Performance Evaluation of various PLC techniques evolved in FPPT considering variable irradiation and load conditions

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Abstract— **The rapid integration of solar photovoltaic (SPV) systems into existing power grids has introduced challenges such as overvoltage, frequency fluctuations, and voltage instability. While Maximum Power Point Tracking (MPPT) is a well-established method for extracting maximum power from SPV systems, situations may arise where power generation exceeds demand. In such cases, the system must operate at points other than the Maximum Power Point (MPP), referred to as Flexible Power Points (FPP). The output power of SPV systems is influenced by variations in solar irradiance, temperature, and the connected load. To address these fluctuations, the duty cycle of the DC-DC converter is dynamically adjusted to operate in either MPP or FPP modes based on system requirements. To mitigate issues such as grid overloading, Power Limiting Control (PLC) strategies, including Direct Power Control (DPC), Current Limiting Control (CLC), and PV Voltage Control, are implemented and thoroughly analysed. This paper presents a simulation study aimed at enhancing the effectiveness of SPV panels by determining ideal operating parameters under varying climatic conditions. The study explores multiple scenarios based on these variations and discusses their implications in detail.**

Keywords— CLC, DC – DC Converter, DPC, FPP, MPPT, PLC, SPV

I. INTRODUCTION

The rising concern over carbon dioxide emissions and environmental degradation around the world has brought significant attention to renewable energy sources mainly solar and wind energy. According to global status report 2024, the fastest growing energy technology is Solar Photovoltaic (SPV). By 2030, more than 100 nations are committed to tripling their renewable energy output and accelerating the annual rate of advancements in energy efficiency [1]. To maximize the energy harvesting from the PV panels, Maximum Power Point Tracking (MPPT) techniques are commonly employed in power systems with photovoltaic (PV) systems. MPPT techniques ensure that the extracted output power adapts to the dynamics of varying environmental conditions [2-3]. However, with the increased solar PV penetration into the grid, a large amount of power may be injected, leading to several security issues such as overvoltage, heating of critical equipment such as transformers, frequency fluctuations, reverse power flow etc. which significantly reduce the reliability of power system [4]. A severe power blackout has been reported in Chile in Feb 2025. A 500 kV transmission line malfunction caused the incident, which resulted in frequency drops and cascading grid instability. The outage draws attention to grid stability issues, especially as the incorporation of renewable energy grows [5].

At times when the grid power requirement is less than the generation, various control approaches are adopted. These approaches include two main techniques: one that does not modify MPPT algorithm and another that does. Without modifying MPPT flexible power can be achieved through introduction of dummy loads, energy storage systems, smart loads, etc. However, these approaches often lead to increase in expenditure and control complexity [6-7]. To address these issues, researchers proposed flexible power point tracking (FPPT), a more cost-effective, safe, and nearly hardware-free option alternative to the current grid system that could be helpful in efficiently extracting solar power. This technique can be used in conjunction with the existing architecture, or as substitute to MPPT when necessary [8]. A higher PV penetration system is enabled by the PLC scheme, which restricts the excess amount of power that is fed into the grid [9]. To the best of the authors' knowledge, very few articles summarize the impacts of FPPT, though advancements in this domain are rapidly increasing, attracting significant research attention. The current method relies on the inconsistent behaviour of source-side parameters like V_{pv} and I_{pv}. While it is evident that the irregular nature of the load requires attention, current methodologies often overlook load-side abnormalities. This paper primarily focuses on analysing the variations in irradiation and connected loads to determine the appropriate operating mode—either MPPT or FPPT—to avoid overvoltage issues. These strategies can be implemented and analysed through Direct Power Control, Current Limiting Control, and PV Voltage Control under the Power Limiting Control technique. Simulations are conducted, and various conclusions are drawn to provide insights into these methodologies. The remaining part of the paper is structured around FPPT are discussed in Section II, III, simulation results are discussed focus on variation of parameters on deciding the operating mode i.e. either to operate in MPPT or FPPT. Finally in the last section a conclusion is drawn for the effectiveness of FPPT on a multivariable approach.

II. FPPT CONTROL STRATEGY

The PV system typically operates in MPPT mode majority of its runtime. Identifying this point is crucial, as the efficiency of solar panels typically ranges between 30-40% [10]. The operating principle of MPPT algorithm with flowchart is shown in Fig. 1 and Fig.2. However, certain situations, such as overvoltage during midday, may cause the PV generation to deviate from the grid's specifications. In these cases, MPPT is not the preferred operating mode. Instead, the operational point must shift to another point that meets grid or load requirements beyond MPPT conditions.

This approach is referred to as Flexible Power Point Tracking (FPPT) [11].

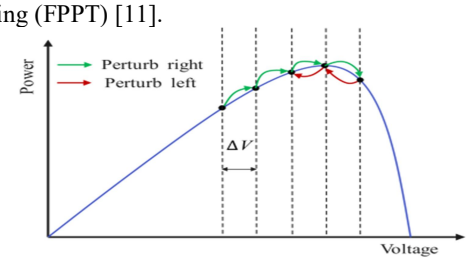

Fig.1. Tracking of Maximum Power Point

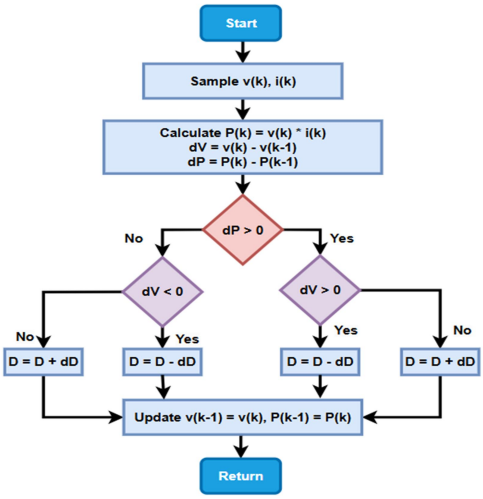

Fig.2. Flowchart of Perturb and Observe Algorithm

To enable active participation of the PV systems in grid regulation, countries such as Denmark, Germany, Australia etc. have updated their grid codes. The primary objective of the FPPT algorithm is to ensure compliance with these standard grid codes. Based on these grid codes, a solar photovoltaic power plant can inject active and reactive power as required by the grid. Various techniques can achieve FPPT, including power limiting control (PLC), also known as constant power generation control (CPGC)/ absolute active power control/ reduced power control, power reserve control (PRC)/ delta power control, and power ramp-rate control (PRRC) [12-14]. In this paper, we focus on power limiting control (PLC) to address the issue of overvoltage in grid infrastructure. In this mode, the extracted power from SPV system is adjusted to a reference point, delivering only the required power P_{ref}. If P_{ref} is less than the available power P_{avail}, the system operates in FPP mode. Conversely, if P_{ref} exceeds P_{avail}, the system switches to MPPT mode. Based on these scenarios, the duty cycle of the DC-DC converter is calculated from the error between available power and the reference power. Due to non-monotonic characteristics of P-V curve, for a fixed power load, there will be two operating point for FPP operation namely FPPT1 and FPPT2 as shown in Fig.3. These points are located on either side of the MPP. The left side of the MPP region, known as the Constant Current Region, and the right side, referred to as the Constant Voltage Region, offer different advantages.

- **Left-Side Operation (Constant Current Region):** This provides slower transitions but improves accuracy with minimal fluctuations in PV power for a given change in operating voltage. However, higher current in this region results in increased ohmic losses.
- **Right-Side Operation (Constant Voltage Region):** This offers quicker transitions and lower losses, making it more suitable for areas with high irradiation. The greater operating voltage in this region reduces current and minimizes ohmic losses, making it ideal for PV power monitoring.

The demand power P_{ref} varies throughout the day and is determined by coordinating with the load side. This coordination is achieved using a communication system between smart meters and the control block. Establishing effective communication further enhances the effectiveness of FPPT.

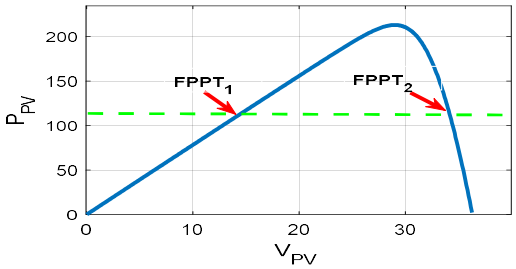

Fig.3. Operating principle of FPPT Algorithm

The Power Limiting Control (PLC) scheme within the FPPT framework is essential for regulating and restricting the amount of power supplied to the grid. Implementing the FPPT's PLC system ensures precise control over the power delivery to the grid, as outlined in [15-16]. Three Control schemes for implementing the PLC scheme of FPPT:

A) Direct Power Control

The PV output power can be limited to the desired reference power using a closed-loop control system and a conditional switch. The conditional switch operates based on the relationship between the available PV power P_{avail} and the connected load demand P_{ref}, determining the mode of operation—either MPPT or FPPT. An error signal is generated by comparing the available PV power P_{avail} with the required load power P_{ref}. This error signal is processed by PI controller, and its steady-state output is compared with a carrier signal to generate a Pulse Width Modulation (PWM) signal for controlling the converter switch. The operating principle can be expressed as eqn.(1). Fig.4 shows the flowchart of MPPT and Fig.5 shows the circuit diagram for its implementation.

$$P_{PV} = \begin{cases} P_{MPPT}, & P_{avail} \le P_{limit} \\ P_{limit}, & P_{avail} > P_{limit} \end{cases} \quad (1)$$

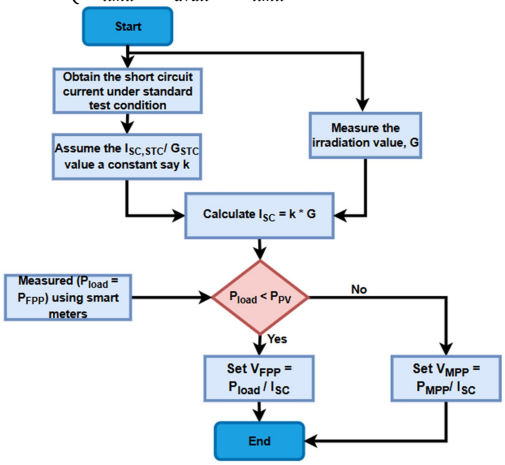

Fig.4. Flowchart for Power Limiting Control

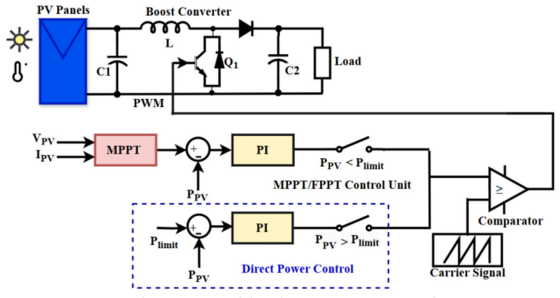

Fig.5. PLC with Direct Power Control

B) Current Limiting Control

In this control strategy, the output PV current i_{pv} is used as the control parameter to implement PLC. From the P-V curve, it can be observed that with varying irradiation levels, there is only a minor change in the PV voltage V_{pv} on the right side of the MPP. In this region, the PV power can be effectively controlled by limiting the output PV current. The limiting current i_{limit} corresponding to the reference power can be computed as eqn.(2). Fig.6 shows the circuit implementation of Current Limiting Control.

$$i_{limit} = \frac{P_{limit}}{v_{pv}} \qquad (2)$$

The primary advantage of current-limiting control is that it does not require switching between different operating modes. However, it may introduce instability under lower irradiation conditions. On the positive side, it exhibits very fast dynamic behavior.

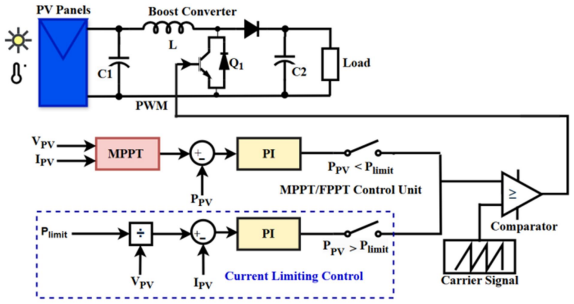

Fig.6. PLC with Current Limiting Control

C) PV Voltage Control

The PV output voltage v_{pv} is taken as a control parameter to obtain PLC. It can be seen from the PV curve that on the left side of MPP, output current is constant. The PV power in this region can be effectively controlled by limiting the PV output voltage. The limiting voltage v_{limit} corresponding to reference power can be calculated as P_{limit}/i_{pv} and implemented in Fig.7.

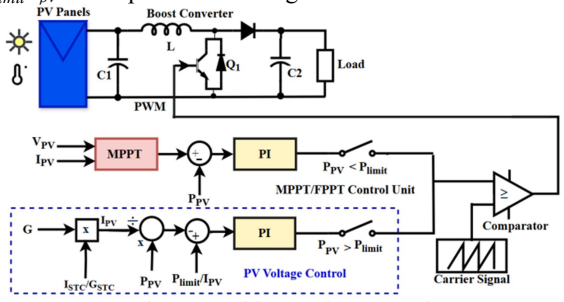

Fig.7. PLC with PV Voltage Control

III. Simulated Results

The PV panel (1Soltech 1STH-215-P) for 100 kW which is considered for simulation performed in Simulink has the following specifications:

TABLE I SPECIFICATION OF PV PANEL

Parameters	Ratings
No. of Parallel Strings	47
No. of Series Strings	10
No. of cells per Module	60
Maximum Power of Module	213.15 W
Open Circuit Voltage	36.3 V
Short Circuit Current	7.84 A
Voltage at Maximum Power Point	29 V
Current at Maximum Power Point	7.35 A
Temperature coefficient of Voltage	-0.36099 /ºC
Temperature coefficient of Current	0.102 /ºC
Shunt Resistance	313.0553 Ω
Series Resistance	0.39381 Ω

A. Direct Power Control

Case (a): Variable Irradiation with Constant Load Demand of 65 kW

The system adjusts to changing irradiation levels to meet a constant demand of 65 kW:

- **1000 W/m²:** 65 kW is extracted at 335.25 V and 193.7 A in FPP mode.
- **800 W/m²:** 65 kW is extracted at 325.5 V and 199.5 A, remaining in FPP mode.
- **600 W/m²:** Available power reduces to 60 kW, and the system operates in MPP mode at 310.9 V and 154.97 A.
- **450 W/m²:** Available power drops further to 45 kW, and the system continues in MPP mode at 301.22 V and 150 A.
- **700 W/m²:** Available power exceeds the demand; the system operates in FPP mode at 315.5 V and 206 A.

This demonstrates the system's ability to seamlessly transition between FPP and MPP modes to maintain performance under varying irradiation levels.

Case (b): Constant Irradiation of 950 W/m² with Variable Load Demand

With a constant irradiation yielding 95 kW of available power, the system responds to changing load demands as follows:

- **0–1 sec**: 65 kW demand is met at 333.5 V and 195 A in FPP mode.
- **1–2 sec**: Demand rises to 75 kW, and the system operates at 326.5 V and 229.5 A.
- **2–3 sec**: Demand increases to 80 kW, with the system operating at 322.4 V and 248 A.
- **3–4 sec**: Demand decreases to 55 kW, and the system adjusts to 338 V and 168.5 A.
- **4–5 sec**: Demand stabilizes at 60 kW, with the system operating at 336.3 V and 178.5 A.

This highlights the system's stability in FPP mode while dynamically adapting to load variations under constant irradiation.

Case (c): Variable Irradiation and Load Demand

The system matches available and demanded power dynamically:

- **0–1 sec**: At 1000 W/m², 65 kW is extracted in FPP mode at 335.3 V and 194 A.

- **1–2 sec**: At 800 W/m², 75 kW is extracted in FPP mode at 313.7 V and 239 A.
- **2–3 sec**: At 600 W/m², 60 kW is extracted in MPP mode at 310.9 V and 154.9 A.
- **3–4 sec**: At 450 W/m², 45 kW is extracted in MPP mode at 301.22 V and 150 A.
- **4–5 sec**: At 700 W/m², 60 kW is extracted in FPP mode at 322.2 V and 186 A.

This analysis confirms the system's ability to optimize power generation by alternating between FPP and MPP modes, adapting to fluctuations in both irradiation and load demands.

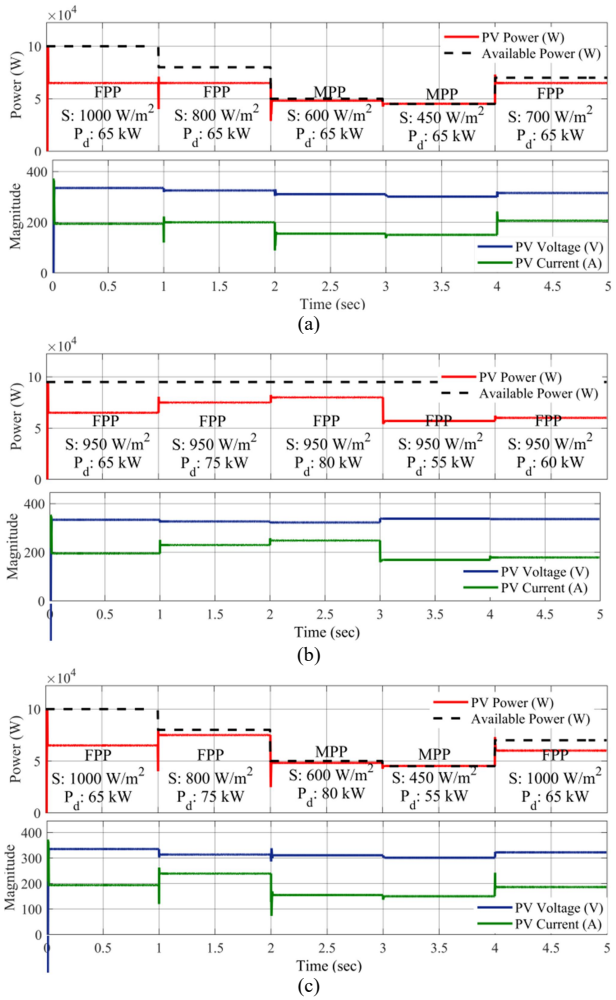

Fig.8. Simulation results of Direct Power Control (DPC) under possible test conditions: (a) Variable Irradiation and Constant Load demand, (b) Variable Load demand and Constant Irradiation, (c) Variable Load demand and Irradiation.

The simulation results of Direct Power Control, depicted in Fig. 8, shows that the system tends to operate on the right side of the MPP. It effectively tracks variations in irradiation and connected load, with minimal power fluctuation under steady-state conditions. Additionally, the computational complexity remains relatively simple.

B. Current Limiting Control

Case (a): The system is tested under variable irradiation while maintaining a constant load demand of 65 kW. The results are as follows:

- At **1000 W/m²,** the system extracts about 65 kW of power at 335.3 V and 193.8 A, operating in FPP mode.
- At **800 W/m²,** power extraction remains at 65 kW, with the system operating at 325.4 V and 199.7 A, still in FPP mode.
- At **600 W/m²**, the available power drops to 60 kW, while the demand remains at 65 kW. In this case, the system switches to MPP mode at 297 V and 204.5 A.
- At **450 W/m²,** only 45 kW of power is available, so the system operates in MPP mode at 293 V and 155.5 A, despite a 65 kW load demand.
- At **700 W/m²,** available power exceeds the demand, and the system operates in FPP mode at 315.5 V and 206 A.

This analysis highlights the system's capacity to transition between FPP and MPP modes based on changes in irradiation, while maintaining the target load demand of 65 kW.

Case (b): Under constant irradiation of 950 W/m² and a variable load demand, the system operates with a constant available power of 95 kW. The system's behaviour is as follows:

- From **0–1 sec**, the load demand is 65 kW, with voltage at 333.3 V and current at 195 A, operating in FPP mode.
- From **1–2 sec**, the demand increases to 75 kW, with the system operating at 326.5 V and 230 A.
- From **2–3 sec,** the demand rises to 80 kW, with voltage and current at 322.4 V and 248 A, respectively.
- From **3–4 sec,** the demand decreases to 55 kW, with voltage at 338 V and current at 168.5 A.
- From **4–5 sec,** the demand is 60 kW, with voltage at 336.3 V and current at 178.5 A.

Throughout these intervals, the system adjusts to varying load demands while maintaining stable power extraction and operating in FPP mode.

Case (c): Under varying irradiation and load demands, the system adjusts power generation to ensure optimal output, as described below:

- From **0–1 sec**, at 1000 W/m² irradiation and a 65 kW demand, the system generates 65 kW at 335.25 V and 194 A, operating in FPP mode.
- From **1–2 sec**, with 800 W/m² irradiation and a 75 kW demand, the system extracts 75 kW at 313.7 V and 239 A, still in FPP mode.
- From **2–3 sec**, with 60 kW available power and an 80 kW demand, the system switches to MPP mode, operating at 295 V and 206 A.
- **From 3–4 sec**, at 450 W/m² and a 55 kW demand, the system operates in MPP mode at 293 V and 157 A.
- From **4–5 sec**, at 700 W/m² irradiation and a 60 kW demand, the system again operates in FPP mode at 322.2 V and 186.4 A.

This dynamic adjustment between FPP and MPP modes ensures that the system optimizes power generation based on available and demand power, adapting efficiently to changes in irradiation.

The simulation results (Fig. 9) show that the system generally operates closer to the right side of the MPP. However, at lower irradiation levels, tracking errors increase, and the computational complexity is higher compared to other control schemes. At higher irradiation

levels, the system effectively adjusts to environmental and load changes.

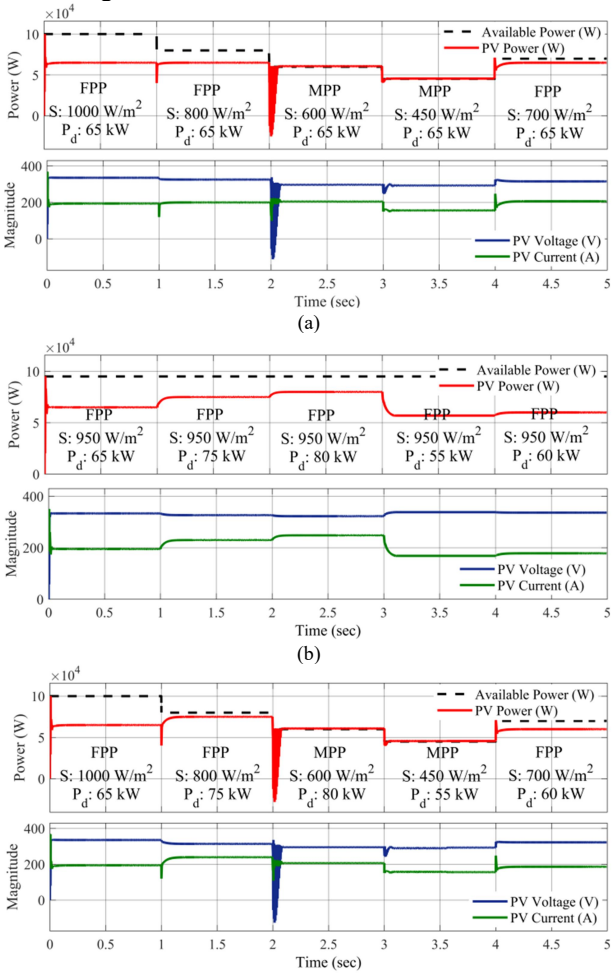

Fig.9. Simulation results of Current Limiting Control (CLC) under possible test conditions: (a) Variable Irradiation and Constant Load demand, (b) Variable Load demand and Constant Irradiation, (c) Variable Load demand and Irradiation.

C. PV Voltage Control

Under varying irradiation and a constant load demand of 65 kW, the system adapts to different conditions by adjusting its operation mode.

In **Case (a)**, with an irradiation of 1000 W/m², the system operates in FPP mode, extracting 65 kW at 176.5 V and 366.55 A. When the irradiation decreases to 800 W/m², the system continues to operate in FPP mode, but now with a voltage of 220 V and a current of 292.5 A. At 600 W/m² Irradiation, the system enters MPP mode as available power drops to 60 kW. In this mode, it operates at 291 V and 209 A to meet the demand of 65 kW. A further decrease in irradiation to 450 W/m² results in only 45 kW available power, so the system remains in MPP mode, now operating at 291 V and 155 A. At 700 W/m² irradiation, the system once again operates in FPP mode at 252 V and 254.9 A as the available power exceeds the demand. These varying conditions highlight how the system adjusts its operation mode based on available power to match the constant load demand.

Case (b) explores the system's response under constant irradiation of 950 W/m² and a variable load demand. The system consistently has 95 kW available power, and it adapts to the changing demand. During the 0-1 sec, with a demand of 65 kW, the system operates at 185.7 V and 348.1 A in FPP mode. As the demand increases to 75 kW in the 1- 2 sec, the voltage rises to 214.2 V and current decreases slightly to 347.6 A. In the 2- 3 sec, when demand reaches 80 kW, the system operates at 228.5 V and 347.2 A. When the demand drops to 55 kW in the 3- 4 sec, the system operates at 157 V and 348.5 A. In the last second, with a 60 kW demand, the system operates at 171.4 V and 348.4 A. This demonstrates the system's flexibility in adjusting to varying load demands while maintaining steady operation at the available 95 kW.

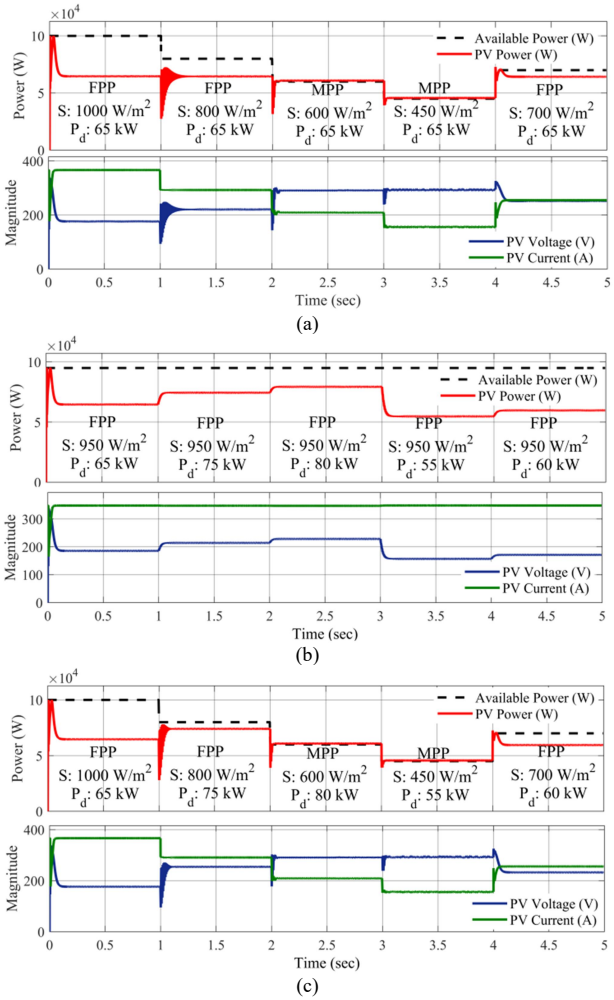

Fig.10. Simulation results of PV Voltage Control under possible test conditions: (a) Variable Irradiation and Constant Load demand, (b) Variable Load demand and Constant Irradiation, (c) Variable Load demand and Irradiation.

Case (c) examines both variable irradiation and variable load demand. Initially, with 1000 W/m² irradiation and a demand of 65 kW, the system operates in FPP mode, extracting 65 kW at 176.5 V and 366.5 A. When irradiation drops to 800 W/m² and the demand increases to 75 kW, the system continues in FPP mode at 254.5 V and 291 A. If irradiation decreases to 600 W/m², with a demand of 80 kW, the system switches to MPP mode, operating at 291 V and 209 A due to the insufficient available power. At 450 W/m² irradiation, the system remains in MPP mode with a voltage of 291 V and a current of 155 A to meet the 55 kW demand.

Finally, at 700 W/m² irradiation and a 60 kW demand, the system returns to FPP mode, operating at 232.6 V and 255.8 A. This analysis underscores the system's dynamic adaptation to both fluctuating irradiation levels and varying load demands, optimizing power generation by switching between FPP and MPP modes as needed shown in (Fig. 10).

The simulation results show that the system typically operates on the left side of the Maximum Power Point (MPP), indicating effective performance under varying environmental conditions and load demands. Compared to the Current Limiting Control (CLC) scheme, the system shows less tracking error at lower irradiation levels, suggesting better performance under less sunlight. Additionally, the computational complexity of the system is similar to that of the CLC scheme, making it an efficient and responsive solution for optimizing power generation in real-world scenarios. Table II shows the various PLC technologies.

TABLE II COMPARISON OF VARIOUS PLC TECHNOLOGIES

Algorithm	Region of operation	Transition between modes	Power Fluctuation in steady state	Tracking error	Design complexity
Direct Power Control (DPC)	Right	Yes	Low	High	Low
Current Limiting Control (CLC)	Right	Yes	High	Very High	Low
PV Voltage Control	Left	Yes	Low	High	Low

IV. CONCLUSION

High PV penetration causes stability issues in the power system which can be mitigated through Flexible Power Point Tracking (FPPT). In this study, different cases are considered to understand the effectiveness of MPP and FPP on a system. It is apparent that while irradiance *S* is varying and demand power *P* is constant in case (a) Direct Power Control (DPC) is showing better tracking from PV Voltage Control which is, in turn, better than Current Limiting Control (CLC), for case (b) under constant irradiation *S* and varying demand power *P*, CLC would be a better choice among the three as it gives less current stress on switch and for case (c) under varying irradiance and load demand, CLC gives better result. Power fluctuation and tracking error are higher in the case of CLC than in DPC and PV Voltage Control. While higher irradiation is the case DPC and CLC can be a preference, otherwise for lower irradiation one can opt for PV Voltage Control technique. The observations are worth justifying based on the results obtained through Matlab simulation.

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