Self-cleaning and self-cooling photovoltaic system with feedback control

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Abstract

One of the most important problems in using photovoltaic systems (PV) is the low power production due to increasing the ambient temperature, and the accumulation of dust on PV panels surfaces. In this work, self-cleaning and self-cooling PV system with feedback control was designed, constructed and operated. The programming method of control of water pumping system is achieved by means of programmable logic controller (PLC) and frequency inverter (FI). The control system consists of two subsystems based upon the same electromechanical system. One system for controlling the cooling of PV system by using temperature sensor and feedback system, and the other system for controlling the cleaning of PV system by using huge pressure of water to push away the accumulated dust on the PV surface. An experimental study was performed to investigate the effect of using self-cleaning and self-cooling system on the electrical power generation at the output of PV system. The electrical power generation at the output of PV modules with self-cleaning and self-cooling system has increased by 34% and the efficiency by 26%.

Keywords: PV system; Feedback control; Self-cleaning; Self-cooling; PLC system; Frequency inverter.

1. Introduction

In the last few years, PV systems and their applications witnessed a wide spread around the world. PV modules are subjected to deposition of sands on their glass cover, and to high ambient temperature. These effects are great, especially, in semi-arid and desert lands, such as, Middle East and North Africa, where the degradation in performance of PV modules is huge. The following studies discussed the effect of dust accumulation and temperature increasing on the performance of PV modules, and different methods for solving these problems. Sontake et al., Muhsen et al., and Elkholy et al. [1,2,3] studied the application of solar photovoltaic water pump systems, various optimization methods, design methods, control strategies and field characteristics. Charabi and Gastli [4] carried out land suitability analysis for large PV farms implementation for the case study of Oman. The results show that several areas are declassified because of their exposure to high temperature and dust risks, where the highly suitable land areas decreased by 81% after considering the temperature and dust.
constraint that the reduction in the free percentage of losses for the plant built in sandy soil and a 1.1% for the one built on a more compact soil have been found.

The results presented showed that both the soil type and the washing technique influence the effect of soiling on energy production for large scale ground mounted PV plants in the country side of southern Italy. The conducted experiments in the temperature interval of 25 to 170 °C and the calculated data, show a real possibility of construction of a two-stage solar-to-electric energy converter with high temperature-second stage, having the overall conversion efficiency of 30-40%. In [7] Royne et al. presented a review of various methods that can be employed for cooling of PV cells. They found that single cells typically only need passive cooling, even for very high concentrations. For densely packed cells under high concentrations, an active cooling system is necessary. Only impinging jets and micro-channels have been reported. Two-phase forced convection would also be a viable alternative. In [8] Akbarzadeh and Wadowski reported about a prototype of an east-west trough solar concentrator using the profile developed for the reflecting surface and incorporating a thermo-syphon cooling system for PV cells.

In [9] Moharram et al. developed a cooling system based on water spraying of PV panels. A mathematical model has been used to determine when to start cooling of PV panels. A cooling model has been developed to determine how long it takes to cool down the PV panels. It is found that the PV panels yield the highest energy if cooling of the panels starts when the temperature of PV modules reaches a maximum allowable temperature (MAT) of 45 °C. The MAT is a compromise temperature between the output energy from the PV panels and the energy needed for cooling. Zhu et al. [10] utilized a 250 x dish concentrator with two axes tracking to evaluate a new CPV system using de-ionized water for immersion cooling. They showed that the cooling capacities of the liquid immersion approach are very favorable. The module temperature can be cooled to 45 °C at a 940 W/m² direct normal irradiance, 17 °C ambient temperature and 30 °C water inlet temperature. The temperature distribution of the module is quite uniform, but the electrical performance of the cell module degrades after a fairly long time immersion in the de-ionized water.

Kaldellis and Kapsali [11] studied and analyzed the effect of three representative air pollutants (i.e. red soil, limestone, and carbonaceous fly-ash particles) on the energy performance of PV installations. According to the results obtained, a considerable reduction of PVs' energy performance is recorded, depending strongly on particles composition and source. Mikhilef et al. [12] studied the impact of dust accumulation, humidity level and the air velocity separately and the impact of each on the other. They showed that each of these three factors affect the other two and it is concluded that, in order to have a profound insight of solar cell design, the effect of these factors should be taken into consideration in parallel.

Biattie et al. [13] presented numerical and analytical models of sand and dust particles accumulation on PV modules in dry regions. Both models and experimental data indicate that the reduction in the free fractional area can be described by an exponential decay resulting from the formation of clusters of particles. Such clusters can support particles in upper layers which reduce the available area for photon capture by a much smaller amount than particles resting directly on the glass surface. Sarver et al. [14] provided a comprehensive overview of soiling problems, primarily those associated with sand and combined dust moisture conditions that are inherent to many of the most solar rich geographic locations worldwide. In [15] Hee et al. investigated the conditions affecting dust fall in Singapore and its effect on the optical transmission through glass modules. It was found that for bar glass samples, transmission reduces despite the heavy rains in Singapore over several months. Also, they investigated the effect of substrate tilt in keeping them clean. Bar glass substrates were tilted at angles of 10, 20, 30, 40, 50, 60, 80, and 90 degrees during outdoor exposure. They investigated the performance of TiO2 films as an outdoor self-cleaning coating for solar panels. TiO2 of different thicknesses were deposited on glass substrate by hydrolysis method which is a low-cost and commercially viable process. In [16] Pavan et al. studied the effect of soiling on energy production for large-scale ground mounted PV plants in the country side of southern Italy. The results presented showed that both the soil type and the washing technique influence the losses due to the pollution. A 6.9% of losses for the plant built in sandy soil and a 1.1% for the one built on a more compact soil have been found.
Ghazi et al. [17] made a review for dust effect on flat surfaces. They showed that since 1942 many efforts have been made to address the severity of deposited particles like dust. Various innovative methods have been employed to clean the surface of the grimy PVs, a holistic approach needs to show the cleaning mechanism under different climate conditions. The pattern of dust distribution in different parts of the world is assessed and it was found that the Middle East and North Africa have the worst dust accumulation zones in the world. Verma et al. [18] showed that simple antireflective coatings on the glass can help alleviate reflection in systems with motorized tracking, the problem of dust accumulation on module surfaces over time remains and can even be exacerbated by certain antireflective coatings. A process of non-lithographic nano-structuring of the packaging glass surface is shown to both reduce reflection at the air/glass interface and to have a self-cleaning property. Kamlesh et al. [19] studied the performance of controllers for solar PV water pumping applications. In [20] Kalogirou et al. presented a study of the characteristics of three types of PV panels: mono-crystalline, polycrystalline, and amorphous silicon and the effects of soiling on their performance using on site measurements. They performed the test of degradation of PVs performance under extreme soiling conditions caused by artificial deposition of dust on the panels when their surface was dry and when it was wet before the dust deposition. The results showed that especially the artificial soiling on the PV surface presents a serious degradation of the PV performance. The effect of natural dust deposition on the panel's surfaces for a year is investigated. The first finding of the study is that in winter the occasional rain is adequate to keep the PV surfaces clean whereas when a dust episode occurs, the panels should be cleaned manually. This is not the case for the summer time, which for Cyprus lasts for more than 8 months. The recommended cleaning is immediately after a dust episode and every 2-3 weeks in summer time according to how much loss the owner of the PV is willing to accept and the associated cleaning cost. In [21] Sayah et al. presented a brief review of the energy yield losses caused by dust deposition on solar collectors, with particular emphasis on flat-panel PV systems. They reported on degradation in the performance of solar plants based on the type of solar collectors, geographical location, local climate, and exposure period of the collectors and absent any manual cleaning. An analysis of the advantages of cleaning processes that include natural, manual, automatic and passive methods is presented.

In [22] Adinoyi and Said studied the effect of dust accumulation on the power output of solar PV modules in the Eastern province of Saudi Arabia. This study indicate that power decrease by as much as 50% can be experienced for PV modules that are left unclean for a period of over six months. Solar tracker improves power output and helps reduce dust accumulation effect by 50% at off-peak time.

In [23] Kaldellis et al. experimentally investigated the performance of two identical pairs of PV panels, the first being clean and the second being artificially polluted with three different commonly met in urban and other environments, air pollutants (i.e. red soil, limestone and carbonaceous fly-ash particles). The results obtained showed a considerable reduction in of PVs energy performance, depending on both particles composition and origin, and on the total mass accumulated on the PV panel's surfaces. The highest reduction is caused by the deposition of red soil particles, followed by the deposition of limestone, and finally by the carbon-based ash. In [24] Jiang et al. studied the dust accumulation onto different types of solar PV modules and the corresponding efficiency degradation. The results indicated the dust pollution has a significant impact on the PV module output. The reduction of PV output efficiency grew from 0 to 29 %. The reduction of efficiency has a linear relationship with the dust deposition density, and the difference caused by the cell types was not obvious. The polycrystalline silicon module packaged with epoxy degraded faster than other modules with glass surface under the same dust concentration.

Aim of this work is the design, construction and operation of self-cleaning and self-cooling PV system with feedback control. The programming method of control of water pumping system is achieved by means of programmable logic controller (PLC) and frequency inverter (FI). The control system consists of two subsystems based upon the same electromechanical set up, one system for controlling the cooling of PV system by using temperature sensor and feedback system, and the other system for controlling the cleaning of PV system by using the pressure of water to push away the accumulated dust on the PV surface.

2. Experimental setup

The panel with self-cleaning and self-cooling system is supplied with controlled pumping system which pumps water into the surface of PV module through the nozzle which is mounted at the upper side of module. The running film of water over the surface of PV module decreases the temperature, and cleans...
the accumulated dust on the panel surface. The control system consists of two subsystems based upon the same electromechanical system. One system for controlling the cooling of PV system by using temperature sensor and feedback system, the cooling frequency of PV module is determined by the module temperature. The other system for controlling the cleaning of PV system by using huge pressure to push away the accumulated dust on the PV surface.

For purpose of experimentation the electromechanical self-cleaning and self-cleaning system was designed and constructed as shown in Figure 1.

![Figure 1. Block diagram of self-cleaning and self-cooling system with feedback control.](image)

The system is consisting of PLC and frequency inverter, AC motor driven centrifugal pump, PV panel, temperature sensor, analog to digital converter, transducer, and DC power supply. The main controller of this system is a PLC-S7-1200, which has 8 inputs, 6 outputs and 24 VDC power supply voltage. Control panel of system including PLC-S7-200 is shown in Figure 2. This PLC system has two functions in this system: one of them is to control pumping flow rate according to the ambient temperature, the more the ambient temperature rises the more the pumping flow rate increases. The other function is to control the pump at maximum power for 1 minute each hour. First function work on cooling the PV panel, while the second function works on cleaning the PV panel. The programming method of control in which stored instructions in PLC memory was used to operate the AC motor driven centrifugal pump. The personal computer is used to write the ladder program then download it to PLC-S7-1200 through communication cable.
The digital to analog converter function is to transfer the digital output value, which ranges from 0 to 27684 digits at the output of PLC into analog value, which ranges from 0 to 10 VDC. Frequency inverter (FI) used in this work is Emerson brand, which has one phase input, three phase output with range from 0 to 240 VAC. The range of voltage at the control input of FI is ranging from zero to 10 VDC. Different values of output voltage are supplied to the AC motor driven centrifugal pump by the FI, which is originally stated by digital to analog converter, where 0 VDC equals 0 VAC at the output of FI, and 10 VDC at the input of FI gives 240 VAC at the output. The flow rate of used centrifugal pump is 10-30 L/min, with a head 14-22 m, temperature sensor used to the feedback control is PT-100, the range of measured temperature 0-100 °C. Transducer is used for linearization the drop of voltage at the output of temperature sensor PT-100. Analog to digital converter is used to transfer the current at the output of transducer from analog value into digital values.

The general characteristics of photovoltaic module used in experiment are as following: module type YL 245P-29b, nominal power 245 W, rated voltage 30.2 V, and rated current 8.11 A.

3. Experimentation and results
In this work, different electronic measurement instruments and devices were used to measure the experimental variables. These instruments and devices were tested and calibrated before being used. Electrical current generated at the output of PV module is measured using a clamp ammeter. The range of measurement is from 0 to 20 A. the accuracy of measurement is 3%. Voltage measurement is accomplished with voltmeter, where the range of measurement is from 0 to 40 VDC and the accuracy of instrument is 4%.

Two identical PV modules one with self-cleaning and self-cooling system and the other without are involved in experiment. Both panels were facing south with the same slope angle of 11 degrees, and they are connected to the same load resistance.

A continuous test during May and June 2015 was done in the Renewable Energy Center at the Applied Science University in Amman, Jordan.

The rate of cooling of the PV module is a very important factor that affects their performance. The PV module temperature depends on solar radiation, ambient temperature and nominal operating cell temperature NOCT. Therefore the module temperature will be a function of time during a day. The solar radiation, ambient air temperature and PV module temperature were measured during one day with cooling and without cooling and presented in Figure 3.

Figure 4 shows generated electrical power at the output of PV modules for the system with cleaning and cooling, and for other system without, the results of experimentation indicate that there were increases in daily measured electrical output power up to 34% in sunny days and 29% in cloudy days. Experimental measurements of the efficiency of the PV module during June 2015 are shown in Figure 5. As seen as the module temperature increase, the PV module efficiency decrease. Its found that PV module efficiency increased from (26 % - 29%) with cooling compared with PV module without cooling system.
4. Conclusions
In this work, the hardware and software elements of self-cleaning and self-cooling PV system were designed, constructed, and operated. Feedback method of control is used to control the pumping flow rate according to temperature rises in purpose of cooling the PV system. Open loop method of control is used to control the pumping flow rate function of time in purpose of cleaning the photovoltaic system. It can be concluded that the proposed
cooling and cleaning system suitable for application in the hot and dusty regions and the use of automatic cleaning and cooling of PV system results in an increase total daily power production up to 29%.

References


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