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A NEW APPROACH OF ELECTROSTATIC CLEANING FOR REMOVING DUST FROM SOLAR PANELS

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ABSTRACT
A novel cleaning technique is proposed in this research, which suggests installing the electrodes of the electrostatic cleaning system on the backside of the PV panel in order to avoid the shading caused by the interference with the sun light reaching the panel. The influence of installing the electrodes on the backside of a glass plate on removing the dust from the front side is examined experimentally, as a function of the glass plate thickness and the material of the back cover of the electrodes. The materials used for the back cover of the electrodes are wood, glass and air, such that the electrodes are sandwiched between the glass plate and the cover. The glass plate mimics a PV panel. The experimental setup depends on two techniques to measure the diffusivity of the electric field on a glass plate and a PV panel as a function of the glass plate thickness and the back cover material. The first technique utilizes an ultra-sensitive electric field sensor based on the Whispering Gallery Modes (WGM), while the second technique is based on visual observation of the excitation voltage required to remove the dust from the glass surface. It has been found that the strength of the electric field above the glass plate and the PV panel in case of using wood as a back cover is higher than that for air and glass back covers. It can be concluded that wood resists the diffusivity of the electric field from the backside of the panel more than air and glass. Also, it has been found that the excitation voltage of the electrostatic cleaning system is proportional to the thickness of the glass plate and adding a wooden cover on the electrodes decreases the excitation voltage, in comparison to the cases of no cover or a glass cover.

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1. Introduction:

Over the past decades, a variety of techniques were developed to obtain energy from renewable energy sources [1], one of these techniques is Photovoltaic (PV) panels [2], which convert light energy from the sun into electricity. PV panels received significant consideration around the world, as they are, simple and sustainable, but when using the panels in semi-arid and desert areas a problem of soiling is encountered [3]. Soiling is the accumulation of dust and other contaminants on the upper surface of PV panels [4], such that the solar irradiation and power yield of the panels are reduced due to absorption or reflection of the sunlight [4]. To restore their power yield, it is necessary to completely clean the upper surfaces of the panels. There are several ways of cleaning such as manual cleaning, vacuum suction cleaning, automatic wiper-based cleaning [5], mechanical removal of dust using mechanical [6] and sonic vibrators [7,8], water-free cleaning with transparent electrodynamic screen [9] and self-cleaning using super hydrophobic coatings [3].

The water-free cleaning with an electrodynamic screen is a suitable method for cleaning the PV panels that operate the street light posts, because it can be operated without water, it requires no labor, and consumes very small amount of energy [10]. This technology was first suggested by Tatom et al.[11] at NASA in 1967 and further developed by Masuda et al.[12] at Tokyo University in 1970. An electrostatic cleaning device was built and used to lift and transport charged and uncharged particles from the surface of the solar panels using electrostatic and dielectrophoretic forces [12]. Sims et al.[13] reported that the voltage is an influencing parameter in electrostatic cleaning and is behind the creation of electric field distribution via electrodes. The geometry of electrodes, ratings of power supply and nature of wave shapes had played an important role during the development stages of the dust mitigation technique [13]. Kawamoto and Uchiyama [14] carried out an experimental study and a numerical analysis on a self-cleaning device in lunar environment and found that, in comparison to air, the higher cleaning rate was observed in vacuum with respect to higher voltage and frequency. Further investigations revealed that it is not economical to use this technology in commercial mega-power plants because of very high costs and complex designs of indium tin oxide (ITO) electrodes [15,16]. To make this technology applicable for commercial use in solar mega power plants, an electrostatic cleaning system was developed by Kawamoto and Shibata [15] that consists of an anti-dust glass cover plate with embedded parallel wire electrodes and a single-phase rectangular high voltage power supply, as shown in Fig. 1.

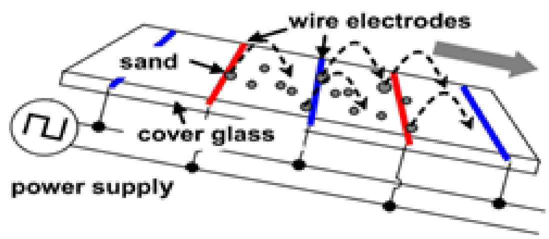

Figure 1. Schematic diagram of the enhanced system that removes dust particles under the influence of standing wave generated by single phase rectangular high voltage power supply and gravity [15].

Kawamoto and Shibata [15] studied the cleaning performance of that device with the inclination of the panel under a standing and travelling electric waves. It was observed that, at an inclination angle higher than 20°, both the standing and travelling waves gave the same cleaning performance before dielectric breakdown. Further, Kawamoto and Shibata [15] also studied the effect of particle diameter on efficiency of the cleaning system and found that particles with diameters smaller than 25 μm and larger than 300 μm were not efficiently removed. Mazumdar et al.[9,17] fabricated a transparent electro dynamic screen (EDS), and tested experimentally the transmission and reflection losses due to the EDS. It was found that more than 90% of power restoration was achieved due to the installed EDS compared to conventional cleaning processes. However, the EDS cleaning system is not easy to apply on the solar arrays that are already installed in semi-arid and desert areas as it is too complicated and expensive. Kawamoto and Guo [18] investigated also the effect of natural wind and anti-dust coating on the cleaning performance of electrostatic cleaning system, and it was found that the cleaning efficiency of the system has improved due to wind and coating. Further studies on the effect of anti-dust coatings [16] using Doha dust particles without application of voltage and at different inclination angles showed that adhesion forces were considerably reduced with the application of coatings. Kawamoto [16] developed a detachable electrostatic cleaning system to overcome the problem of shading the PV panel due the installed transparent electrodes, and an experiment was performed using Doha, Qatar, dust particles and a high voltage power supply. The result was nearly 100% cleaning efficiency at 1 g/m² of initial dust load which equals dust accumulation in three days. Kawamoto and Guo [18] further studied the effect of applied voltage and frequency on cleaning efficiency. It was found that they had no effect on cleaning performance at frequencies less than 10 Hz. However, at higher frequencies there was rapid cleaning rates till the process was limited by higher values of frequency because particles were unable to follow the high speed of polarity change [16]. Kawamoto [16] further conducted an experiment with high AC pulsed voltage with dust particles from solar panel installed in Doha (Qatar) and found a cleaning efficiency of 80% with no water spray and 65% with water spray. Sayyah [19] conducted an experiment for the cleaning of a dusty PV cell using an integrated EDS in an environmentally controlled test chamber. The results clearly showed that an EDS was able to restore the initial short-circuit current of the cell to more than 95% of its original value. Also, it was found that a higher applied voltage is needed to prevent dust coagulation at lower inclination angles of the solar panels. Sayyah et al.[20] conducted a number of experiments and examined how electrode width and inter-electrode spacing, and two operational parameters; namely applied voltage and relative humidity (RH) affect dust particle's charge. The charge on the dust particles was studied via charge-to-mass ratio measurements, which depends on the intensity of the electric field on the EDS surface. It was found that the charge-to-mass ratio decreases when the electrode width and the inter-electrode spacing is increased, consequently, it hinders the removal of dust particles. The decrease in the charge-to-mass ratio was attributed to the decrease in the electric field intensity on the EDS surface. Increasing the applied voltage on the EDS, results in increasing the electric field intensity, which subsequently increases the charge-to-mass ratio and improves the performance of the EDS, while, increasing the relative humidity lowers the charge-to-mass ratio. Guo [21] has applied a hydrophobic fluorinated SiO_2 nanoparticle coating on the EDS surface, and it was found that the coating showed an excellent durability property to water rinse and the dust-removal efficiency has been increased to 99%.

As can be seen from the literature survey, the electrostatic cleaning is a well-known technique for dust removal from the surface of soiled PV panels. Increasing the number of electrodes improves the cleanability of the system, but on the other hand, it could influence the amount of light reaching the PV cells, as well as the price of the system. In this study, the influence of installing the electrodes of the electrostatic cleaning system on the backside of a glass plate on the removal of dust is experimentally examined as a function of the glass plate thickness. The glass plate mimics a PV panel. The electrodes are sandwiched between the glass plate and a back cover of different materials including wood, glass or air (no cover). The distribution of the E-field above the glass plate depends on many factors such as electrodes configuration (shape, size and type) and properties of materials. However, to avoid any nonlinearities into calculations and any approximations that would be taken into consideration while calculating the E-field mathematically, it is decided to measure the electric field using an ultra-sensitive E-field optical sensor to get the actual data without any kind of approximations. The performed experiments are based on two techniques to measure the diffusivity of the electric field in a glass plate as a function of the glass plate thickness and the back cover material. The first technique utilizes an ultra-sensitive electric field sensor, based on the Whispering Gallery Modes (WGM) [22-24], to measure the diffusivity of electric field in the upper glass surface as a function of the back cover material. The developed experimental setup consists of a glass plate with a back cover plate from a material, which is the medium to be examined. Between the two plates, a couple of electrodes are installed as the source of electric field. In the first technique, the electric field above the glass plate is measured using a micro-optical sensor with a high resolution of 6.7 V/m and a sensitivity of 0.0344 pm/Vm-1; where the (pm) is representing the deformation of the cavity (Sensing Element) measured in pico-meter. The second technique is based on visual observation of the dust removal as a function of the excitation voltage. The excitation voltage is defined as the minimum voltage required mitigating the dust from the upper surface of the glass plate.

2. Experimental Setup, Procedure and Results

2.1. 1st Technique Based on the Whispering Gallery Modes

A schematic and a photograph of the opto-electronic setup that is used to measure the electric field above the glass surface of the PV panel due to an applied voltage at the back side of the panel as shown in Figs. 2 and 3, respectively. The setup consists of a sensing element fixed by an X-Y-Z micro-translational stage, to adjust the sensor position relative to the glass surface, i.e. the surface that mimics a PV panel. The glass surface together with the back cover are all installed in a plate holder, and the whole setup is mounted on an optical table to avoid any vibrations coming from the surrounding medium, as can be seen in Figs. 2.a and 3. The sensing element is a micro-optical sphere that is made from the polydimethylsiloxane (PDMS) following the same procedure that was reported in [22]. Details about the developed optical sensor could be found in [23-28]. The sensitivity of the optical sensor used is 0.0344 pm/Vm-1 and its resolution is 6.7 V/m with a high quality factor ~ 107. The average quality factor for the typical electrical transducers to measure the electric field is ~ 102, and for that reason, an optical sensor is used instead of the traditional electrical transducers. Consequently, the resolution of the sensor is sufficient to measure the applied electric field above the glass surface with an ultra-sensitivity. All experiments conducted were done using the same optical fiber and the same coupling angle of the light and the same position of the sensor, and that is for the sake of consistency and to compare the results under the same conditions.

A C-shape holder is used to fix the sensing element and to adjust its location on the top of the testing samples using the micro-translational stage, as can be seen in Fig. 2.b. The C-shape holder is mainly used to hold the optical fiber relative to the micro-optical sensor, in order to avoid any possible alteration during the performed experiments. The optical fiber is connected with the laser source to the photodiode, and it is mechanically coupled with the sensing element in the middle, as indicated in Fig. 3. The photodiode is used to measure the light intensity of the laser source after passing through the micro-optical sensor, as shown in Fig. 2.c. The measurements will be based on satisfying the optical resonance condition, which is also named as the Whispering Gallery optical Modes (WGM). The optical resonance occurs once the round trip of the light becomes equal to the multiple integers of the wavelength, λ, as follows [23]:

$$2\pi r n0 \approx m\lambda \qquad (1)$$

where, r, is the radius of the sensor, which is equal to ~ 475µm, n0 is the refraction index of the sensor, and m is the integer number which indicates the circumferential mode number. The nominal wavelength of the laser light that is used during the experiment is equal to 1314.6 nm. The Whispering Gallery Modes would be seen as sharp dips [24] on the transmission spectrum when the optical resonance condition is satisfied. And, due to the high optical quality factor of the sensing element [25,26], any minute change in the physical conditions of the surrounding, e.g. an applied electric field, can be detected with high resolution, which improves the feasibility and reliability of the electric field measurement during this research

2.1.1 Principle of measurement

The change in the sensor morphology due to the applied electric filed is the principle of measurement in this experiment. The change in the radius of the sensor, i.e. Δr, as indicated in Fig. 2.c, which is due to the applied electric field at the back side of the glass plate, is related to the strength of the applied electric filed [23,27,28]. Δr can be calculated by measuring the WGM shifts from the transmission spectrum [23,29].

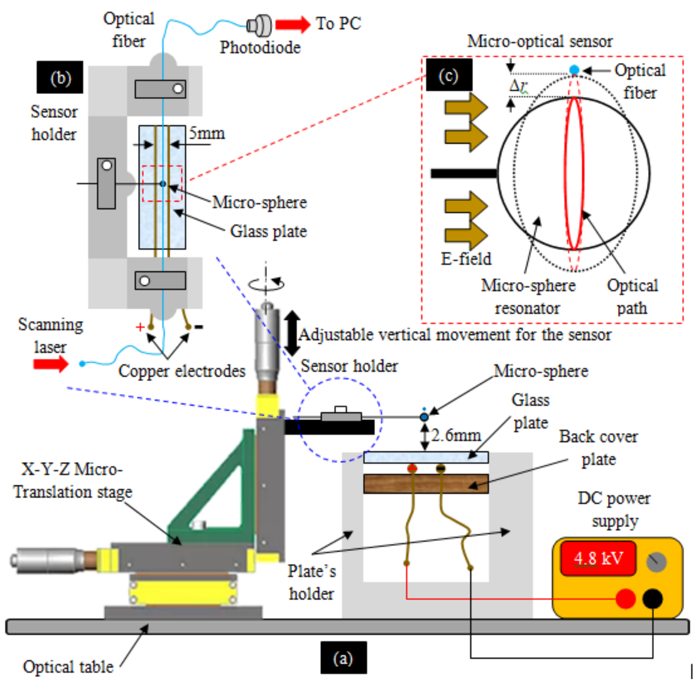

Fig. 2. A schematic of the experimental setup based on the Whispering Gallery Modes, where (a) is the X-Y-Z Micro-Translation stage, (b) is the sensor holder in the form of a C-shape and (c) is the micro-optical sensor.

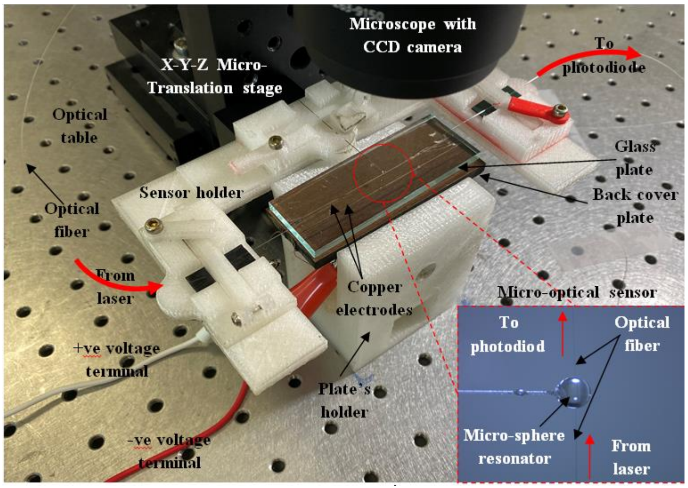

Fig. 3. A photograph of the experimental setup used to measure the electric field above a glass surface due to an applied voltage.

2.1.2 Experimental Results

The measured electric field above the surface of the glass plates as a function of the plate thickness and the back cover material is presented in Fig. 4. The electric field has been developed due to a couple of copper electrodes installed at the back side of the glass plate. The thickness of the glass plate varies between 1 mm, 2.4 mm, 3 mm and 4 mm. It can be concluded from Fig. 4 that as the glass thickness increases the transmitted electric field through the glass decreases, i.e. the resistance of the glass to the diffusion of the electric field is directly proportional to the glass plate thickness. The electric field above the glass surface in case of a wooden back cover is higher than that of a glass cover by ~ 2 times, and 3 time greater than that in case of no cover, as can be concluded from Fig. 4. Therefore, it can be concluded that the wooden back cover resists the diffusion of the electric field more than glass and air, such that most of the generated electric field is confined above the glass plate, where the WGM sensor can measure.

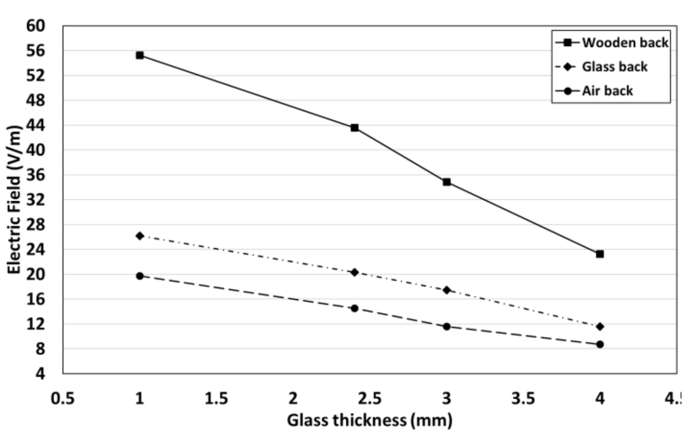

Fig. 4. The electric field above a glass surface as a function of the glass thickness and the back cover material; wood, glass and no cover, i.e. air.

The above experiment has been repeated using a PV panel instead of just a glass surface, in order to examine the applicability of such method on cleaning of PV panels. Two experiments have been performed as shown in Fig. 5. In the first experiment, a wooden back cover is used, while in the second experiment no cover is used. It has been found that the electric field at the top of the PV panel in case of using a wooden cover is 19.78 V/m, which is almost 3 times larger than in case of no cover, i.e. air. Again, it can be concluded that the wooden cover resists the propagation of the electric field and confines it at the upper surface of the PV panel. It is noted from Fig. 4 that the produced electric field above the glass surface of a thickness of 4 mm is 23.25 V/m, which is close to the produced electric field in case of a PV panel of thickness 4.5 mm, i.e. 19.78 V/m, as can be seen in Fig. 5.

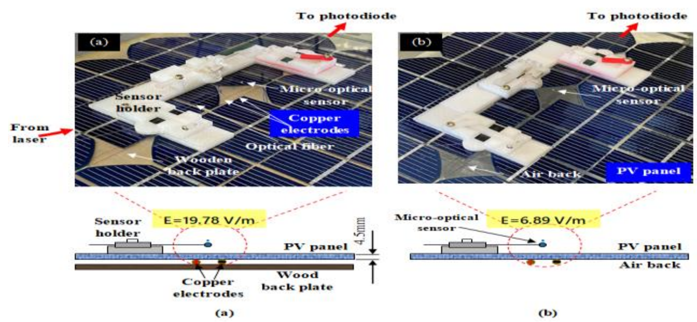

Fig. 5. The electric field above the glass surface of the PV panel as a function of the back cover material, i.e. (a) wood and (b) no cover, i.e. air.

2.2. 2nd Technique Based on measuring the excitation voltage.

2.2.1 Excitation voltage

The experimental setup used to study the removal of dust from a glass surface by electrodes that are attached to the backside of the plate is shown in Fig. 6. The experimental setup consists of a high voltage DC power supply model LEYBOLD 521721. The specifications of the power supply are suitable for the planned experiments such that the supply voltage can be varied from 0 kV up to 25 kV. The power supply is connected to the copper electrodes that have a diameter of 0.7 mm. The electrodes are attached to the back of the glass plate, upon which the dust particles are placed and a cover sheet is placed under the electrodes such that the electrodes are sandwiched between the glass and the back cover, as can be seen in Fig. 6. The dimensions of the glass plate are 4 cm × 12.5 cm and its thickness varies between 1 mm, 2.5 mm, 2.7 mm, 3 mm and 4 mm. The glass plate dimensions are similar to the geometry used in the literature to prove the applicability of EDS systems, e.g. Kawamoto and Guo [18] used a glass plate of dimensions 10 cm × 10 cm, while Guo et al. [30] used a glass plate of dimensions 3.4 cm × 2.8 cm to determine the cleaning efficiency of EDS systems. Semolina flour particles, of an average diameter of 0.5 mm with a standard deviation of + 0.2 mm, is used as dust particles. Semolina flour is selected as dust particles for clear visualization of the motion of the particles because of its white color. Also, it is an organic material that represents an important portion of the dust particles that deposit on the PV panels, which has not been studied before. The microscopic motion of semolina flour was observed with a digital microscope model ZEISS Axiolab 5, which is connected to a personal computer, as shown in Fig. 6. All the experiments, either using the optical sensor or the excitation voltage experiments, were all operated under the same illumination conditions.

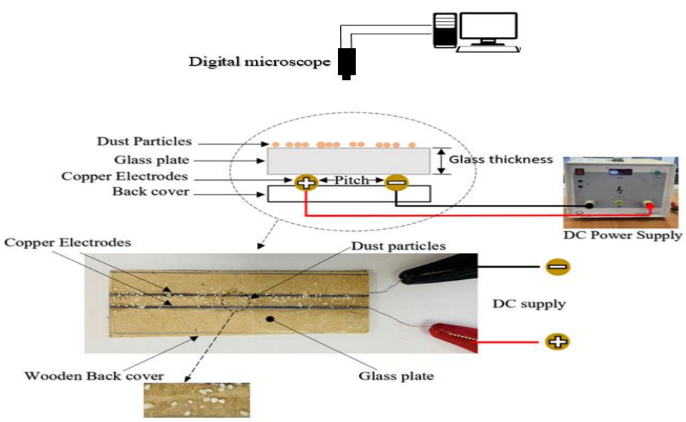

Fig. 6. A Schematic diagram of the experimental setup used for studying the removal of dust from the glass surface of PV panels by electrostatic forces.

2.2.2 Experimental Procedure

Two sets of experiments have been performed to categorize the parameters that influence the removal of dust from a glass surface by electrodes that are attached to the backside of the plate surface. During the performed experiments, dust particles were spread over the upper surface of the glass plate and the electrodes voltage was slowly increased step by step until the dust is repelled off the surface. However, it was noticed that there are two values of the voltage that are responsible for the motion of the particles, where the first value is responsible for the lateral vibration of the particles, while the second value is responsible for bouncing-off the particles from the glass surface, which is named the excitation voltage. In the first set of experiments, the excitation voltage, i.e. the voltage required to bounce off the particles from the glass surface, was measured as a function of the glass thickness, while in the second experiment the influence of the back cover material was examined. Three back cover materials have been examined, which are wood, glass and air.

2.2.3 Experimental Results

The influence of the glass plate thickness on the excitation voltage is presented in Fig. 7 as a function of the back cover material, i.e. wood, glass and air. The results show that it is possible to remove the dust from the upper surface of the glass plate using electrostatic fields generated by electrodes that are attached to the backside of the plate. It can be seen from Fig. 7 that as the thickness of the glass plate increases the required excitation voltage increases. This is because as the glass plate thickness increases the attenuation of the electric field by the glass material increases, because it is a function of the path that the electrical field travels inside the material, and in order to account for such an attenuation and get the same cleaning effect the required excitation voltage increases. The results of the performed experiments are in line with those of the previous set of experiments, also they are in line with the results of the conventional electrostatic cleaning systems, where the electrodes are installed on top of the PV panel glass surface and below a thin cover (screen). The screen is so thin with a thickness of 0.3 mm [15], in order to minimize the influence of the cover thickness on the applied excitation voltage. It was concluded from Figs. 4 and 5 that the produced electric field above the glass surface of a thickness of 4 mm is close to the produced electric field in case of a PV panel of thickness 4.5 mm. Therefore, if the dust particles can be bounced off the glass surface using a certain excitation voltage, it will also be possible to be bounced off in case of an actual PV panel at a similar excitation voltage. The excitation voltage is related to the bouncing of the dust particles off the PV panel and cleaning of the panel is related to the bouncing of the particles, therefore, the excitation voltage can be taken as a measure of cleaning, i.e. operating the electrode at a voltage higher than the excitation voltage will cause cleaning and vice versa. It can be concluded based on the results of the performed experiment shown in Fig. 7 that the electric field above the glass surface is inversely proportional to the thickness of the panel, consequently, the excitation voltage increases with thickness. Therefore, it is possible to remove deposited dust on the PV panel surface using such a technique, however, the cleaning efficiency of the proposed technique [30] as a function of the dust particle size and material is a point of further research.

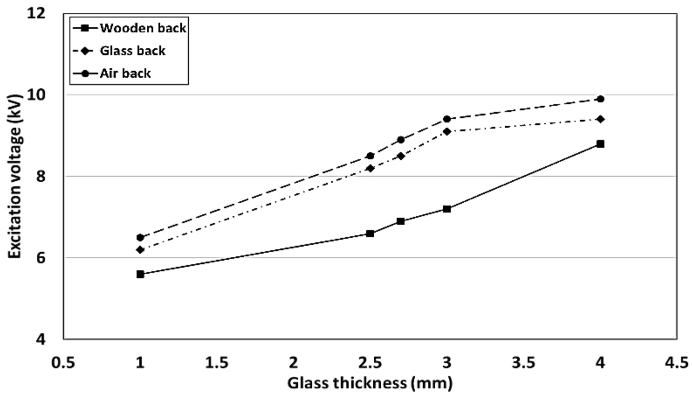

Fig. 7. Influence of glass thickness and the electrodes back cover material on the excitation voltage of the electrostatic cleaning system. The diameter of the electrodes is 0.16 mm and the pitch of the electrodes is 2 cm.

3. Discussion of Results

Adding a wooden cover, at the backside of the electrodes enhances the effect of electrostatic cleaning of PV panels in such a way that the excitation voltage required to bounce off dust particles from the PV surface becomes lower. The excitation voltage in case of using a glass plate as a back cover of the electrodes is higher than that in the case of a wooden back cover and it is the highest in the case of no back cover, i.e. air cover, as can be seen in Fig. 9. It can be assumed that the wooden cover blocks the electrostatic field to escape from the back side of the electrodes, such that it is confined in the upper side of the electrodes, while the glass and air are less obstructive than wood.

4. Conclusions

Experiments have been performed to study the parameters influencing the electrostatic cleaning of PV panels based on installing the electrodes of the cleaning system on the backside of the panel and not on the top. The influence of installing the electrodes on the backside of a glass plate on removing the dust from the front side is examined experimentally, as a function of the glass plate thickness and the material of the back cover of the electrodes. The materials used for the back cover of the electrodes are wood, glass and air, such that the electrodes are sandwiched between the glass plate and the cover. The glass plate mimics a PV panel. The experimental setup depends on two techniques to measure the diffusivity of the electric field on a glass plate and a PV panel as a function of the glass plate thickness and the back cover material. The first technique utilizes an ultra-sensitive electric field sensor based on the Whispering Gallery Modes (WGM), while the second technique is based on visual observation of the excitation voltage required to remove the dust from the glass surface. It can be concluded from the results of the performed experiments that,

1. As the thickness of the glass plate of PV panels increases the electric filed decreases and the required excitation voltage to remove dust increases.
2. Adding a wooden cover at the backside of the electrodes enhances the effect of electrostatic cleaning in such a way, that the electric filed increases and the excitation voltage required to bounce off the dust particles decreases.
3. The wooden cover blocks the electrostatic field in one direction, such that it is confined in the upper side of the electrodes, while the glass and air are less obstructive than wood.
4. Further research should be done to examine the influence of the inclination angle of PV panels, the size and material of dust particles on the required excitation voltage of the newly proposed cleaning system.
5. As a final conclusion, this study proved, for the first time, that it is possible to remove the dust from the upper surface of the PV panels using electrostatic fields generated by electrodes that are attached to the backside of the panel and using a back cover enhances the cleaning efficiency.

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