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Analysis of electrical behavior of PV arrays covered with nonuniform snow

S. Hosseini, S. Taheri ✉, E. Pouresmaeil and H. Taheri

Snowfall during cold months impacts the performance of photovoltaic (PV) installations. In real field operations, different ambient conditions often cause nonuniform snow accretion on PV panels. This can have a considerable effect on PV power production depending on array configuration, pattern of snow coverage, and bypass diodes included in a PV system. In this paper, the electrical behavior of snow-covered PV cells is experimentally characterized. Then, the true impact of nonuniform snow accretion on PV system performance is investigated. Effect of employing bypass diodes on a PV string power generation is also verified. Different PV array layouts are studied to improve the PV harvest efficiency in cold climate regions. This research may be regarded as a practical tool for the design and selection of PV modules subjected to snowfall.

Introduction: Photovoltaic (PV) systems have found different applications in cold areas for a long time such as remote research facilities in the South and North Pole, and space travelling. The majority of the PV energy plants are presently installed in geographical cold locations with a considerable amount of snowfall every year [1]. Furthermore, solar energy industry is expanding competitively in cold climate regions. For example, in Canada, the installed capacity of solar PV grew from 95 MW to more than 2500 MW during 2009-2016 [2]. PV panel efficiency is not only influenced by PV technology, but environmental conditions can also influence their energy production. Accumulation of snow/ice decreases solar radiation on the PV panels, which results in a significant loss. The issue of snowfall has been investigated by the researchers in PV area. This includes methods of removing snow from PV solar cell roofs, [3], monitoring PV installations power production to estimate the energy loss during cold months [4], and proposed models to predict the average monthly and annual snow loss based on meteorological parameters and tilt angle [5-7]. These studies basically obtain the energy loss due to snow by comparing the expected energy against the collected data from the PV system. However, they are not applicable to characterize a snow-covered PV array.

Nonuniform snow accretion on PV panels often occurs due to ambient conditions such as wind, temperature variation, partial snow shedding, and ground interference. This leads to power loss that is dependent on the configuration of the PV system. Due to the increasing deployment of PV systems, there is a significant interest in optimal utilization of PV potential in cold climate regions. The aim of this study lies on the fundamental need of knowledge of the impact of nonuniform snow accretion on PV systems. Electrical characteristics of snow-covered PV cells with different snow depths are studied. The impacts of different snow patterns, different array layouts, and bypass diodes are also investigated. The main contribution of the present work is to provide an applicable vision for investigating the effects of nonuniform snow on the electrical characteristics of PV modules. This study is helpful for PV system designers to take advantage of maximum potential of solar power in cold regions.

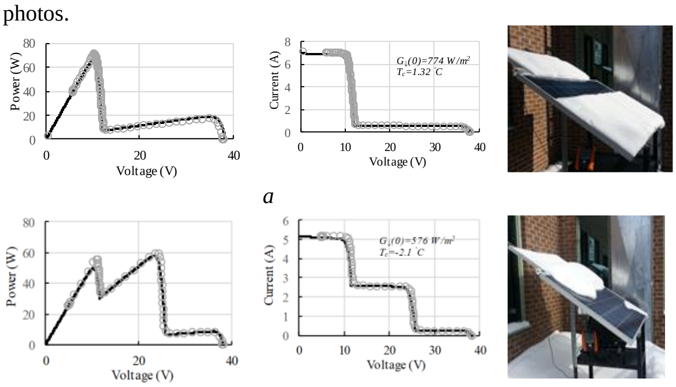
Evaluation of PV characteristics: This section evaluates the electrical characteristics of nonuniformly snow-covered PV modules. The outdoor tests were conducted using a PV module, CS6P-260P, manufactured by Canadian Solar. The electrical specifications under standard test conditions (STC) from the manufacturer are listed in Table 1. The PV module includes 60 series-connected polycrystalline cells in conjunction with three bypass diodes. The I-V and P-V graphs were measured utilizing HT Instruments I-V 400 PV Panel Analyzer and irradiance meter test kit. The module back sheet temperature was measured by a Fluke 62 Mini infrared thermometer.

Table 1: Electrical parameters of the CS6P-260P PV module

Peak power (STC)	260 W
Peak power voltage (STC)	30.4 V
Peak power current (STC)	8.54 A
Open circuit voltage (STC)	37.5 V
Short circuit current (STC)	9.12 A

The snow depths were measured with an electronic digital caliper. The snow densities were obtained using a digital scale. A millimeter-scale grid and a magnifying glass were used to estimate the grain size.

In the course of experiments, there were many sunny days where snow still existed on PV modules after a snowfall. A snow layer may melt or partially shed which causes nonuniform accumulation of snow on PV modules. Extensive outdoor experiments were conducted in cold months for different natural nonuniform snow patterns. Moreover, artificial nonuniform patterns were created by partly removing the snow coverage that help eliminate the problems related to randomness in the position of snow free areas. Fig. 1 shows the experimental I-V and P-V graphs for two nonuniform snow patterns as well as their associated photos.



a

b

Fig. 1 *Experimental P-V and I-V graphs under nonuniform snow accretion on the CS6P-260P PV panel (a) $G_{\downarrow}(0)$=774 W/m2; Tc=1.32 ºC, (b) $G_{\downarrow}(0)$=576 W/m2; Tc=-2.1 ºC.*

The PV characteristic becomes more complex, characterized by multiple peaks, due to the bypass diodes under nonuniform snow coverage. In the case of Fig. 1a, almost two third of the PV module is covered with a snow depth of 6.82 cm. Consequently, two peaks are created at 17.6 W and 71.4 W. In the case of Fig. 1b, two different snow depths of 7.53 cm and 1.7 cm partially cover the PV module. As a result, three peaks are produced at 8W, 59.4 W, and 55.4 W. Pattern of the snow coverage and snow depth influence the resulting PV characteristics exhibiting local maximum power points (MPPs) along with a global MPP. It is obvious from Fig. 1 that the difference between the local MPPs and the global MPP is noticeable, which indicates the importance of an appropriate maximum power point tracking (MPPT) controller to operate at the true global MPP in these situations.

Effect of bypass diodes: This subsection verifies the effect of bypass diodes on snow loss of a PV string. The PV string consists of four series-connected CS6P-260P PV panels, as shown in Fig. 2. Two scenarios of the PV string are developed with and without the bypass diodes. Snow accumulation at three different depths of 1 cm, 4 cm, and 7.5 cm is considered. The studies are carried out when each snow depth covers different areas of the PV string. Actually, it is assumed that the snow-covered area expands from the bottom cells of the leftmost PV panel.

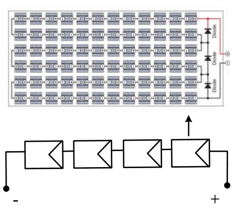


Fig. 2 *A PV string of four series-connected panels*

Fig. 3 shows the power loss due to nonuniform snow accretion versus snow-covered area with and without bypass diodes. The snow-covered area is normalized with respect to the total area of the PV string. The percentage of power loss is determined by comparing the global MPP of the snow-covered PV string against its expected MPP without snow cover in the same irradiance and temperature condition. The amount of power loss of a PV string without bypass diodes significantly increases as the snow depth increases. It can be seen that even a small area of snow accretion on the PV string without bypass diodes noticeably restricts its power generation. The PV string with bypass diodes generally experiences less power loss. The difference is more obvious for bigger snow depths and smaller snow-covered areas. In fact, the negative effects of nonuniform snow accretion could be greatly mitigated by utilizing the bypass diodes if the MPPT controller is capable of tracking the global MPP.

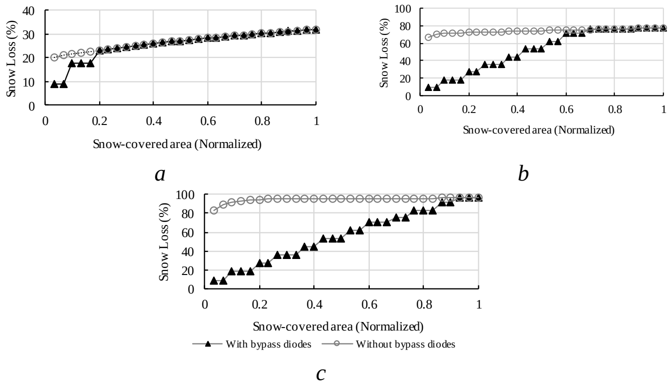


Fig. 3 *Power loss of a PV string due to different snow depths of (a) 1 cm, (b) 4 cm, and (c) 7.5 cm.*

Effect of PV Panels Layout: PV panels layout could affect the power loss due to snow. This is investigated by comparing the power loss of the PV panel when installed in landscape and portrait position, as shown in Fig. 4. The white rectangle on the PV panel demonstrates the snow-covered area variation. Fig. 5 shows the result of snow loss when a snow depth of 2 cm covers different areas of the PV panel starting from the bottom cells. Generally, the PV panel with landscape position experiences less power loss, especially for smaller snow-covered areas. This difference would be greater for higher snow depths.

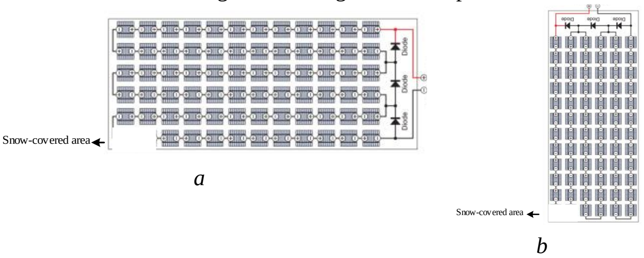


Fig. 4 *Snow-covered area change on PV panel in (a) landscape position, and (b) portrait position.*

The PV modules in an array can be electrically connected together in either a series, a parallel, or a mixture of the two, to yield the desired voltage and current level. In cold climate regions, PV arrays often experience nonuniform snow accretion. The output power of a PV array not only depends on ambient condition, but also depends on other factors such as the interconnection of the individual PV panels. Hence, the physical layout of PV modules mounting could also affect the PV power production. To study this effect, two PV arrays with horizontal and vertical layout, as shown in Fig. 6, were studied. Both PV arrays have the same series-parallel structure and include 12 identical PV modules. Investigations were conducted for a variety of snow depths starting from 1cm to 10 cm and different snow patterns on the PV panels. In fact, for each snow depth, different possible nonuniform patterns with different areas were examined. Table 2 shows the average snow loss for the two layouts based on different nonuniform snow patterns. The vertical PV array layout faces greater power loss due to nonuniform snow accretion. Hence, the horizontal PV array layout would more effective in snowy climates.

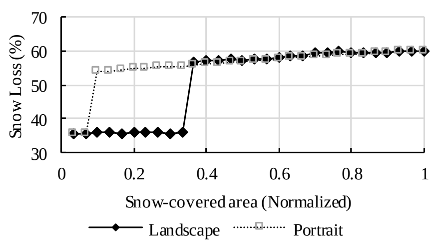


Fig. 5 *Power loss due to different snow-covered areas of a depth of 2 cm for landscape and portrait positioning.*

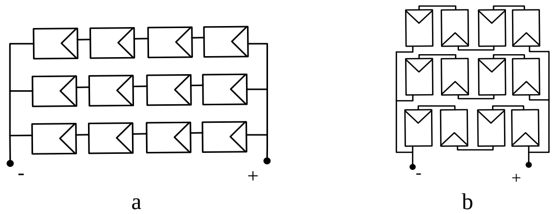


Fig. 6 *A PV array configuration with (a) horizontal layout, and (b) vertical layout.*

Table 2: Power loss for two PV array layouts

Layout	Horizontal	Vertical
Average power loss (%)	34%	48%

Conclusion: Outdoor measurements of a PV panel during cold months were used to evaluate the PV characteristics. Different investigations for verifying the effect of bypass diodes and different layouts have been carried out. The PV string without bypass diodes generally experiences more power loss. The vertical and horizontal PV array layouts were tested to determine power loss due to nonuniform snow accretion. The horizontal PV array layout would more effective in snowy climates. The snow-covered PV panels can still produce a significant amount of energy depending on the pattern and depth of the snow accumulation. The portion of this energy that could be collected is decided by configuration of the PV array as well as the MPPT technique. Hence, a proper design of a PV system considering the effect of snow accretion is essential to benefit from the solar energy potential in cold regions. This study is helpful for PV system performance assessment, MPPT development and testing, power generation prediction, and proper arrangement of panels in cold regions.

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