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Optimal switching control of PV/T systems with energy storage using forced water circulation: Case of South Africa

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ABSTRACT

In this paper, the optimal switching control of flow in hybrid PV/T systems with forced water circulation is presented. Actual historic exogenous data obtained from a weather station in the considered area is used as input for the established model.

The aim was based on developing an optimal control model to maximize the energy output of the PV module using water circulation to collect the heat and persevering in maintaining the surface temperature as minimal as achievable.

Comparisons between the baseline and the proposed model yields an output power improvement of 2.65% during summer, whereas a 5.90% deterioration during winter. Therefore, the simulation results further demonstrate the proposed model yields a daily heat gain of 9.37×10^7 J, 26.03 kWh inside the water storage tank during the selected summer day and 2.61×10^7 J, 7.25 kWh during the selected winter day.

A true payback period (PBP) analysis is presented, where the project lifetime is chosen to be 30 years. The PBP analysis shows it takes up to 4 years and 2 years for the investor to generate profit from the standard PV system and the optimal switching control model, respectively. However, when looking at both systems over their predicted lifetime, the optimal switching control strategy generates a higher profit of 92.41%.

1. Introduction

One of the most widespread technologies of renewable energy generation is the use of photovoltaic (PV) systems which convert sunlight into usable electrical energy [1]. This type of renewable energy technology, which is pollutant free during operation, diminishes global warming issues, lowers operational cost and offers minimal maintenance and the highest power density compared to the other renewable energy technologies; highlights the advantages of solar photovoltaic (PV) energy [2,3].

Apart from the several advantages displayed by the PV technology, this conversion system has a few general problems such as hail, dust and surface operating temperature which can negatively affect the efficiency of the conversion system [4]. Exogenous climatic parameters such as wind speed, ambient temperature, relative humidity, accumulated dust and solar radiation are the most common natural factors which influence the surface temperature of a PV module [5]. Every 1 °C surface temperature rise of the PV module causes a reduction in efficiency of 0.5% [6]. Therefore, due to the temperature rise, not all of the solar energy absorbed by the photovoltaic cells is converted into electrical energy. To satisfy the law of conservation of energy, the remaining solar energy is converted into heat. The consequences of this wasted heat bring about a reduction in the overall conversion efficiency.

Efficiency improvements in solar energy conversion systems need to be made in order for this renewable energy technology to be a viable solution. To make it a viable solution, there is a need to find different means of solving this temperature problem, which needs to result in an increase of the overall conversion efficiency.

Very few authors have tried to put together and conduct an extensive review of different technologies that can be used to cool the operating surface of solar panels, with the aim of increasing the overall efficiency of the solar conversion system.

The authors of the paper cited in reference [7] have briefly discussed various solar PV panel cooling technologies. However, only a few technologies were introduced, while the main focus of the paper was on the testing and performance of a developed ground-coupled central panel cooling system (GC-CPCS).

In reference to [8], the authors presented an overview of various methods that can be employed for cooling photovoltaic cells. However,

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when studied closely, it can be observed that the focus of the paper was only on examining the passive, forced air and liquid forced convection cooling methods applied to different solar concentrator systems.

Siecker et al. [9] has compiled a review paper based on different PV cooling technologies to improve the electrical and thermal performance thereof. The study has highlighted that efficiency improvements can be obtained using solar photovoltaic/thermal (PV/T) systems cooled by forced water circulation. However, optimal control must be made in order for this PV cooling system to be a viable solution.

The authors of the paper cited in reference [10], developed a theoretical model based on the heat transfer process to evaluate the overall performance of a heat pipe PV/T system. The effectiveness–number of transfer unit (*ε–NTU*) method in heat exchanger design was introduced.

In reference to [11], a model was developed to maximize the overall energy gain extracted by the heat exchanger whilst minimizing the energy consumption of the pumps of solar water heating system. This was implemented with a continuous control method.

In reference to [12], the authors have presented the design of a covered PV/T collector, made with thin film PV technology and a roll-bond flat plate absorber. A simulation model was developed, through the elaboration of several mathematical equations, to evaluate the performance of covered PV/T water collectors.

The authors of the paper cited in reference [13] developed a model based on a hybrid PV/T system cooled by forced water circulation. This system provides a constant flow rate and the characteristics were measured using the PROVITEST PV ANALYZER.

The authors of the paper cited in reference [14] developed a hybrid PV/T system, where water circulates through connecting pipes with fins attached to back part of the PV module. Electrical efficiency enhancements have been observed by using this cooling technique.

In reference to [15], the authors performed experiments on hybrid PV/T systems to analyse hot water to the consumer. The results show that the system is able to supply 60% of the consumer's hot water needs during cloudy days and 100% during sunny days.

In Ref. [16], the authors performed experiments on hybrid PV/T systems to optimize the output power, whilst producing hot water. The results show that the system delivers a higher output power, whilst producing hot water. It is also found that the feasibility of the current system is highly dependent on the geographical location.

In Ref. [17], a hybrid PV/T system with Nano-fluids as a working fluid is developed and studied. Experimental tests indicate a significant improvement in efficiency when Nano-fluids are used as the working fluid.

In Ref. [18], a hybrid PV/T system is developed to increase the efficiency with an automatic water cooling system. The results show a reduction in the average operating temperature and a 33.28% increase in the efficiency. The results further demonstrate that this type of system appears to be promising to implement in tropical countries.

The authors in Ref. [19] have developed a hybrid PV/T system, consisting of transparent PV modules, double pass flat plate air collector, copper water tubes and storage tank. Controlled indoor tests were performed at 800 W/m^2 solar radiation, 0.05 kg/s air flow rate and 0.02 kg/s water flow rate; the output temperature reading measured was 27.4 °C. The results indicate a 17% electrical efficiency with an average output of 145 W and a 76% thermal efficiency.

In Ref. [20], an optimal switching control model is developed for a grid-connected photovoltaic system. An optimal switching control model is proposed to enhance the utilization of the solar energy and minimizing the cost of electricity under the time-of-use tariff structure. The results show the optimal switching of a grid connected PV system can achieve a significant cost saving.

The authors in Ref. [21] have developed an optimal switchable load sizing and scheduling model for standalone renewable energy systems. The objective of the current study was to utilize maximum solar energy without the need for costly energy storage systems. The proposed algorithm determined the optimal on/off switching to maximize the solar energy utilization. The results show the solar energy utilization is optimized to 73% when using two loads and can be enhanced to 98% when using 6 loads.

Hybrid PV/T systems are more expensive when compared to forced air cooling systems, due to added cost to ensure the system is leakage proof and electrically insulated thermal unit water circulation pipes [22]. If there exists a high temperature difference between the top part of the PV module heated via the solar radiation and the back part of the PV module, it causes a significant reduction in the performance of the PV module [23]. Unlike the above-mentioned studies, the current paper is based on developing an optimal control model to maximize the energy output of the PV module using water circulation to collect the heat and persevering in maintaining the surface temperature as minimal as achievable. The use of forced circulation will therefore result in reducing the panel temperature, hence improving its efficiency and in the meanwhile, producing hot water. Since the system produces both electrical and heat energy, it is referred to as a hybrid solar PV/Thermal system. However, the efficiency of the hybrid PV/T system will depend on the surface operating temperature and fluid flow at which the system operates.

The current paper only focuses on improving the performance of the PV module and included the required components to obtain the desired results, which means the current system must not be observed from a classical perspective.

This paper is organized as follows: Section 2 presents the optimal control model development; Section 3 main simulation input parameters. The baseline model is presented in Section 4. Simulation results of the optimally controlled hybrid PV/T system cooled by forced water circulation are discussed in Section 5 with the aim to evaluate the effectiveness of the developed model, compared to the baseline. The economic analysis of the system is presented in Section 6. Lastly, in Section 7, the Conclusions and recommendations are presented.

2. Methodology

2.1. Model development

2.1.1. Dynamic model of the hybrid PV/T system

Mathematical modelling of hybrid systems' operation can be developed for simulation purposes, when conducting experiments on an actual system, would be impossible or impractical [24].

Fig. 1 presents the schematic of the hybrid PV/T system cooled by forced water circulation. The dynamic model of the hybrid PV/T system consists of the variation of the storage tank temperature with the solar irradiance and ambient temperature. A flat plate solar collector is used in this setup to absorb heat from the surface of the PV panel. The flat plate solar collector supplies heat to the water storage tank (thermodynamic system) and is modelled in this section. Fig. 2 illustrates the flowchart of describing the optimization methodology process.

The first law of thermodynamics is applied to the circulation fluid storage tank, in order to obtain the energy balance in the tank. The following equation describes the energy balance equation:

$$M.\ C.\ \frac{dT_s}{dt} = Q_{in} - Q_{load} + Q_{cw} - Q_{loss} \tag{1}$$

where:

$$Q_{in} = \dot{M}_a.\ C.\ (T_{c,o} - T_{c,i}) \tag{2}$$

$$Q_{load} = \dot{M}_b.\ C.\ T_{d,o} \tag{3}$$

$$Q_{cw} = \dot{M}_b.\ C.\ T_{d,i} \tag{4}$$

$$Q_{loss} = \frac{(T_s - T_a).\ A_s}{\frac{\Delta x}{k} + \frac{1}{h}} \tag{5}$$