hydrogen system for standalone operation, but with minimum cost, first, there is a need to develop the performance model for each of the system component to simulate the performance of the entire system. Fig. 2 shows the energy management of the proposed standalone CPV-hydrogen system configuration. Weather data, in form of direct normal irradiance (DNI) of solar energy and ambient temperature, acts as the main power input for the system performance model. Depending upon the concentrating assembly configuration, either single