INTERNATIONAL JOURNAL OF
ENERGY AND ENVIRONMENT

Volume 9, Issue 1, 2018 pp.49-56

Journal homepage: www.IJEE.IEEFoundation.org

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

Issameddin Abdullah[1], Ali Akayleh[2], Mohammed Al-Soud[2], Salah Abdallah[3]

[1] Department of Industrial Engineering, Business and Technology University, Jeda, Saudi Arabia.
[2] Department of Electrical Engineering, Tafila Technical University, P.O.Box-66, Tafila 66110, Jordan.
[3] Department of Mechanical & Industrial Engineering, Applied Science University, Amman 11931-166, Jordan.

Received 23 Jul. 2017; Received in revised form 14 Sep. 2017; Accepted 23 Sep. 2017; Available online 1 Jan. 2018

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 layers. Different PV technologies are considered and it is found that the concentrated PV technology provides higher potential for implementing large scale solar plants. Lai and Chen [5] suggested the using of heat pipe as a channel for heat dissipation to conduct the heat out of PV modules. Because DC combiner boxes are waterproof, dust proof, air tight and made of heat-insulating material, thermal energy is easily accumulated, affecting the performance and safety of power cables and other electronic components near the diodes in the DC combiner box.

Meneses-Rodriguez et al. [6] investigated the possibility of PV cell work at a relatively high temperature (from 100 to 200 °C). 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.

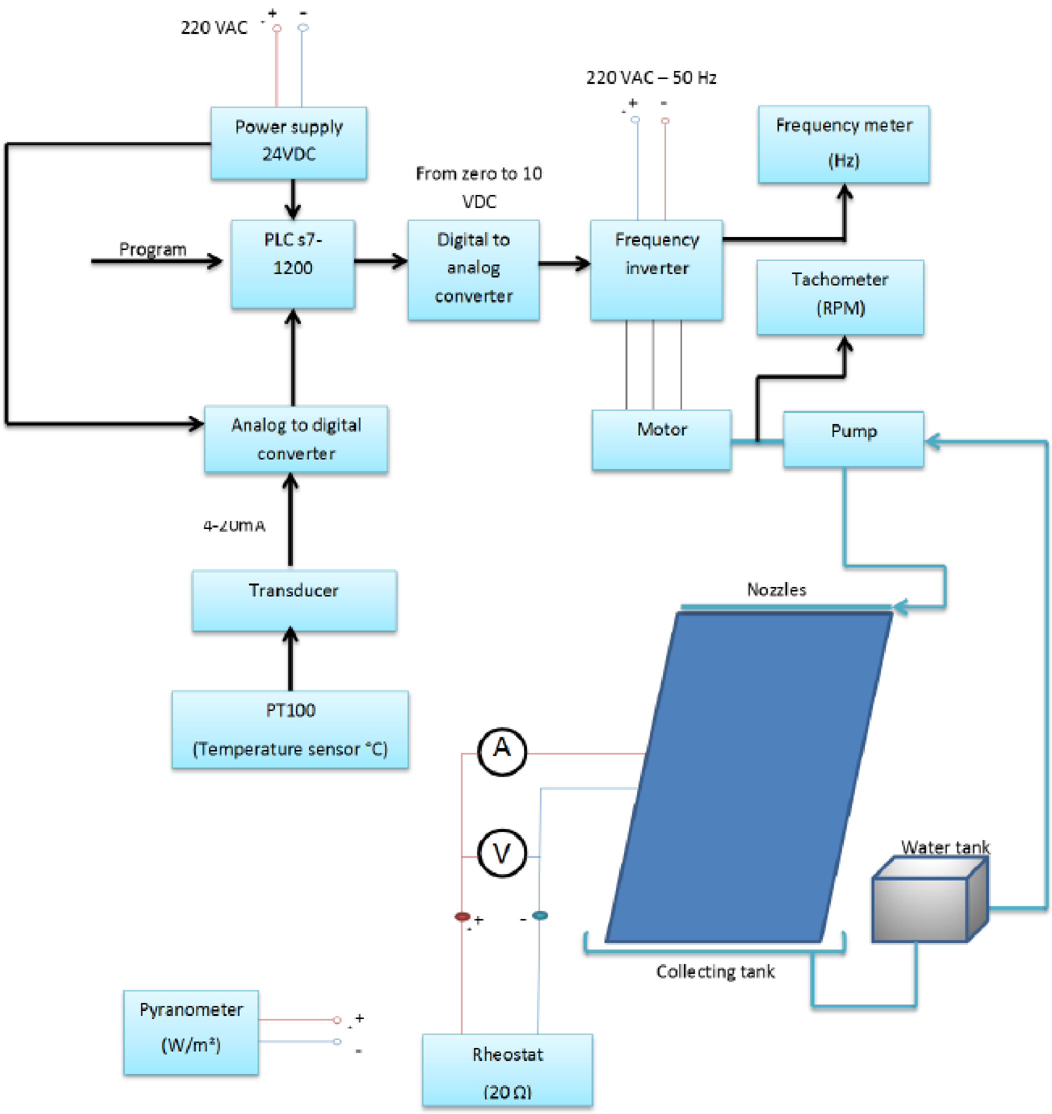

Figure 1. Block diagram of self-cleaning and self-cooling system with feedback control.

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.

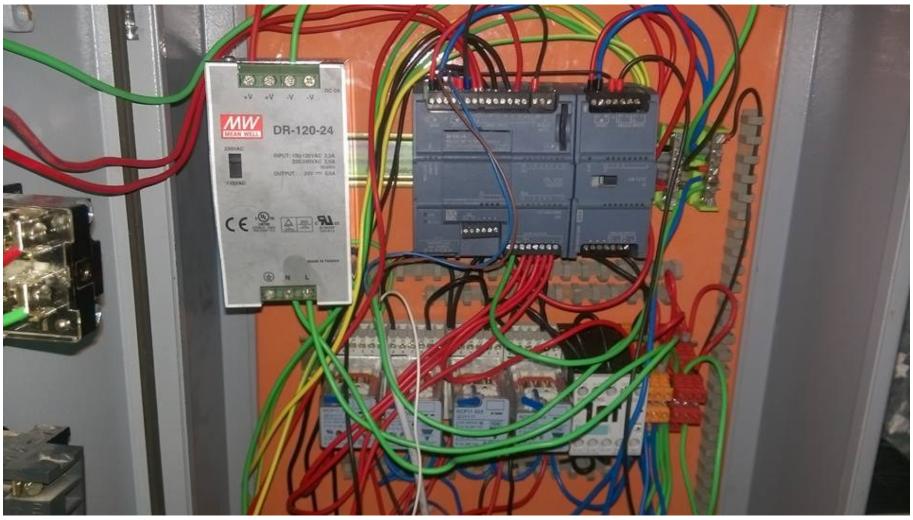

Figure 2. Control panel of self-cleaning and self-cooling system.

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.

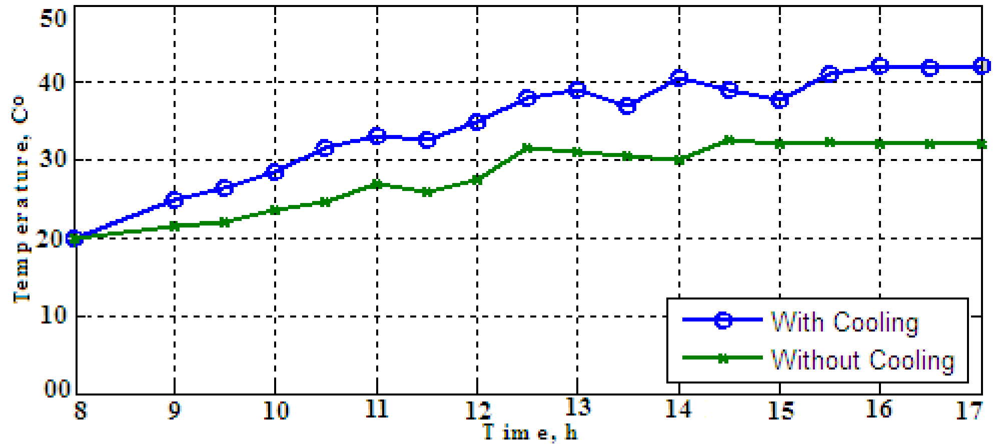

Figure 3.The measured module temperature during June 2015.

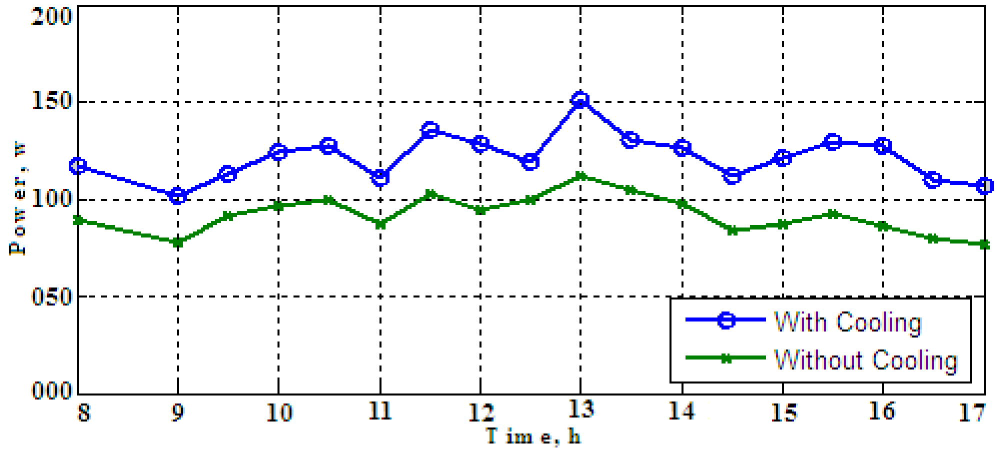

Figure 4. Generated electrical power at the output of PV modules.

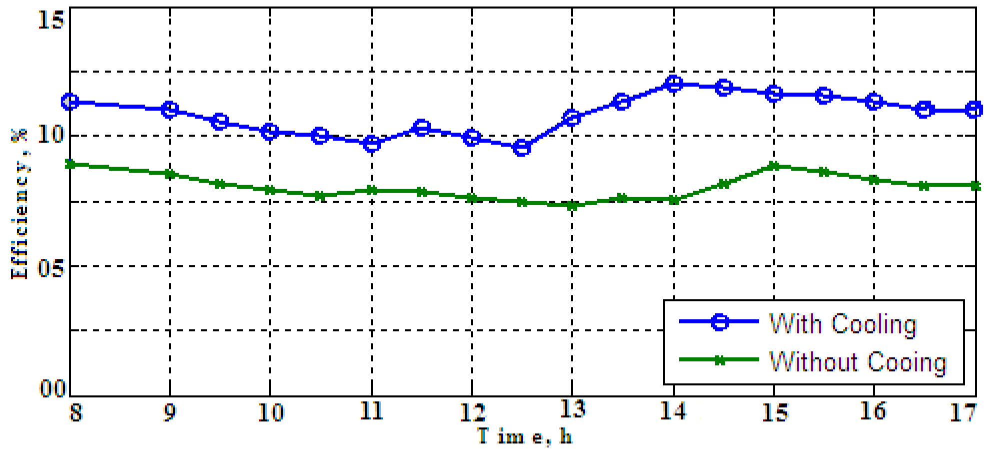

Figure 5. Experimental measurements of the efficiency during June 2015.

4. Conclusions

In this work, the hard ware and software elements of self-cleaning and self-cooling PVsystem 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

[1] Vimal Chand Sontake, Vilas R.Kalamkar. Solar photovoltaic water pumping system-A comprehensive review. Renewable and Sustainable Energy Reviews, 59(2016)1038–1067.

[2] Dhiaa Halboot Muhsen, Tamer Khatib, Farrukh Nagid. A review of photovoltaic water pumping system designing methods, control strategies and field performance. Renewable and Sustainable Energy Reviews 68 (2017) 70–86.

[3] Mahmoud M. Elkholy, Ahmed Fathy. Optimization of a PV fed water pumping system without storage based on teaching-learning-based optimization algorithm and artificial neural Network. Solar Energy 139 (2016) 199–212.

[4] Yassin Charabi, Adel Gastli. Integration of temperature and dust effects in sitting large PV power plant in hot arid area. Renewable Energy. 57(2013) 635-644.

[5] Chi-ming Lai, R.H.Chen. Novel heat dissipation design incorporating heat pipes for DC combiner boxes of a PV system. Solar Energy. 85(2011)2053-2060.

[6] David Meneses-Rodriguez, Paul P. Horley, Jesus Gonzalez-Hernandez, Yuri V. Vorobiev, Peter N. Gorley. Photovoltaic solar cells performance at elevated temperatures. Solar Energy. 78(2005)243-250.

[7] Anja Royne, Christopher J. Dey, David R. Mills. Cooling of photovoltaic cells under concentrated illumination: a critical review. Solar Energy materials and solar cells. 86(2005)451-483.

[8] Akbarzadeh, T. Wadowski. Heat pipe-based cooling systems for photovoltaic cells under concentrated solar radiation. Applied Thermal Engineering .16(1996)81-87.

[9] K.A Moharram, M.S. Abd El-hady, H.A.Kandil, H.El-Sherif. Enhancing the performance of photovoltaic panels by water cooling. Ain Shams. 4(2013) 869-877.

[10] Li Zhu, Robert F Boehm, Yiping Wang, Christopher Halford, Yong Sun. Water immersion cooling of PV cells in a high concentration system. Solar Energy Materials and Solar Cells. 95(2011)538-545.

[11] J.K.Kaldellis, M.Kapsali. Simulating the dust effect on the energy performance of photovoltaic generators based on experimental measurements. Energy. 36 (2011)5154-5161.

[12] S.Mekhilef, R. Saidur, M.Kamalisarvestani. Effect of dust, humidity and air velocity on efficiency of photovoltaic cells. Renewable and sustainable energy reviews. 16(2012) 2920-2925.

[13] Neil S. Beattie, Robert S.Moir, CharlsleeChacko, Giorgio Buffoni, Simon H. Roberts, Nicola M. Pearsall. Understanding the effects of sand and dust accumulation on photovoltaic modules. Renewable Energy. 48(2012) 448-452.

[14] Travis Sarver, Ali Al-Qaraghuli, Lawrence L. Kazmerski. A comprehensive review of the impact of dust on the use of solar energy: History, investigations, results, literature and mitigation approaches. Renewable and Sustainable Energy Reviews. 22(2013) 698-733.

[15] Jai Yun Hee, Lalit Verma Kumar, Aaron James Danner, Hyunsoo Yang, Charanjit Singh Bhatia. The effect of dust on transmission and self-cleaning property of solar panels. Energy Procedia, 15(2012) 421-427.

[16] A.Massi Pavan , A. Mellit , D.De Pieri. The effect of soiling on energy production for large-scale photovoltaic plants. Solar Energy. 85(2011)1128-1136.

[17] Sanaz Ghazi, Ali Sayigh, Kenneth Ip. Dust effect on flat surfaces – A review paper. Renewable and Sustainable Energy Reviews. 33(2014)742-751.

[18] L.K Verma, M. Sakhuja, J.Son, A.J.Danner, H.Yang, H.C.Zeng, C.S.Bhatia. Self-cleaning and antireflective packaging glass for solar modules. Renewable Energy. 36(2011)2489-2493.

[19] Kamlesh Yadav, O.S.Sastry, R.Wandhare. Performance comparison of controllers for solar PV water pumping applications. Solar Energy. 119 (2015) 195–202.

[20] Soteris A. Kalogirou, Rafaela Agathokleous, GregorisPanayiotou. On-site PV characterization and the effect of soiling on their performance. Energy. 51(2013)439-446.

[21] Arash Sayyah, Mark N.Horenstein, Malay K. Mazumder. Energy yield loss by dust deposition on photovoltaic panels. Solar Energy. 107(2013)576-604.

[22] Muhammed.J.Adinoyi, Syed A.M.Said. Effect of dust accumulation on the power outputs of solar photovoltaic modules. Renewable Energy. 60 (2013) 633-636.

[23] J.K.Kaldellis, P. Fragos, M.Kapsali. Systematic experimental study of the pollution deposition impact on the energy yield of photovoltaic installations. Renewable Energy. 36(2013) 2717-2724.

[24] Hai Jiang,Lin Lu ,Ke Sun .Experimental investigation of the impact of airborne dust deposition on the performance of solar photovoltaic (PV) modules. Atmospheric Environment. 45(2011) 4299-4304.

Issameddin Abdullah, Associat Professor, received his PhD from Irrigation Institute, Uzbekistan, 1997, and the Bachelor's degree in Institute of Oil and Gas, Russian-Moscow 1985. From 1997-2009. Dr. Issameddin is a lecturer at the Mechanical & Industrial Engineering, Al-Balqa Applied University, From 2009 to present is a lecturer at the Industrial Engineering, Business and Technology University, Jeda, Saudi Arabia. His field of scientific interests includes modeling simulation of mechanical and pumping systems.

Akayleh Ali Saqer, Associat Professor Since 2010, received his PhD from Electric Drive and Industrial Automation Faculty of Institute of Automation and Energy, Uzbekistan, 1995, and the BSc degree in Electric Drive and Industrial Automation. Faculty, of Karkov Technical University, Ukraine 1992. From 2002 –present Dr. Akayleh is a faculty member at the Department of Electrical Engineering in Tafila Technical University - Jordan. His area of research interest includes modeling and simulation of dynamic complex systems, Speed synchronization of multi-motor systems.

Mohammed Al-Soud, Associat Professor Since 2010, received his PhD from Science Academy of Uzbekistan, Uzbekistan, 1994, and the BSc degree in Electrical Engineering, Power plants. Kharkof Polytechnic Institute, Ukraine, 1991. From 2002 - present Dr. Mohammed is a faculty member at the Department of Electrical Engineering in Tafila Technical University - Jordan. His field of scientific interests includes Renewable Energy / Photovoltaic Technology.

Salah Abdallah, Full Professor Since Oct.2010, received his PhD from Institute of Engineering and Irrigation, Tashkent-Uzbekistan, 1995. And the Bachelor's degree from Kharkov Polytechnic Institute-Kharkov-Soviet Union, 1990. From 1998 to present Dr. Salah is a faculty member at the Mechanical & Industrial Engineering, Applied Science University. His area of research interest includes sun tracking systems, solar energy and modeling of electromechanical systems.

