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Grid-connected PV system's voltage stabilisation using model predictive control based MPPT during abrupt changes in irradiance.

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***Abstract*— Voltage fluctuations or disturbances caused by discontinuous power generation of photovoltaic systems can impact the grid's power quality and stability, potentially leading to disruptions or equipment damage. A stable and regulated output voltage is necessary for increasing the penetration of photovoltaic systems in the grid. For photovoltaic systems connected to the grid with a boost DC/DC converter, the output DC voltage can be adjusted using a model predictive controller to meet the desired setpoints of the control of the DC/AC stage. Maximum power point tracking techniques also play an essential role in system stability and have to be coordinated with the control of both converters. This paper presents the development of a proposed model-based predictive controller for the maximum power point tracking algorithm in order to improve voltage stability of the DC/AC controller for any weather condition. The proposed maximum power point tracking based on model predictive controller has been compared with a modified perturb and observe algorithm using numerical simulations in MATLAB/Simulink environment. The results show that MPC based MPPT algorithm provides more smooth voltage to inverter as compared to modified P&O based MPPT algorithms.**

Keywords—Photovoltaic systems, maximum power point tracking, model predictive controller.

I. Introduction

Photovoltaic (PV) systems have gained significant attention for the generation of renewable power due to the recent advances of new materials increasing the power density and conversion efficiency. However, the amount of electricity produced by PV systems is highly dependent on weather conditions and on the adopted control method. Photovoltaic power generation can be maximised using maximum power point tracking (MPPT) control approaches [1].

The technical literature has reported several MPPT algorithms for PV systems [2]. The most popular algorithm is the perturb and observe (P&O) because of its simplicity of implementation. The main disadvantage of the P&O technique is the substantial power oscillation at steady-state and the poor tracking of the maximum power point (MPP) under rapidly changing irradiance. In this regard, numerous modified P&O algorithms have been documented. A modified P&O algorithm with reference voltage perturbation was presented in [3] in order to optimise the power generated by a PV system under both slowly and quickly variations in the weather conditions. A direct duty ratio perturbation of the DC/DC converter was used to evaluate the power variation, and then the duty-ratio variation adjusted the operating point of the PV system to maintain maximum power extraction by either increasing or decreasing the duty cycle based on the power variation observed. This direct perturbation ensured accurate tracking of the MPP by continuously aligning the duty ratio with the optimal power point. In [4], a variable step size P&O algorithm has been proposed to reduces power oscillation and speeds up MPP tracking, by linking the step size to the voltage derivative.

A modified P&O algorithm with an efficient PID controller controlled by genetic algorithms was proposed in [5], which was based to adapt the step size to the weather conditions. The variable step size showed decreased power oscillations at steady-state while the correct direction of MPP tracking was obtained by a preset list of instructions that continuously measure the PV array's current voltage and power and compare the current power with the previous power to determine the direction of MPP. A modified P&O algorithm that prevents drift in the event of an abrupt increase in irradiation level allowing the system to stabilize before resuming MPP tracking. This is achieved by monitoring the rate of change in power (dP/dt) and adapting the step size accordingly has been presented in [6].

While MPPT algorithms focusses on the maximisation of the power generated, grid-connected PV systems must be also controlled to reduce voltage disturbances to the grid for variable weather conditions while operating at optimal performance. In fact, the boost DC/DC converter of a PV system may introduce voltage oscillations of the DC output that can create instability of the DC/AC converter controller and, in some cases, also grid voltage instability [7]. The boost converter's non-minimum phase characteristic may make it challenging to establish a reliable and stable control for the output voltage for all irradiance and temperature conditions [8]. This may have an impact on the PV system's transient and steady-state performance, resulting in inadequate regulation and tracking mistakes [9]. Therefore, it is crucial to ensure the stabilization of the output voltage of the DC/DC converter at any weather condition.

Several methodologies have been proposed to mitigate voltage stability problems of PV systems. Some of the proposed solution focusses on the compensation of the voltage variation caused by PV system at grid's level, while others look directly at the control of individual converters connected to each PV system.

Compensation at grid's level has been proposed with a local static synchronous compensator (D-Statcom) in conjunction with a dynamic voltage restorer (DVR). This solution regulates the grid's frequency and voltage providing reactive power support and voltage correction, respectively. This ensures stability and power quality by dynamically compensating for voltage sags and harmonics in the grid. Another control method is based on the estimation of the virtual impedance, this impedance is not a physical component but a calculated parameter used to inject reactive current, thereby stabilizing the local grid bus voltage by counteracting voltage drops and disturbances dynamically [10].

Several methods have focussed on individual PV systems. One technique applied to PV systems with string inverters involves the use of a perturb and observe (P&O) technique for maximum power point tracking (MPPT) combined with a DVR, which effectively reduces the boost converter output voltage fluctuations caused by variation of the weather conditions. If the power has increased, continue perturbing in the same direction, and if the power has decreased, reverse the perturbation direction. This process helps the system to converge towards the maximum power point despite variations in environmental conditions like irradiance and temperature [11].

This paper proposes that when snow covers the PV panel, the modified P&O algorithm detects a flat power curve and fails to find the accurate MPP, leading to inefficiencies, or during sudden change in the irradiance due to uncertain circumstances then modified P&O MPPT is not working properly. In contrast, MPC-based MPPT can identify the global MPP despite such conditions due to its fast switching, ensuring efficient system operation. This approach provides a constant and smooth voltage not varying more than 10 % of the desired voltage to the DQ control based three-phase inverter, optimizing overall performance of the Grid.

Figure 1 shows the block diagram of a grid connected PV system using MP&O algorithms for MPPT.

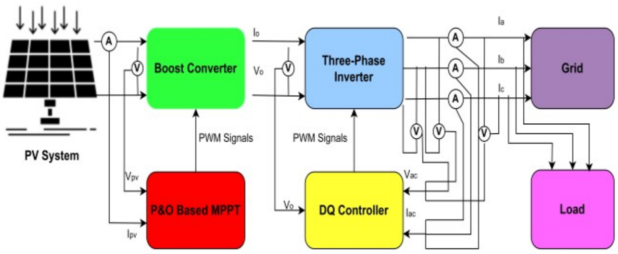

Fig. 1. Block diagram of benchmarked technique

II. MODEL PREDICTIVE CONTROLLER

Model Predictive Control (MPC) is a control strategy that uses a model of the system to optimize future system behaviour by computing the applied input by minimising a cost function obtained from equation 3 and 4. The previous and the predicted current values could be measure using the following equations:

$$I_{L0} = I_L + \frac{T_S}{L}(V_{PV} - V_0) \quad (1)$$

$$I_{L1} = I_L + \frac{T_S}{L}V_{PV} \quad (2)$$

where I_L is the inductor current, I_{L0} is the inductor current at the start of the inductor charging time, I_{L1} is the inductor current at the end of the inductor charging time, T_s is the sampling time, L is the inductor's inductance, V_{PV} is the PV voltage, V_0 is the dc-bus voltage.

The cost function is used to measure the absolute error with respect to the previous and new predicted value of the current as given by these equations:

$$G_0 = |I_{L0} - I| \quad (3)$$

$$G_1 = |I_{L1} - I| \quad (4)$$

where I is the reference current.

In MPC based MPPT technique, the switching state that has the minimum absolute difference with respect to the reference current will be selected. The basic principle of MPC involves solving an optimization problem at each time step to determine the optimal control action. The optimization problem can be decomposed into an unconstrained optimization problem and a constrained optimization problem, where the unconstrained problem has the familiar solution of Linear Quadratic Regulator (LQR) for linear systems with quadratic cost. This decomposition allows for the separation of constraints and the application of MPC to penalize only the control input [12], [13].

The MPC strategy improves the dynamic performance and robustness of the PV system by dividing the perturbing step into large and small step sizes and using the changing value of PV output power to modify the reference current [14]. The block diagram of the MPC for the control of the PV current is shown in Figure 2.

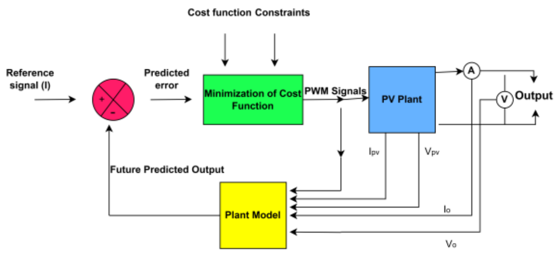

Fig. 2. Model Predictive Control Block Model

III. PROPOSED MODIFIED MPPT ALGORITHM

The proposed MPC has the objective to ensure a quick and effective MPPT as well as constant output voltage of the DC link even for rapidly changing weather conditions. The control is based on the selection of switching states of the converter which yields the highest possible power extraction from the PV arrays [15]. Boost converter have been designed using equations 5-10 for proposed method.

$$D = 1-(V_{mpp}/V_o) \quad (5)$$

$$P_{max} = I_L * V_{mpp} \quad (6)$$

$$I_L = P_{max} / V_{mpp} \quad (7)$$

$$I_o = P_{max}/V_o \quad (8)$$

$$L_c >= (V_{mpp}*D)/ (f_s * \Delta I_L) \quad (9)$$

$$C_o >= (I_o * D)/(f_s*\Delta V_o*V_o) \quad (10)$$

Input Capacitor is in the range of 1800μF to 3500μF.

Additionally, the use of MPC in conjunction with a DQ controller of the DC/AC converter reduces tracking errors [16].

The modified perturb and observe (P&O) control provides the reference for the MPC algorithm [14]. The MPC algorithm then uses a cost function design to obtain the optimal switching signals for the boost converter as shown in Figure 3 without the need of using a modulator [17]. This method provides faster response compared to traditional MPC methods, as demonstrated through testing under different weather conditions [18]. Both techniques have been implemented in MATLAB/Simulink at different weather conditions for the PV system specified in Table 1. The proposed technique has been compared with modified P&O based MPPT used as a benchmark.

Table 1. Specification of the Grid connected PV system

Parameters	Portion	Benchmarked Technique
Maximum power (PV panel)		300 W
Maximum PV system power	PV system	4,500 W
MPP current (PV panel)		8.37 A
Short circuit current (PV panel)		8.93 A
MPP voltage (PV panel)		35.8 V
Open circuit voltage (PV panel)		44.5 V
Input capacitor	Boost converter	2,000 μF
Output capacitor		1,800 μF
Boost inductor		2.0 mH
Bus voltage	Grid	400 Vrms
Bus frequency		50 Hz

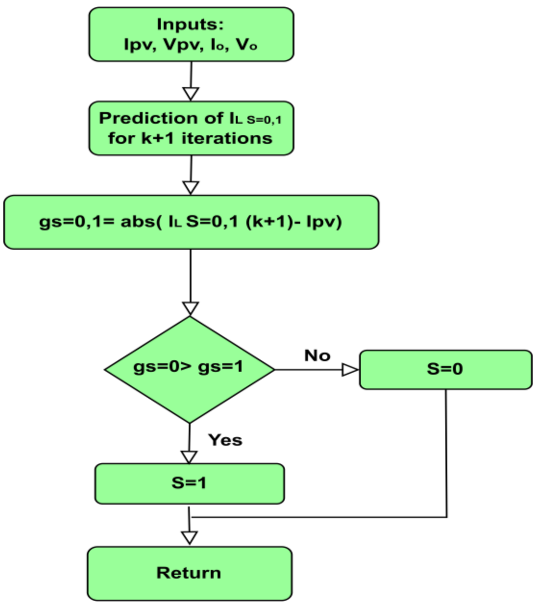

Fig. 3. *Flow chart of Model Predictive Control*

IV. DQ CONTROLLER

A DQ controller is used for synchronizing and injecting photovoltaic power to the three-phase grid [19]. The DQ controller allows for better control of power injection to the three-phase grid, which is crucial for addressing power quality issues in grid-connected PV installations. The boost converter is responsible for increasing the output voltage of the PV system, and any variation in its output voltage can impact the stability of the system. If the boost converter's output voltage is not constant due to changing weather conditions, it can lead to fluctuations of the DC-link voltage, affecting the performance of the DQ controller. Therefore, it is important to ensure that the boost converter maintains a constant output voltage with a maximum tolerance of 10% to enable the DQ controller to function smoothly [20], [21].

The MPC based MPPT approach provides a constant and smooth voltage not varying more than 10 % of the desired voltage to the DQ control based three-phase inverter, optimizing overall performance of the Grid.

V. SIMULATION & RESULTS

The proposed PV system has been analysed for 3 different weather conditions. Figures 5, 7 and 9 shows the irradiation pattern that is employed in the analysis at temperatures of 0 ºC, –5 ºC and -10 ºC respectively. Both irradiation variation and temperature values have been chosen to represent typical winter conditions in the UK. It is incorporated an irregular irradiance pattern by modifying data sourced from an irradiance platform in the UK. This adaptation aimed to reflect the dynamic fluctuations in irradiance caused by various factors such as sudden changes in weather conditions, including the emergence of black clouds over the photovoltaic (PV) panel, obstruction of sunlight by someone, or the sudden presence or removal of snow covering the PV panel. By integrating these uncertainties into the irradiance data, the aim is to provide a more realistic representation of the challenges and variability encountered in Grid-connected PV systems. Figure 6, 8 and 10 shows the boost converter's input/output voltage, power and current waveforms obtained from the benchmarked technique and those from the proposed MPC.

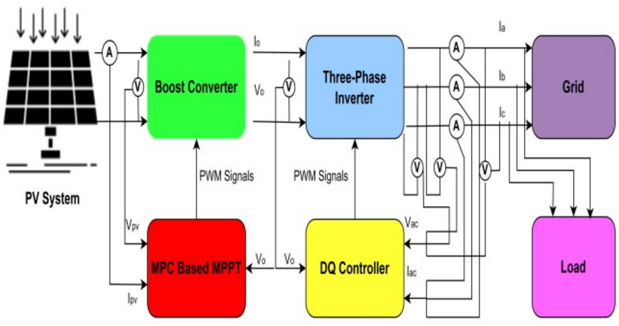

Fig. 4. *Block diagram of Model Predictive Control based MPPT*

A. Simulation results of 1st weather condition

The irradiation pattern shown in Figure 5 is a rapidly changing irradiance obtained with a pseudo-random sequence and temperature of 0 ºC. Figure 6 shows that the MPC based MPPT provides more smooth and stable voltage to the inverter as compared to the modified P&O based MPPT.

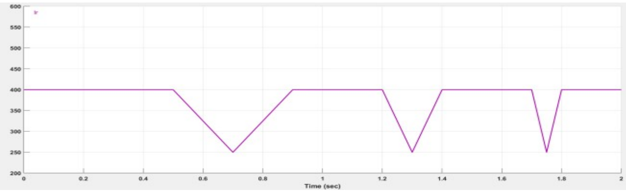

Fig. 5. *Irradiation (W/m²) pattern at 0 °C*

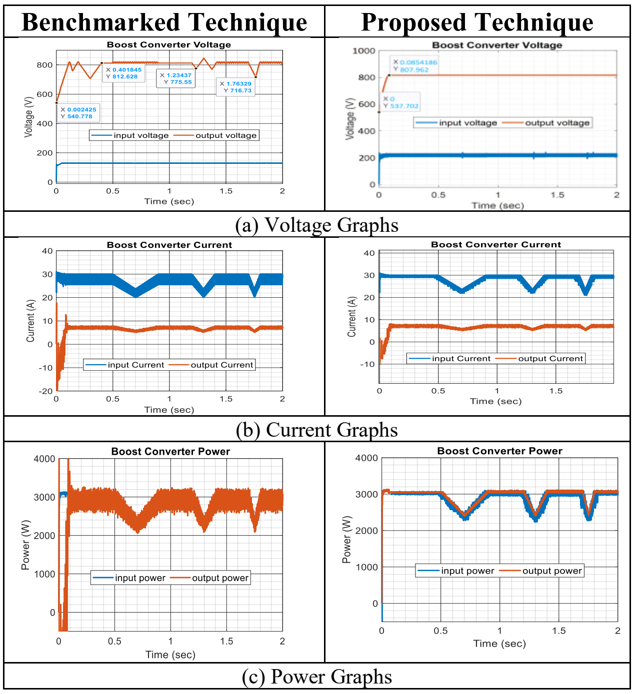

Fig. 6. *Simulation results of benchmarked and proposed techniques at 0 °C*

B. Simulation results of 2nd weather condition

The irradiation pattern shown in Figure 7 is chosen another worst environmental condition due to its un predictable and irregular shape of irradiance with low temperature at –5 ºC. Figure 8 shows the boost converter's input/output voltage, power and current waveforms based on benchmarked as well as MPC based technique at given worst condition.

In a grid-connected PV system, the use of a starter resistor in conjunction with a boost converter serves a crucial purpose. Initially, during startup, the resistor helps stabilize the output voltage of the boost converter, ensuring a smooth transition. Once the system is operational and the boost converter has reached its stable operating state, the resistor is then removed from the circuit. This method facilitates efficient energy conversion and optimal performance of the PV system by managing voltage fluctuations during startup without compromising long-term functionality.

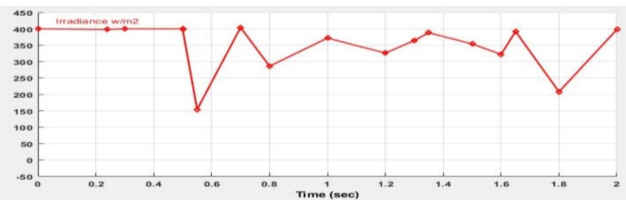

Fig. 7. *Irradiation (W/m²) pattern at –5 ºC*

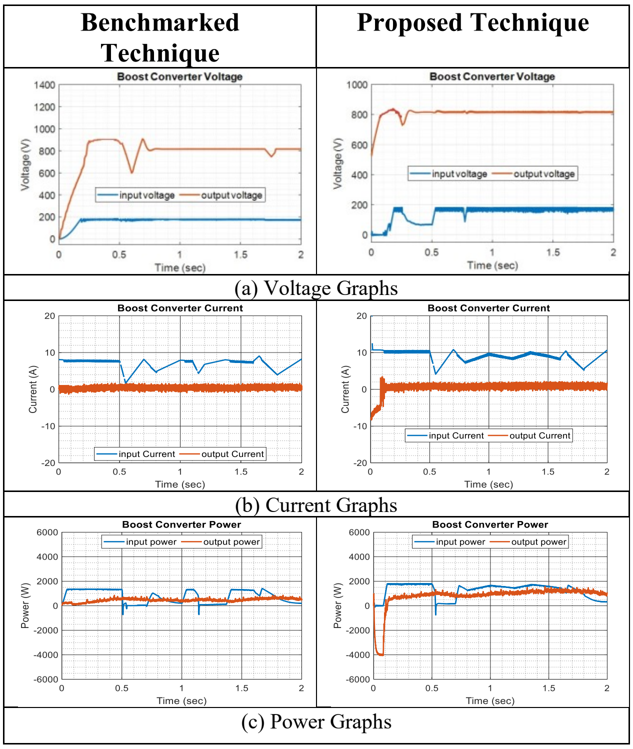

Fig. 8. *Simulation results of benchmarked and proposed techniques at –5 ºC*

C. Simulation results of 3rd weather condition

The irradiation pattern shown in Figure 9 is chosen another worst environmental condition due to its un predictable and irregular shape with lowest temperature at –10 ºC. Figure 10 shows the boost converter's input/output voltage, power and current waveforms based on benchmarked as well as MPC based technique at given worst condition.

Same experiment has been conducted three times using the same photovoltaic (PV) system under varying irradiance and temperature conditions to assess their respective impacts on efficiency. The results demonstrated that irradiance has a significantly greater effect on efficiency compared to temperature variations. While temperature did exert some influence, its impact on efficiency is comparatively minor.

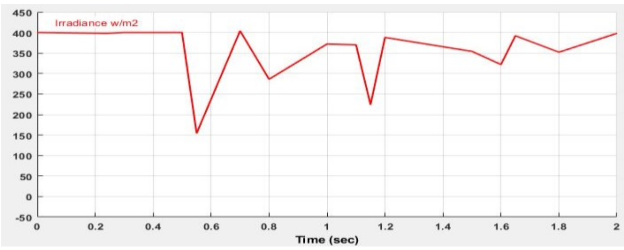

Fig. 9. *Irradiation (W/m²) pattern at –10 ºC*

Benchmarked Technique	Proposed Technique

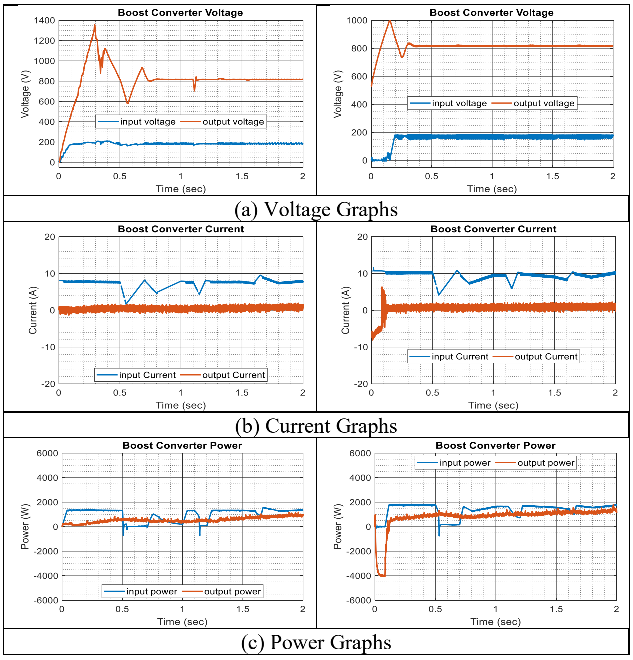

Fig. 10. *Simulation results of benchmarked and proposed techniques at −10 ℃*

VI. ANAYSIS OF THE IRRADIANCE AND OUTPUT VOLTAGE OF TWO SYSTEMS

The irradiance pattern in figure 12 has been compared with the output voltage of two Maximum Power Point Tracking (MPPT) systems – one based on MP&O and the other based on Model Predictive Control (MPC) given in figure 13.

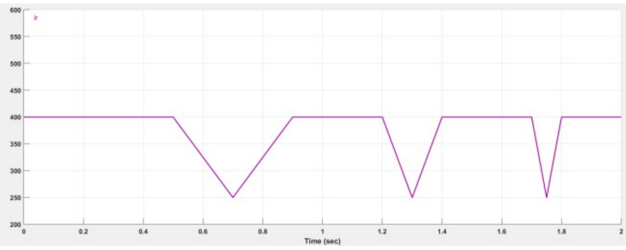

Fig. 11. *Irradiation (W/m^2) pattern at −5℃*

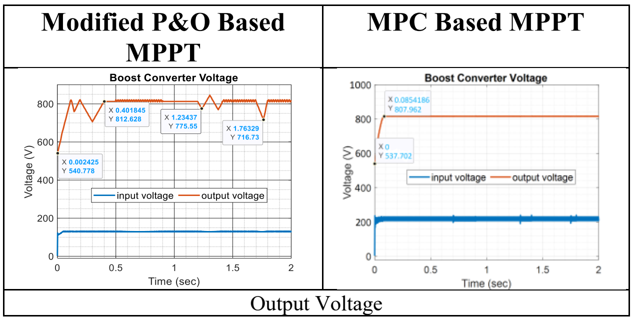

Fig. 12. *output voltage waveforms of P&O based and MPC based MPPT at −5℃*

Table.2 Irradiance vs Output Voltage of two systems

Duration (sec)	ΔE ((W/m2)/sec)	ΔV in MP&O based system	Change in Vo	ΔV in MPC based system	Change in Vo
0.5-0.7	375	0 V	0 %	0 V	0 %
0.7-0.9	375	0 V	0 %	0 V	0 %
1.2-1.3	1500	35 V	4.3 %	0 V	0 %
1.3-1.4	1500	35 V	4.3 %	0 V	0 %
1.7-1.75	3000	94 V	12 %	0 V	0 %
0.75-0.8	3000	94 V	12 %	0 V	0 %

So, from the comparison of the two techniques shown in Tab. 2, when the irradiance changes by more than 1,000 (W/m2)/sec, the MP&O based MPPT system will not be capable of providing a constant voltage for the DC bus, while the MPC based MPPT system can quickly adjust to changes in irradiance and temperature, minimizing oscillations around the MPP and improving overall efficiency. The model-based predictive nature of MPC allows it to respond faster and more accurately to changing conditions, leading to quicker stabilization.

VII. CONCLUSION

The paper has shown that model predictive control-based maximum power point tracking offers an advantage over traditional perturb and observe algorithms in delivering smooth DC voltage to the inverter of Grid connected PV systems. This superiority stems from the dynamic and adaptive nature of MPC, which enables real-time adjustments in response to changing weather conditions.

In addition to guaranteeing the precise MPP point, the suggested technique considers variations in irradiation during cold weather. After comparing the computing costs of the proposed and conventional procedures, it is determined that the suggested technique has less computational load than the conventional technique.

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