Analysis of photovoltaic MPPT methods for power efficiency and voltage flicker

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Abstract

Power quality issues are one of the challenges associated with increasing photovoltaic power generation. In this study, three maximum power point tracking (MPPT) methods are implemented for a photovoltaic system connected to a case network – incremental conductance (IC), perturb and observe (P&O) and fractional open circuit (FOC). Experimental data of solar irradiance is used as an input to the PV array in the system. Comparison based on the power extracted from the PV system and the flicker indices measured from the grid voltage with each technique is conducted. From analysis, it can be seen that P&O and IC methods give the best results with respect to power and flicker indices.

Keywords: Distribution grid, flicker, MPPT, Photovoltaics

1. Introduction

In recent years, the utilization of photovoltaic (PV) power generation has increased significantly. PV systems can be used in stand-alone or grid-connected configurations. Due to the intermittent nature of solar radiation and the presence of power electronic converters in PV systems, power quality issues related to grid-connected PV generation have become a concern.

One of such issues is flicker which means visible changes in the brightness of a lamp caused by fast fluctuations of the supply voltage. Such fluctuations are typically caused by large, rapidly variating loads such as arc furnaces and certain types of motor applications. Cloud movements can cause rapid variations in solar irradiance which in turn causes variations in the power produced by photovoltaic arrays. Rapidly variating power flow can cause voltage fluctuations in the power system which may result in flicker.

Maximum power point tracking (MPPT) techniques are implemented for PV to extract the maximum available power. Several different MPPT technologies exist, having different performance and possibly different characteristics with respect to the power quality issues.

In a power quality investigation carried out at the University of Queensland [1], power quality parameters were measured in a network containing PV systems. Flicker was mostly within the limits defined in Australian power quality standards, but significant flicker was observed during some individual days.

Power quality problems caused by different single-phase PV inverters were studied in [2]. According to the study, irradiance variations caused by moving clouds were not a significant source of flicker. The MPPT controller design, however, was identified as a potential source of flicker.

In [3], the effect of irradiance variations on flicker in the distribution grid of Ohau, Hawaii was studied. Irradiance samples from five sensors and a generic inverter model were used to simulate a photovoltaic plant with varying output power. In the simulations, flicker was below the limits defined in local power quality requirements. The results of these simulations were also compared to those obtained by assuming an instantaneous 80 to 100% drop in the output power of the PV plant. According to the study, assuming such a drop does not accurately represent the effects of varying solar irradiance, but the operation of PV control should be also considered.

Power quality issues caused by a large photovoltaic plant in Shanghai were studied in [4] using measurement data from Shanghai Power Quality Monitoring System. During a one-day study period, flicker was far below the limit defined in Chinese power quality standards. A statistical analysis of power quality from July to December, 2012, was also performed.

Power quality at a photovoltaic plant connected to the low-voltage distribution system of Peng-Hu, Taiwan, was studied in [5]. Flicker during a 7-day measurement period was analyzed.

Several studies about PV and power quality issues including flicker have been conducted. Flicker caused by PV has been mostly studied by actual voltage measurements or simulations based on generic inverter and PV array models. However, no previous papers about the differences between different MPPT methods with respect to flicker exist.

The purpose of this study is to examine the differences between different MPPT technologies related to the output power and flicker based on real measurements of solar irradiance. Three different MPPT methods were simulated and tested by flicker calculations.

The paper is organized as follows. Section 1 is the introduction. Section 2 presents the MPPT algorithms and their implementation. Section 3 describes flicker characterization and measurement methods. Section 4 describes solar irradiance measurements and data collection. In section 5, the system structure and configuration are described. Section 6 presents the simulation results for different MPPT algorithms with respect to power and flicker. The main conclusion is presented in section 7.

2. Maximum Power Point Tracking (MPPT) Algorithms

A. Incremental Conductance

The incremental conductance (IC) algorithm is calculated by differentiating the PV array power with respect to voltage and setting the result equal to zero [6]. This is shown in the following equation:

$$\frac{dP}{dV} = \frac{d(VI)}{dV} = I + V\frac{dI}{dV} = 0 \text{ at MPP} \tag{1}$$

Re-arranging (1) gives

$$-\frac{I}{V} = \frac{dI}{dV} \tag{2}$$

The left-hand side of (2) performs the opposite instantaneous conductance of the PV array, while the right hand side represents its incremental conductance. Therefore, the magnitude of these two quantities must be equal but with opposite sign for the MPP.

If the operating point is off of MPP a set of inequalities can be derived from (2) that indicates whether the operating voltage is above or below the MPP voltage. These relationships [7] are concluded in the following equations:

$$\frac{dI}{dV} = -\frac{I}{V}; \quad \left(\frac{dP}{dV} = 0\right) \qquad \text{at MPP} \tag{3a}$$

$$\frac{dI}{dV} > -\frac{I}{V}; \quad \left(\frac{dP}{dV} > 0\right) \qquad \text{, left of MPP} \tag{3b}$$

$$\frac{dI}{dV} < -\frac{I}{V}; \quad \left(\frac{dP}{dV} < 0\right) \qquad \text{, right of Mpp} \tag{3c}$$

The direction in which a perturbation must occur to move the operating point toward the MPP is shown in (3b) and (3c), and the perturbation is repeated until (3a) is satisfied. Once the MPP is reached, the MPPT continues to operate at this point until a change in current is detected. This change in current will correlate to a change in irradiance on the array.

Figure 1 describes a flow chart for the incremental conductance algorithm [6]. Increment size determines how fast MPP is tracked. Fast tracking can be achieved with bigger increments but the system might not operate exactly at the maximum power point and oscillate about instead. This method has complex size, which is usually fixed for the conventional incremental conductance method [8].

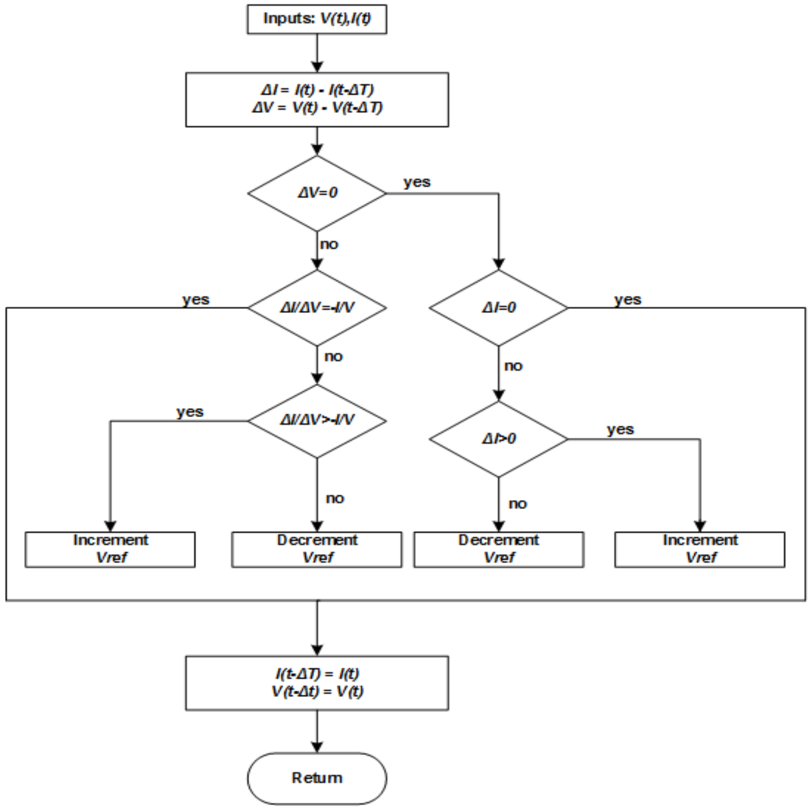

Figure 1: Algorithm of Incremental Conductance [9, 10]

B. Perturb and Observe

Perturb and observe (P&O) algorithm is the most commonly used in practice because of its ease of implementation [11]. It perturbs the PV array's terminal voltage periodically, and then it compares the PV output power with that of the previous cycle of perturbation [12-14].

It can be seen from Table 1 that if the change in power is positive (P) and perturbation is positive then the next perturbation will be positive whilst if the change in power is negative and the perturbation is positive therefore the next perturbation will be negative (N) (reversed).

Table 1: P&O Algorithm Summary

		Change in Power	
		P	N
Perturbation	P	P	N
	N	N	P

The process is repeated periodically until the MPP is reached [15].The system then oscillates about the MPP. The oscillation can be minimized by reducing the perturbation step size. However, a smaller perturbation size slows down the MPPT. Figure 2 shows a flow chart for perturb and observe algorithm [12].

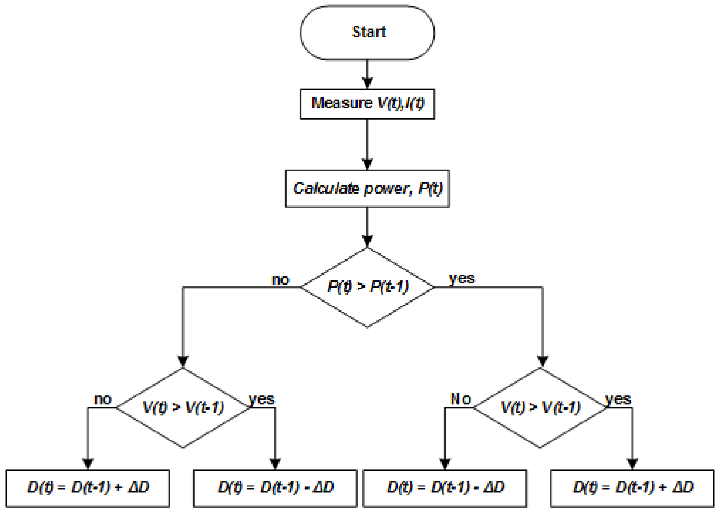

Figure 2: Algorithm of Perturb and Observe

C. Fractional Open Circuit

The voltage based MPPT technique is based on the fact that the PV array voltage corresponding to the maximum power exhibits a linear dependence with respect to the array open circuit voltage for different irradiation and temperature level [16].

$$V_{mpp} = M_v \, V_{oc} \tag{4}$$

Where, V_{mpp} is the maximum power point voltage, V_{oc} is the open circuit voltage of the PV array and M_v is the voltage factor that has value between 0.7 - 0.8 depending upon the PV array characteristics [17]. The block diagram of the voltage based MPPT is shown in Figure 3.

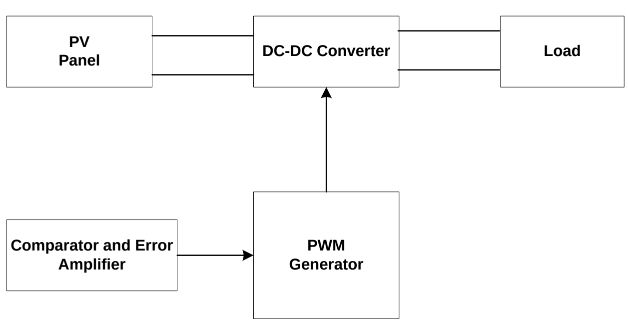

Figure 3: Operation of Fractional Open Circuit

To operate the PV panel at the MPP, the actual PV array voltage V_{pv} is compared with the reference voltage, V_{ref} which corresponds to V_{mpp}. The error signal is then proceed to make $V_{pv} = V_{ref}$. Normally, the panel is disconnected from the load momentarily to sample its open circuit voltage. The fraction of open circuit voltage corresponding to V_{mpp} is measured and kept in a hold circuit to function as V_{ref} for the control loop [17].

3. Flicker measurement and characterization

Several different indices and limit curves have been defined to characterize flicker. The standard IEC 61000-4-15 [18] describes the flickermeter, a device to measure flicker from grid voltage. The flickermeter consists of a series of filters that simulate the operation of a 60-watt incandescent lamp and the response of human eye and brain. The output signal of these filters represents the instantaneous flicker sensation. The flicker severity indices are calculated statistically from this signal. The short-term flicker index P_{st} is calculated using the formula

$$P_{st} = \sqrt{0.0314\, P_{0.1} + 0.0525\, P_{1s} + 0.0657\, P_{3s} + 0.28\, P_{10s} + 0.08\, P_{50s}} \quad (5)$$

where, $P_{0.1}$, P_{1s}, P_{3s}, P_{10s} and P_{50s} are the instantaneous flicker levels exceeded for 0.1, 1, 3, 10 and 50% of the time during a 10-minute observation period, respectively. The smoothed values marked with the suffix “s” are calculated using the following equations

$$P_{50s} = \frac{P_{30}+P_{50}+P_{80}}{3} \quad (6)$$

$$P_{10s} = \frac{P_{6}+P_{8}+P_{10}+P_{13}+P_{17}}{5} \quad (7)$$

$$P_{3s} = \frac{P_{2.2}+P_{3}+P_{4}}{3} \quad (8)$$

$$P_{1s} = \frac{P_{0.7}+P_{1}+P_{1.5}}{3} \quad (9)$$

The long term flicker index P_{lt} is calculated as the cubic mean of 12 successive P_{st} values over a two-hour period using the following formula.

$$P_{lt} = \sqrt[3]{\sum_{i=1}^{12} \frac{P_{st,i}^{3}}{12}} \quad (10)$$

In this study, the flickermeter was simulated in Matlab. A modified version of a Matlab script created by Solcept AG [19] was used to calculate the instantaneous flicker sensation signal and the short and long term flicker indices.

Several power quality standards set limits to the occurrence of flicker. According to the standard EN 50160 [20], for example, the long-term flicker index P_{lt} must stay below 1 for 95% of the time during any one-week test period.

4. Solar radiation data and analysis

In this study, real measurement data of solar irradiance was used. The data was collected at the PV research plant of Tampere University of Technology [21] using SP Lite2 photodiode sensors (Kipp & Zonen) and sampled at a rate of 10 Hz. For the simulations, a two-hour period in 6th of June, 2016 from 12:00 to 14:00 (GMT+3) was selected and the irradiance measured by one SP Lite2 sensor was obtained.

5. System description and configuration

The structure of the simulated system is shown in Figure 4. The system consists of a 100-kilowatt photovoltaic array connected to a distribution grid model via a boost converter and an inverter. The MPPT controller adjusts the duty cycle of the boost converter. Experimental irradiance data is used as an input for the PV array. Voltage and flicker are measured from the point of common coupling.

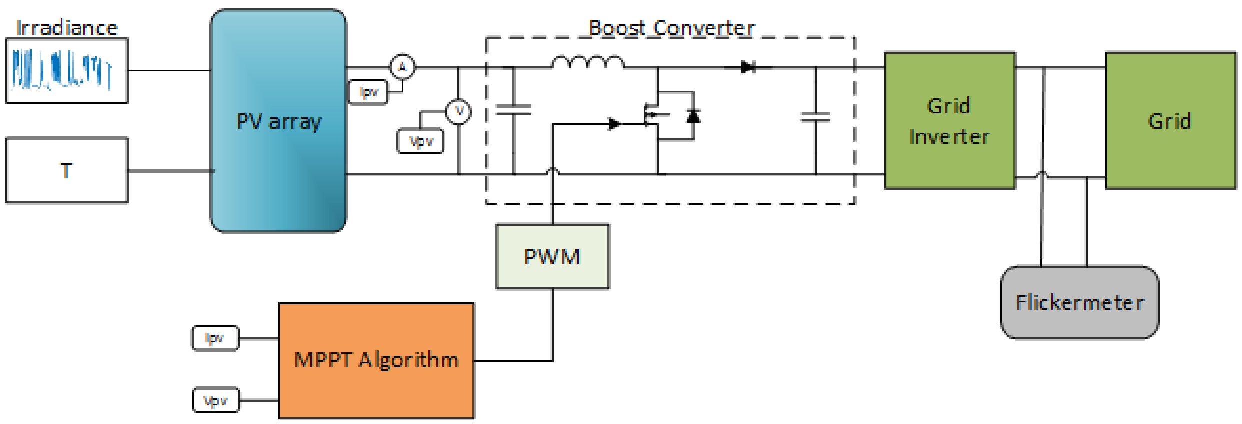

Figure 4: Structure of the simulated system

6. Results

Solar irradiance and simulated PV output power using three different MPPT techniques are shown in Figure 5. As can be seen from the figure, perturb and observe (P&O) method produces slightly higher power than incremental conductance (IC). Power achieved with fractional open circuit (FOC) method is significantly lower and there are more fast fluctuations. Incremental conductance and perturb and observe methods have better response to rapidly changing solar irradiance than fractional open circuit.

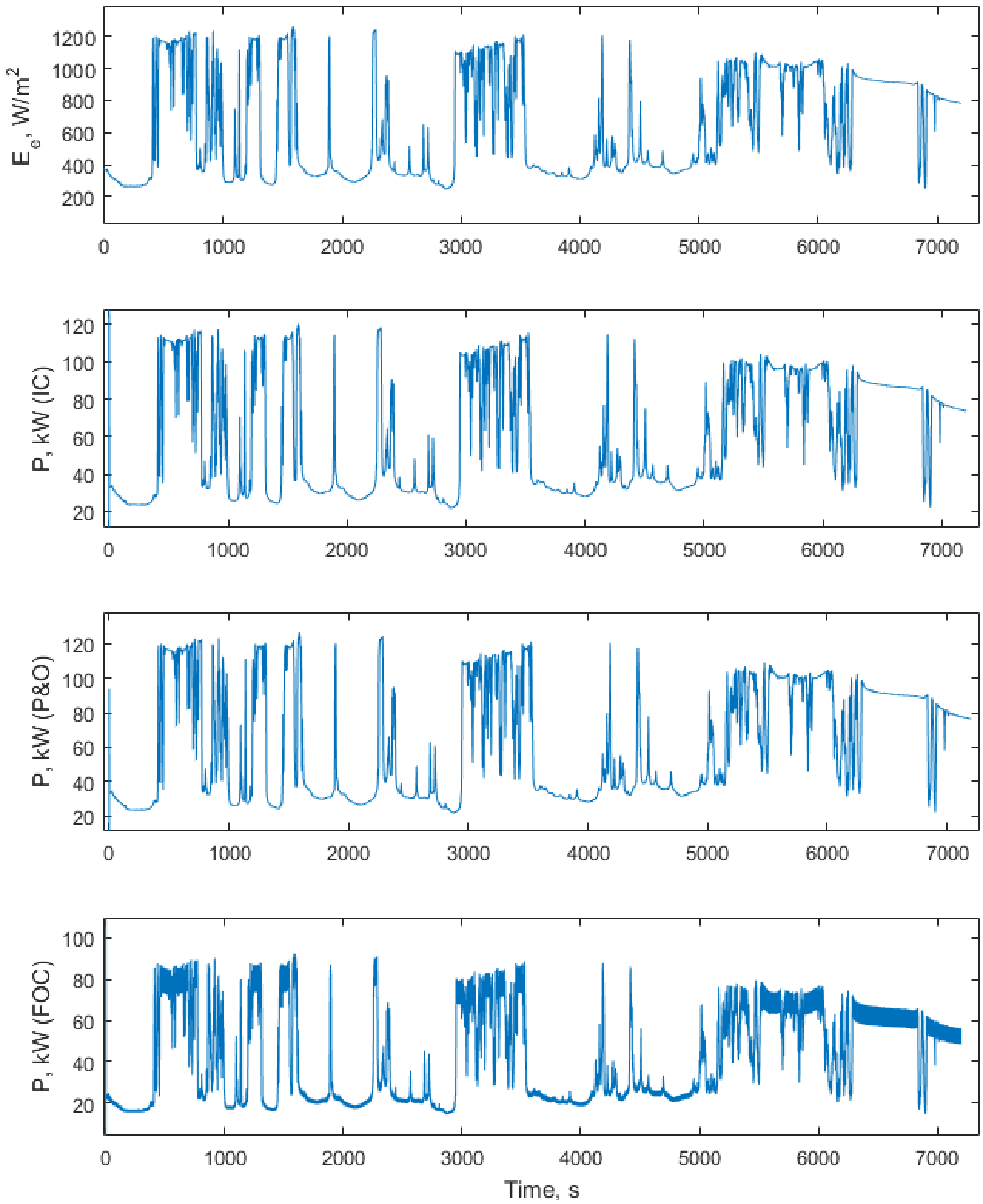

Figure 5: Solar irradiance and power extracted using different MPPT methods

The instantaneous voltage flicker using different MPPT techniques is shown in Figure 6. All observed flicker values are low, but fractional open circuit method produces significantly more flicker than incremental conductance or perturb and observe.

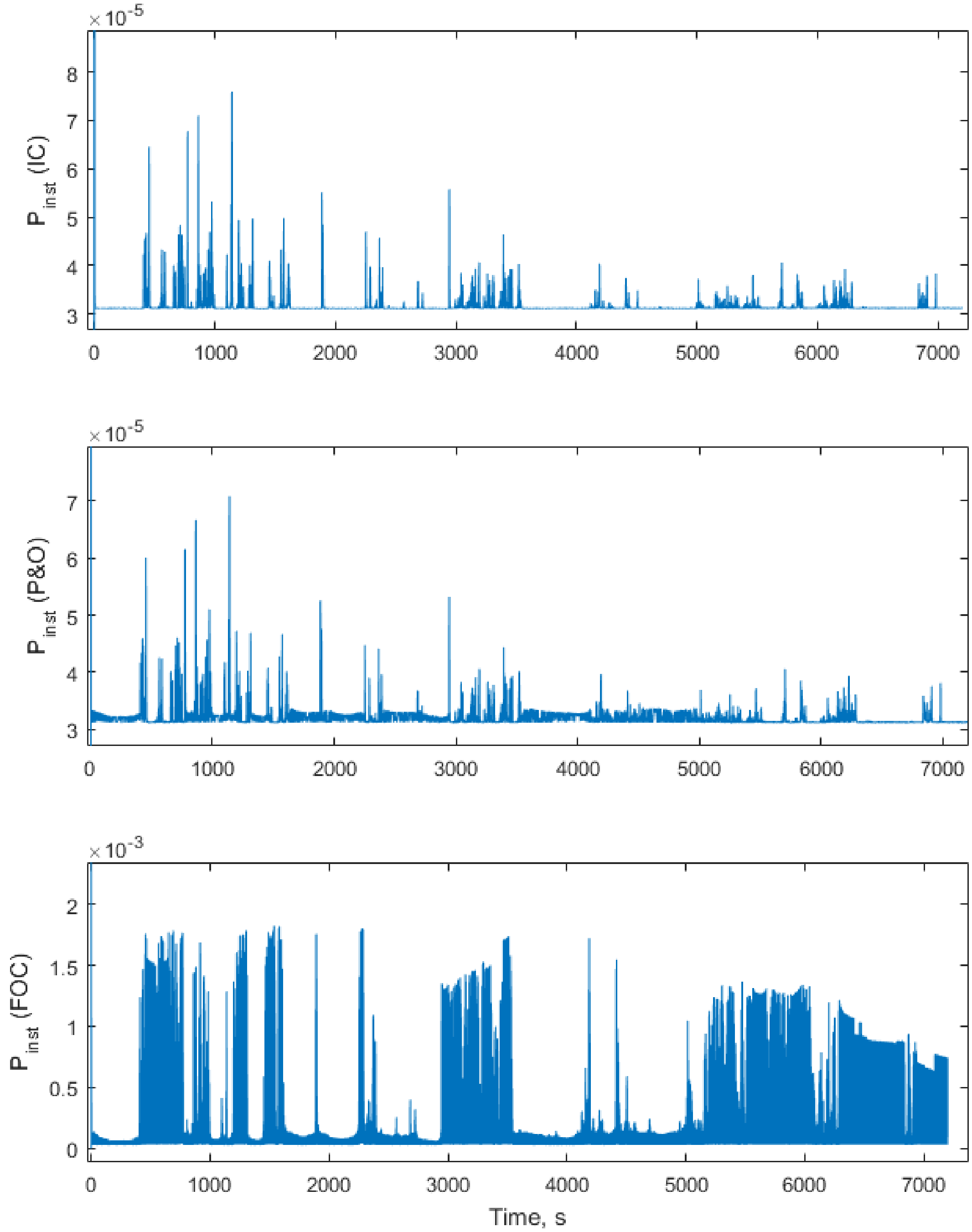

Figure 6: Instantaneous voltage flicker when using different MPPT methods

The short-term flicker index with different MPPT methods is shown in Figure 7. As seen from the figure, fractional open circuit method produces more flicker than incremental conductance or perturb and observe.

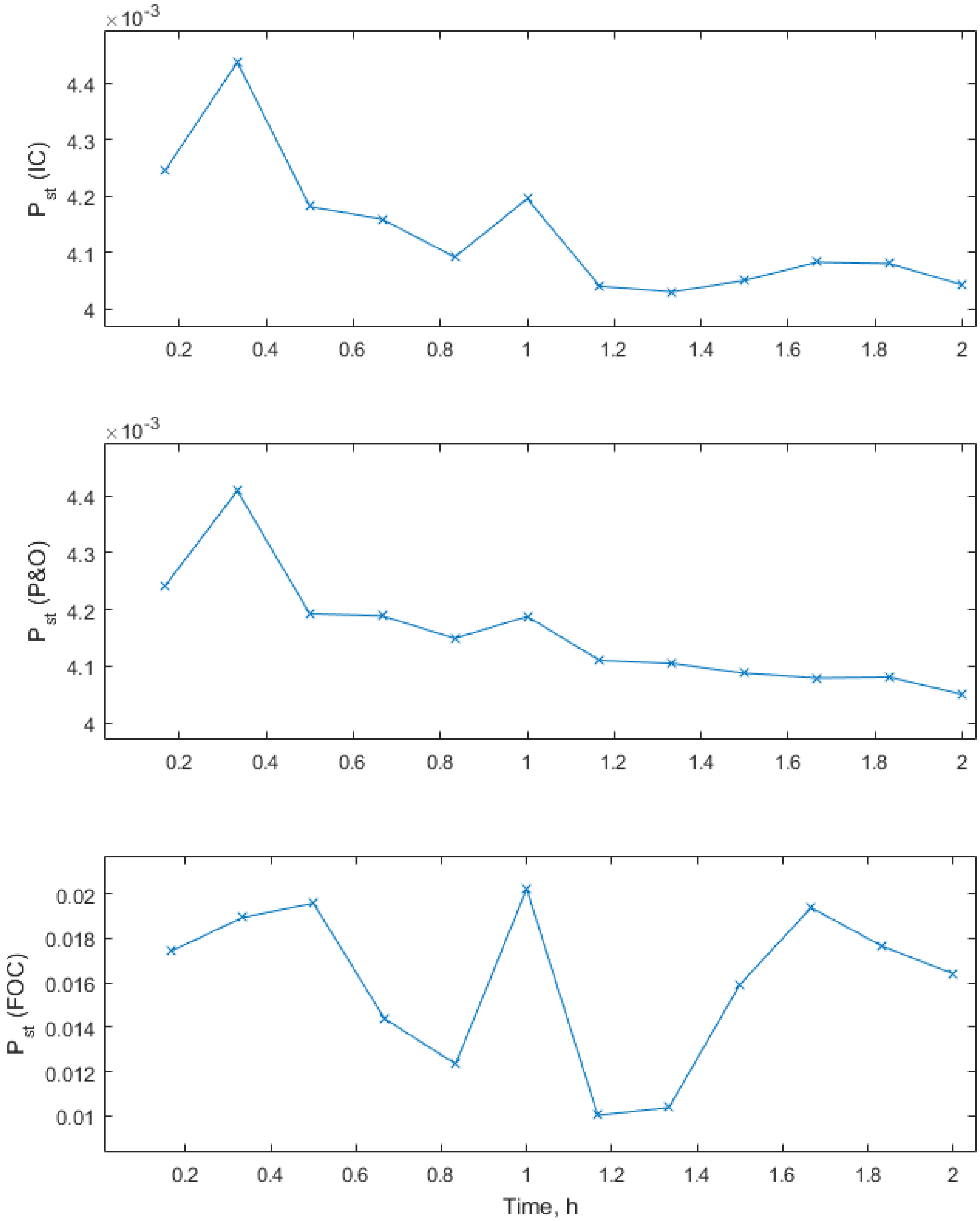

Figure 7: Short-term flicker index with different MPPT methods

Different MPPT methods are compared with respect to average output power, short-term flicker index and long-term flicker index in Table 2. As seen from the table, perturb and observe method produces highest average power. Incremental conductance is slightly better with respect to flicker, but the difference is not very significant. Fractional open circuit produces significantly lower average power and more flicker than the other two methods.

The average power achieved with perturb and observe method is 61.6% of the nominal power of the PV array defined at 1000 W/m^2 irradiance. The average irradiance in the simulation was 636.7 W/m^2. In such conditions of irradiance and average power extracted from this technique is 61.6% therefore MPPT performs well.

Table 2: Comparison between MPPT methods with respect to average power and flicker

MPPT Method / Point of comparison	Incremental conductance	Perturb and observe	Fractional open circuit
Average power, kW	59.73	61.61	42.86
P_{st}, max	0.0044	0.0044	0.0202
P_{st}, mean	0.0041	0.0042	0.0161
P_{lt}	0.0041	0.0042	0.0167

7. Conclusion

In this study, three MPPT methods – incremental conductance, perturb and observe, and fractional open circuit – were compared with respect to output power and flicker. From analysis, it can be seen that perturb and observe and incremental conductance methods provided best results judging by output power and flicker with respect to atmospheric condition that had lower irradiance values at some times. They also had good responses to rapidly changing solar irradiance compared to fractional open circuit.

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9. References

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