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On enhancing energy harvesting performance of the photovoltaic modules using an automatic cooling system and assessing its economic benefits of mitigating greenhouse effects on the environment

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HIGHLIGHTS

- An automatic water-cooling system is developed based on WSN technology.
- An estimation method is developed to accurately estimate the module temperature.
- The electrical properties and output power of PV module are evaluated real time.
- The automatic water-cooling mechanism using WSN technology is established.
- An average increase of 17.75% in energy harvested by using WSN-based cooling system.

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ABSTRACT

The performance of photovoltaic (PV) modules under outdoor operation is greatly affected by their location and environmental conditions. The temperature of a PV module gradually increases as it is exposed to solar irradiation, resulting in degradation of its electrical characteristics and power generation efficiency. This study adopts wireless sensor network (WSN) technology to develop an automatic water-cooling system for PV modules in order to improve their PV power generation efficiency. A temperature estimation method is developed to quickly and accurately estimate the PV module temperatures based on weather data provided from the WSN monitoring system. Further, an estimation method is also proposed for evaluation of the electrical characteristics and output power of the PV modules, which is performed remotely via a control platform. The automatic WSN-based water-cooling mechanism is designed to avoid the PV module temperature from reaching saturation. Equipping each PV module with the WSN-based cooling system, the ambient conditions are monitored automatically so that the temperature of the PV module is controlled by sprinkling water on the panel surface. The field-test experiment results show an increase in the energy harvested by the PV modules of approximately 17.75% when using the proposed WSN-based cooling system.

1. Introduction

Renewable energy sources have attracted more attention in recent years due to the diversity and changeability of use and applications [1,2]. By combining multiple renewable energy sources, hybrid energy systems and power sources can be improved to save energy, decrease the use of fossil fuels, and eventually reduce carbon dioxide emissions [3,4]. For most renewable energy sources, photovoltaic (PV) energy has unique properties and versatile applications because PV systems can directly convert light energy into electricity [5,6]. The energy harvesting performance and current-voltage (*I-V*) properties of PV modules are important to the operation and applicability of both standalone and grid-connected PV systems [7,8]. However, these properties are greatly affected by environmental factors such as irradiation intensity, temperature, incident angle of the light, non-uniform irradiation, and shading [9–11]. Changes in these factors will lead to a reduction of the

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output power and changes in the *I-V* characteristics of fixed PV modules, including their open-circuit voltage (V_{oc}), short-circuit current (I_{sc}), maximum output voltage (V_{mpp}) and maximum output current (I_{mpp}) at the maximum power point (MPP), as well as the characteristic ratios of V_{mpp}/V_{oc} and I_{mpp}/I_{sc} [9,12,13]. Experimental and field-test results [9,13,14] show that the changes in irradiation mainly affect PV output current, while changes in ambient temperature mainly influence PV output voltage, resulting in variations of the maximum output power. In comparison with changes of irradiation intensity, the characteristic ratios of PV modules (V_{mpp}/V_{oc} and I_{mpp}/I_{sc}) are more sensitive to changes in temperature [9].

In addition, there is a gradual increase in the PV module temperature under continuous operation and solar irradiation. The increased module temperature induced by solar irradiation and ambient temperature can lead to serious deterioration of the *I-V* characteristics and power generation efficiency of the PV modules. According to previous studies [15,16], about 5% of the output power is lost for a 10 °C increase in the ambient temperature. A difference between PV module temperature and ambient temperature due to extensive heat storage in the interior of the module was also found [15,16]. Thus, it is necessary to pay more attention to the effect of various environmental and irradiation conditions on PV module temperature to achieve the goal of real-time maximum power output.

In general, the module temperature is considered to be a function of various environmental factors, such as the ambient temperature, radiation intensity, relative humidity, and wind speed [16–22]. The measured PV module temperature and environmental factors have been used to establish various empirical rules or formulas [16–22]. The experiment results and measurement data indicate a considerable variation in the temperature of PV modules if they were installed in different areas. However, the weather data were not monitored and recorded in real-time in these studies [16–22], resulting in incorrect estimation of PV module temperature. A large difference between the estimated and actual module temperature was likely to be found, and this further causes a significant loss on power generation efficiency. Some methods have been developed to cool down PV modules. For example, a forced convection in the air channel was experimentally used to achieve the cooling of building integrated photovoltaics modules [22], but such a method might increase the overall costs and its way of estimating module temperature was complicated. Thus, it is very difficult to use conventional methods or empirical formulas to accurately estimate the temperature of PV modules or to further evaluate their MPPs and energy harvesting performance under various irradiation conditions.

Currently, cooling systems can use either air or liquid to cool down PV modules [23]. Air cooling systems employ either a natural ventilation system [24,25] or a forced ventilation system [26–28] to improve the power generation efficiency of the module. However, liquid cooling systems are much more efficient than air cooling ones, because the thermal conductivity of water at 20 °C (0.599 W/m·K) is much higher than that of air at 20 °C (0.0257 W/m·K) [29]. Additionally, flowing water not only achieves approximately 2–4% reduction in reflection loss but also cleans dust particles from the surface of the PV modules, contributing to the further improvement in their power generation efficiency [30–32]. Kim et al. developed a model based on the heat transfer theory to predict the module temperature and evaporation rate in order to evaluate the performance of a PV module with a cooling system [33]. Moreover, differences in the increase in the output power are related to the design adopted for the cooling system and the environmental conditions. In some studies [30–33], it is found that water flowing over the surface of a PV module on a sunny day lowers the module temperature from 10 °C to 35 °C, increased the average output power by 4–12.5% in a day, and reduces the reflection loss by 2–4%.

In the past, it was a very difficult task for a water-cooling system to conveniently obtain the information about the status of each PV module, because the impact of weather factors could not be monitored in a real-time manner. This means that the operation of PV modules could not be effectively controlled to increase the power generation. It was also unmanageable for conventional methods to quickly acquire real-time data of module temperature monitoring. Moreover, the generating capacity of the PV generation plants is generally around 100–300 kW and the power generation facilities generally occupy 1980–2980 m^2. If these plants use wired monitoring systems to detect the related parameters, and each individual parameter requires corresponding transmission cables so it can be monitored, the costs of the cables and the monitoring system construction are very high.

To achieve quick and accurate estimation of PV module temperatures, real time solar radiations and weather conditions at local installation sites should be taken into consideration by the estimation models. This can be easily done by using wireless sensor network (WSN)-based monitoring systems with the communication and surveillance ability proposed in this study. By applying WSN technology, not only can an interest region be monitoring in real time, but also can sensing data be wirelessly transmitted to a collection database [34,35]. Moreover, the deployment of the proposed wireless monitoring system is flexible, so the problems of high costs and the difficulties of hard wire deployment can be overcome. The convenience and scalability of using a cooling system with WSN technology can also be substantially enhanced. Besides, a PV module temperature estimation method and a cooling mechanism are proposed by the study to increase the overall power generation of PV modules. The energy-harvesting increment achieved by the PV module with the proposed cooling system further mitigates the greenhouse effects on the environment and its economic benefit is also evaluated in this study.

2. The architecture of the proposed automatic cooling systems

In this study, a WSN-based automatic water cooling system for PV systems was developed. The architecture of the proposed cooling system is depicted in Fig. 1. In order to reduce the thermal degradation of PV modules during operation, water was used as the cooling medium to cool down the module temperature and enhance the energy harvesting performance of the PV modules. With a wireless communication protocol, this study established a front-end monitoring platform and a back-end database for all kinds of PV systems without the demolition of the original system structure. The operating status and power generation efficiency of a PV module with this automatic cooling system and the remotely controlled platform could be quickly and accurately monitored. Furthermore, the developed system could analyze the data related to the operating status of the PV module and evaluate the module temperature. If the module temperature exceeded a threshold, the wireless automatic cooling system would be activated to cool down the temperature of the PV module thereby further improving the power generation efficiency.

As depicted in Fig. 1, the frontend part of the proposed cooling system consisted of a gateway, several wireless nodes and cooling

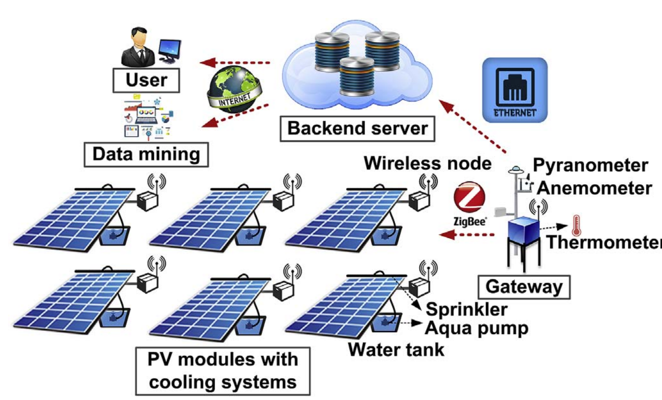

Fig. 1. The architecture of the proposed cooling system for PV modules.