Feasibility Study of Snow Removal from PV Module Using Universal Power Electronic Interface

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***Abstract*—The green and sustainable nature of photovoltaic (PV) energy and falling PV module prices make this technology relevant and economically viable. However, the placement of PV panels may have numerous challenges. One of the challenges is managing snow accumulation on the PV panels, which reduces power generation and causes mechanical stress on the PV panel structure. Removal of snowfall is a cumbersome and recurring task. This work experimented with the heating of the PV panel by utilizing the basic diode nature of PV panels. In this work, the dc-dc converter is modified at the control level to achieve the functionality of ingfeed power back to the PV panel for snow melting. An experimental setup with a 350 W dc-dc converter connected to an individual PV module is tested to assess the feasibility of the snow melting process by feeding power back to a PV module. Furthermore, this approach may be a practical and affordable alternative for dummy loads, which are necessary in certain settings, such as islanded DC microgrids.**

Keywords—photo voltaic system, self-heating, snow removal, universal power electronic interface converter

I. Introduction

The climate crisis has developed due to the rapid growth in population and its associated energy demand, which can be mitigated by the meticulous deployment of renewable energy resources. Our sun has a tremendous amount of energy, of which around 44 quadrillion watts of average power are received by Earth annually [1]. So, photovoltaic (PV) systems have become the most prevalent and sustainable technological means of harvesting solar energy [2]-[4]. The current PV industry is gradually progressing in terms of PV module efficiency and cost. However, the most common external factors affecting solar power generation, such as sand, fog, clouds, and temperature, are frequently ignored. Snowfall is a critical factor, reducing PV energy generation by up to 34% annually, particularly in high-altitude or near-polar areas [5].

The industry has adopted passive and active prevention methods to remove the snow from PV panels. One common method is to heat the entire panel using a heater placed between the back of the panel and the insulation sheet [6]. Some literature reported the usage of hydrophobic coatings that are repellent to ice and snow. However, these coatings were unreliable and did not work well in the long term [7]. So, finding a method that can be practiced reliably in the long term was necessary. In [8], melting, shedding, and their aspects were analyzed. It was concluded that using both coatings and heating panels for melting and shedding snow is necessary to achieve the optimal solution.

Passive mitigations are considered the default, minimal solutions to snow accumulation. Active mitigation of snow solutions can be achieved using self-heating with conduction losses. This is possible due to the diode nature of PV cells, which can conduct current in the forward direction with some voltage drop [9]. Apart from snow removal applications, the self-heating of PV panels can be considered an alternative to dummy loads in DC microgrids without battery energy storage [10], [11].

The consideration of dummy loads for the dissipation of instantaneous excessive power in a microgrid can help its stability [12]. However, incorporating dedicated resistive dummy loads necessitates extra space and increases capital costs [13], [14]. This work emphasizes the self-heating phenomenon using a universal power electronic interface (UPEI) presented in [15]. In earlier reports, the UPEI has been applied to residential PV module and low-voltage battery energy storage applications. This work explores the feasibility of using the UPEI to feed power back to the PV modules, employing its bidirectional nature. This paper aims to investigate the feasibility of snow removal utilizing the self-heating phenomenon of PV modules. The proposed concept is described in Section II, along with the self-heating phenomenon, its influencing factors, the use of the UPEI converter, and modifications to its control diagram for self-heating. Furthermore, the experimental study and discussion are presented in Section III. Finally, the results obtained have been analyzed, and the paper has been concluded.

II. Proposed Concept

A. Self-heating phenomenon in PV module

The p-n junction is fundamental to photovoltaic cell structures [16]. Applying a sufficiently high positive voltage to a PV module covered with snow generates heat due to the parasitic resistance and forward voltage drop of the PV cells, melting the snow at the surface. The melted snow creates a water layer that facilitates snow sliding, enabling efficient snow removal. The proposed concept of snow removal is depicted in Fig. 1. Each UPEI is connected to an individual PV module, where individual PV cells are connected in series or series-parallel configuration (half-cut solar cell technology). The used UPEI is fundamentally a bidirectional dc-dc converter, which allows us to harness its capability to feed power back. Its input voltage range of 10-60 V defines compatibility with PV modules of no more than 66 cells.

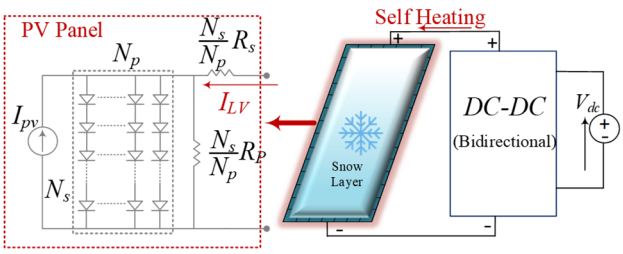

Fig. 1. Concept of self-heating method of snow removal from PV module.

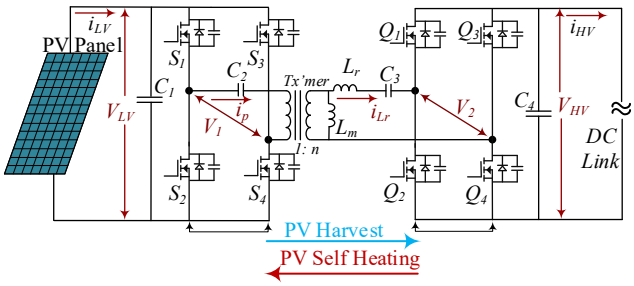

Fig. 2. The topology of a universal power electronic interface under study.

B. Snow Melting Process for PV Modules

1) *The Equivalent Height* (*EH*): Snow melting on PV modules is a phase-changing phenomenon. Snow acts as a porous material, allowing water to move upward through capillary action. As a result, the snow near the module became soaked with water, while the top layer remained dry. The combination of gravity and capillary effect causes snow slush to reach its maximum height, known as the equivalent height (EH) [17]. After getting energized, the module begins to heat up and melts the dry snow that is sticking to it. It is observed in [10] that if the snow coverage thickness, *H*, exceeds the *EH*, snow slush will form on the lower layer, with a maximum thickness equal to the *EH* and an upper layer of dry snow. If *H* is smaller than *EH*, heating the module will result in a snow slush on the entire PV module. Hence, the thickness of the snow is the key factor influencing the self-heating process.

2) *Melting Phases of the Snow*: For ease of understanding, this melting process is characterized into two phases. In the first phase, the snow is about to melt. The moment when the PV module received input power to the instance when the snow on the surface began melting. A thermal equilibrium is established between the PV module, the snow, and the surrounding environment, resulting in temperatures equal to those of the ambient air. During this period, the module's surface temperature increased but remained below 0°C, keeping the snow layer dry.

The second phase is the melting process. During this phase, the module's surface temperature reached 0 degrees Celsius. But the snow melts only at temperatures above 0°C. During the melting process, the snow absorbs heat, causing the surface temperature to drop below 0°C and remain there until the snow is removed. The surface temperature at the end of the first phase reaches the peak value. During this phase, the dry snow on the PV module transforms into slush upon contact with the surface. The thickness of dry snow gradually decreased until the snow slush reached the *EH*. The resulting snow slush acted as a lubricant between the snowpack and the PV module, causing it to slip off the inclined surface.

C. Factors Influencing Snow Removal Using the Self-Heating Method

The heating of PV modules serves as a trigger point to melt the snow, but other factors also influence the melting process, either directly or indirectly. These factors are described as:

1) *Snow Layer Thickness*: Since the snow can be treated as a porous material. Therefore, the layer of snow on top of the PV module serves as an insulating material. Hence, the thickness of the insulating layer of snow directly influences the melting process of snow.
2) *Ambient Temperature*: The ambient air temperature has a significant impact on convection heat transfer between the upper surface of the snow coverage and the air, as well as between the rear surface of the module and the surrounding environment. The ambient air temperature affects the heat exchange of the PV module, influencing heat transfer during snowmelt and the effectiveness of snow removal.
3) *Input Power*: The PV module uses electricity to melt snow and heat the surrounding area of the module. The quantity of energy input to the system has a significant impact on snow removal time. The input power per square meter (W/m^2), therefore, defines the rate of the snow melting process.
4) Tilt angle of PV mdoule: Self-heating PV modules remove snow by heating and melting it into water. The slush worked as a lubricant, allowing the snow to slide down and be removed from the surface. The larger the tilt, the easier it is for snow to slide down the surface. To enhance snow removal efficacy and power generation efficiency, the tilts should be tuned for each location based on latitude.

D. Universal Power Electronic Interface Converter

Prior studies in the self-heating process of snow removal used a distinct auxiliary power supply connected to a PV module, bypassing the PV converter [9]. However, this work employs a UPEI converter from [15] for self-heating of the PV module. This technology provides software-defined functionalities, including reverse power flow, as shown in Fig. 1. The dc-dc converter is fundamentally a series resonant based dual active bridge topology, which is shown in Fig. 2 and rated for 350 W. It features a very wide input voltage range of 10 V to 60 V, which can be interfaced with 350±30 V residential dc microgrids due to its flexible topology morphing control. It can feed constant current back to a PV module to realize PV module self-heating with conduction losses. Since the passive characteristics of the PV module define a threshold voltage above which the self-heating phenomenon starts working [9]. In this case, the converter is more likely to operate in a zone where the voltage and current are higher than those in typical PV operation. The threshold voltage also defines the operating mode of the converter. Which could be decided from the gain curve of the converter in reverse power flow. Fig. 3 represents the gain versus duty cycle curve for

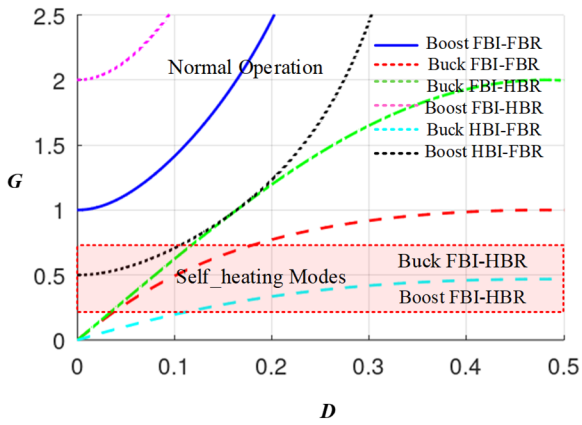

Fig. 3. Gain versus duty cycle curve for different modes during normal and self-heating operation of the UPEI converter.

normal operation for PV harvesting, as well as distinguishing between modes during snow melting operation, since the converter will operate in reverse power flow with different gain settings. The minimum value of V_{LV} in self-heating mode is determined by the passive characteristics of the PV module, as shown in Fig. 7. It is based on the threshold voltage, which is approximately 41 V for 60-cell Si PV modules. This value dictates the required converter gain and operating mode of the converter. It also ensures that the converter operates in the FBI-HBR configuration, with either buck or boost mode, depending on the required gain. The operating gain range is around (0.45-0.75), which is calculated using the following relation of gain G with bus voltage V_{HV} and PV voltage V_{LV} and turn ratio n of the transformer.

$$G = {V_{HV}}/{(n.V_{LV})} \qquad (1)$$

A basic PI controller has been used to regulate the duty cycle that defines the converter gain. A simplified version of the control is shown in Fig. 4, where normal operation mode (PV harvesting) is not described in detail, as it is outside the scope of this work. Therefore, only current-based control is described for the understanding of the self-heating mode. It employs a self-heating control block, which serves as either an input or a sensor-based input, determining whether to switch from PV harvesting to self-heating operation.

Furthermore, the simulation results shown in Fig. 5 were obtained for the reverse power flow in the converter, as depicted in the circuit of Fig. 2, under the conditions listed in Table I. Both boost (Fig. 5(a)) and buck (Fig. 5(b)) modes are tested for the 7 A constant current (I_{LV}), which is fed back to PV module. Here, V_1 and V_2 represent the output voltages of the H bridges, V_{C3} is the voltage across the resonant capacitor C_3, and the resonant inductor current is I_{Lr}.

III. Experimental Verification and Discussion

As the UPEI converter can control bidirectional current flow, it is essential to verify that it can accommodate snow-melting applications within its input voltage range. Snow accumulation on the PV module surface requires a special detection algorithm that triggers the snow-melting routine, which is outside the scope of this paper.

TABLE I. Key Parameters of the DC-DC Converter

Parameter	Label	Value
Input voltage range	V_{LV}	10-60 V
Maximum PV current	I_{LV}	±12 A
Maximum DC link current	I_{HV}	±1.1 A
DC link voltage	V_{HV}	320-380V
Switching frequency	f_s	100 kHz
Turn ratio	n	12.8

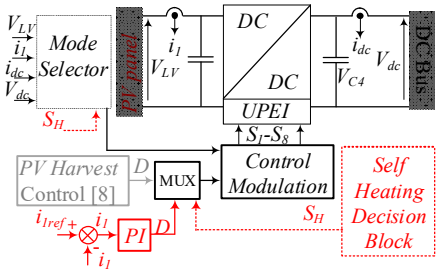

Fig. 4. Simplified control for self-heating of PV panel.

As this study considers droop-controlled dc microgrids, different droop control curves can be defined. Based on the Current/OS set of rules, three curves were synthesized and plotted in Fig. 7. In the normal (PV harvesting) mode, the power must be curtailed gradually if the dc bus voltage exceeds a certain threshold (370 V in this case). In contrast, snow-melting mode can be engaged when the dc bus voltage exceeds a minimum allowed operating voltage (for example, 325 V). Moreover, the dummy load mode can complement the power curtailment in the normal mode. In such a case, power is fed back to a PV module gradually after the power generation is curtailed to zero. This enables the stabilization of dc microgrid operation during abnormal conditions.

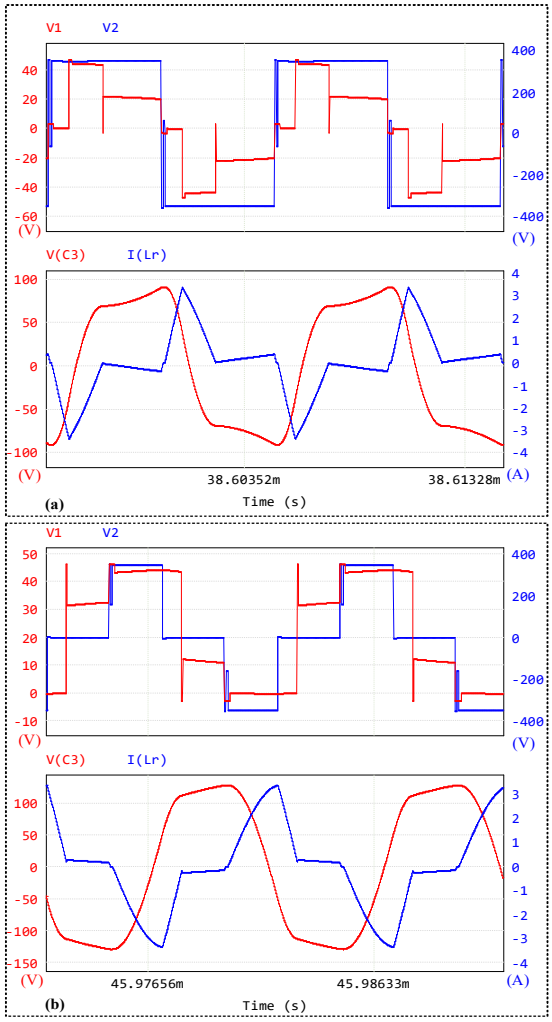

Fig. 5. Simulation waveforms for reverse power flow with 7 A constant current in (a) boost mode and (b) buck mode.

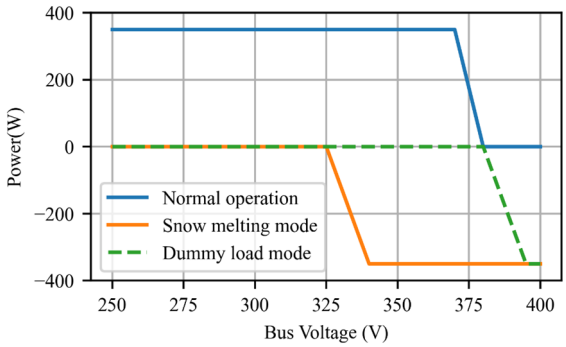

Fig. 6. Curtailment curves for PV harvest and snow melting operations.

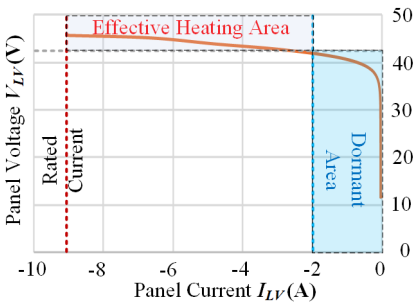

Fig. 7. Measured volt-ampere characteristics of 400 W 60-cell monocrystalline Si PV module at the ambient temperature of -5 ˚C.

A. *Case Study for Snow Melting Process*

This study considers typical residential 60-cell monocrystalline Si PV modules RIS-400MHC-FB with a nameplate power of 400 W. Under the test conditions, PV modules were covered with a 2-4 cm snow layer at an ambient temperature of around -5 to -3˚C. The direct solar irradiance ranged from 170 to 290 W/m².

First, the volt-ampere characteristics of the PV module was measured experimentally before melting the snow. The experimental passive characteristics plotted in Fig. 7, distinguished the effective and dormant (insignificant heating) areas. After turning on the converter, the snow started melting within 10 minutes of applying the reverse power. It took around two and a half hours to completely remove the snow. Still, the total removal of snow depends on several factors, including the inclination angle of the panel, ambient temperature, and snow thickness. In this case, approximately a 2 cm layer of snow was fully removed from the panel within the first 90 minutes, as shown in Fig. 8(a). The effective panel area appears to be cleared in the first 55 minutes, as shown in Fig. 8(b), and remains so for the next half hour, as shown in Fig. 8(c). The melting time generally depends on the external temperature and the width of the snow layer to be shed.

B. *DC-DC Converter Waveforms*

The waveforms of the converter during the self-heating of the PV panels with the specified parameters are presented in Fig. 10 for an operation of 7 A. While the voltage was in the range of 43 V to 46 V, it is evident that the UPEI can perform snow melting with 60-cell Si PV modules within this range. Additionally, it can be assumed that it is also compatible with snow melting on 72-cell PV modules based on the same PV

Fig. 8. Snow melting instances and time taken by the PV module after applying the self-heating method at an ambient temperature of -5 ˚C: (a) initial conditions, (b) after 55 min, and (c) after 90 min.

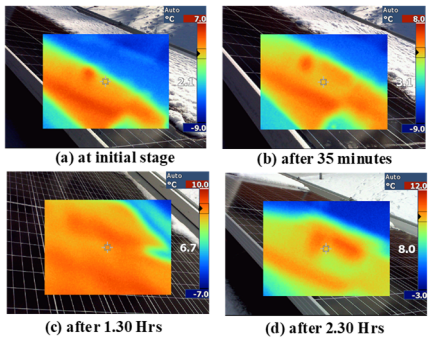

Fig. 9. Thermal imaging during heat up with 7A constant current at an ambient temperature of -5 ˚C .

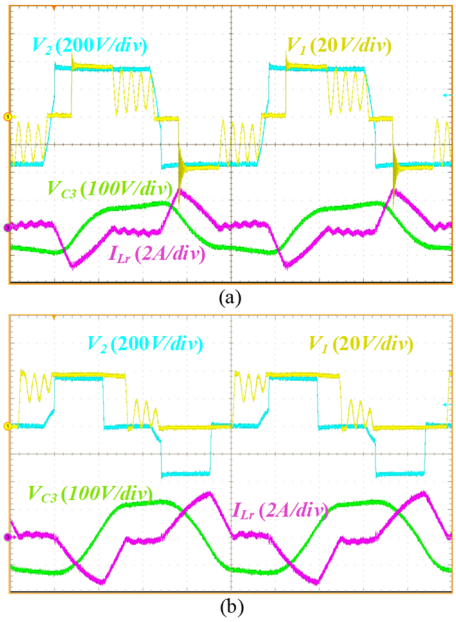

Fig. 10. Converter waveforms during reverse power flow with 7 A: (a) in the boost mode and (b) in the buck mode.

technology, which operates at 20% higher voltage and power levels. The thermal images shown in Fig. 9 and UPEI waveforms in Fig. 10 validate that the operation of UPEI during self-heating is feasible and safe to practice. It can be stated that the thermal modes during the self-heating of the PV module are also within the allowed range.

C. *Possible Scalability of the Analyzed Concept*

The operating voltage of PV modules is higher in snow-melting mode than in PV energy generation mode. Therefore, the converter, which is rated for the PV module's nameplate power, cannot operate at the rated current of the PV module. Current derating is needed to limit the operating power of the dc-dc converter. The proposed concept eliminates the need for manual labor and associated travel expenses, as well as auxiliary power supplies for heating and mechanical or robotic methods for snow removal. Hence, it reduces the maintenance costs and efforts associated with a PV system. The following points can be additional aspects of this concept:

1) Some liquid water content (LWC) sensors [8] and embedded temperature sensors, as well as weather forecasting, can provide additional advantages to automating self-heating for PV modules. The heating system can operate optimally based on the upcoming weather. Hence, the energy

can be optimally invested in heating the PV panels to remove snow only before prolonged clear sky conditions. Using an energy management system (EMS) to automate the process based on sensor feedback and forecasts can be a viable solution. EMS can predict upcoming sunny days when snowmelt can be justifiable in terms of predicted energy generation.

2) PV modules, designed to handle their rated current, can tolerate reverse power flow at lower magnitudes without damage. The self-heating effect enables PV modules to serve as dynamic braking or dummy loads in dc microgrids, particularly during transient or abnormal conditions. In systems using droop control, overvoltage scenarios may require dissipating surplus energy. Leveraging the PV converter for this purpose eliminates the need for dedicated dumping resistors and associated converter(s), simplifying system design.

IV. Conclusion

This study demonstrated the feasibility of utilizing the inherent diode nature of PV cells for self-heating by reversing the power flow, thereby enabling snow melting directly on the module surface. In addition to electrical heating, snow shedding is aided by the panel's tilt and the weight of the snow itself. Experimental results showed that feeding up to 350 W into the PV module at a 15° tilt effectively melted a 2 cm snow layer within 55 minutes. This was achieved with minimal modification to the converter, allowing it to operate in reverse power mode within the rated power range. The proposed approach offers a cost-effective alternative to manual snow removal or dedicated heating systems, reducing maintenance requirements. Furthermore, the self-heating capability can serve a dual purpose by acting as a dump load during transient overvoltage conditions in dc microgrids, enhancing system resilience beyond snow removal.

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