Comparative performance analysis on off-grid power systems

Rowland McFadden[1], Radian Belu[1] and Zhengmao Ye[1]

[1] *College of Engineering, Southern University, Baton Rouge, LA 70813, USA*

Abstract

This paper is structured to illustrate the modelling, design, analysis, and simulation of an off-grid power system. An extensive analysis will be conducted to evaluate the performance of the maximum Perturb & Observe (P&O) and Incremental Conductance (INC) maximum power point tracking (MPPT) techniques, focusing on the pros and cons of each. Maximum Power Point Tracking (MPPT) algorithms for photovoltaic systems have been researched to increase the performance and efficiency of the incident sunlight's irradiance entering a photovoltaic array. Perturb & Observe (P&O) and Incremental Conductance (INC) algorithms are the most common algorithms which have been compared for robustness. Previous papers have been published stating that the INC algorithm outperforms the P&O algorithm. This paper shows by fine tuning the Boost Converter and adjusting the PI Controller gains the PV system with the P&O algorithm can perform just as well as the PV system with P&O algorithm. Although the most common constraint of the P&O algorithm is that the tracking consistency decreases during abrupt irradiances while the INC algorithm tracks well under abrupt irradiance changes.

Keywords

Perturb and observe (P&O), incremental conductance (INC), boost convertor, irradiance (G), maximum power point tracking

1. Introduction

Photovoltaic renewable energy is an effective alternative for both production and consumption. Renewables used in power systems can provide numerous advantages: reducing fossil fuel emissions, having a continuous supply of power, backup power when the grid loses power due to black out or electrical faults, and attributing to reducing the demand load on the power-grid. Combining renewable energy generation with a stand-by PV array or energy storage device can render the renewable energy sources more reliable and affordable. This kind of electric power generation system with a main power source from renewable energy and backup power generation or energy storage is known as a "Off-Grid PV system". The main objective of such systems is to produce as much energy as possible from the renewable sources while maintaining acceptable power quality and reliability.

Swarnav Majumder [1] proposed a paper on the performance attributes of a perturb and observe (P&O) and PSO MPPT methods using Matlab/Simulink simulation software. According to this approach, the PSO method produced less oscillations than the P&O MPPT algorithm at the maximum power point. All MPPT methods are confined to high transient time and produced high steady state oscillations. Prasad Sahu and Dixit Tekeshwar [4] presented a paper illustrating the comparative analysis between constant duty cycle and P&O algorithms for extracting power form the proposed PV array. This study utilized the Buck-Boost converter with has a bi-directional voltage control switch. When the voltage exceeds the rated voltage the Buck converter will turn on reducing the overvoltage level. The Boost converter will turn on when the voltage level is below the rated reference voltage. It was concluded in this paper that the PV system output power increased at lower temperatures while the increase in irradiance also increased the power output. Saikat Banerjee, Selvan Saikat, and Jeevananathan N. Thamizh [5] introduced a study comparing the standard MPPT methods concluding that the P&O algorithm is efficient excluding the need for periodic tuning but has a slight oscillation stability issue at high irradiances.

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EMAIL: rowland_mcfadden_00@subr.edu (R. McFadden); radian_belu@subr.edu (R. Belu); zhengmao_ye@subr.edu (Z. Ye)
ORCID: 0000-0003-0108-6005 (R. McFadden); 0000-0002-5892-3225 (R. Belu); 0000-0001-8897-574X (Z. Ye)

Malika Zazi [6] presented a paper illustrating simulated data using PSIM and Matlab Simulink simulation for stagnant and variable irradiances for P&O and INC. The voltage and power levels were approximately the same but the response time for the INC displayed settled more rapidly. Dr. Sharma Bhushan, Fani, Makhija. Prachi [7] conducted an analysis for PSO, P&O, and INC simulating the peak power, reaction time, and stability. The PSO algorithm produced 625W, while the INC and P&O had power values of 415W and 350W, respectively. Reaction time and stability time was also lower for the PSO MPPT method implemented.

R. Ramesh and W. Christopher [2] introduce a paper on the comparison of P&O vs Incremental Conductance (INC) MPPT methods concluding that the Incremental Conductance method produced better stability and power output values than the P&O method. The simulation results illustrated reduced tracking response time with less overshoot for the Incremental Conductance MPPT method. Moznuzzaman, Md [3] also presented a paper comparing P&O vs INC MPPT techniques analyzing the waveform characteristics for changing atmospheric conditions. The INC method adapted better to the changes in irradiance and temperature opposed to the P&O method. The incremental conductance (IC) algorithm seeks to overcome the limitations of the perturbation and observation algorithm by using the incremental conductance of the photovoltaic. The major function of the INC algorithm is to track the voltage operating point where the conductance is the same as the incremental conductance. The advantage of this algorithm is that it tracks the distance from the maximum power point which enables it to find the MPP. INC also performs better under changing irradiation conditions. Many MPPT methods have been developed on the sole purpose of maximizing the sunlight (irradiance) to produce maximum power under changing conditions.

However, popular photovoltaic systems have numerous challenges that must be accounted for. The diurnal and seasonal movement of the Earth affects the radiation intensity on solar energy systems, thus the output system energy. In order to harvest maximum power, solar panels have to operate at maximum power point despite the inevitable changes in the environment. A comprehensive overview on the sun-tracking and maximum power tracking algorithms has been provided [10]. The component rating capacity for the system has been computed in this research. The simple PID controller has also been applied for fine tuning to maximize the system's performance. It also has the potential to be further enhanced via Fractional Order PID control, which could outperform PID controller with respect to swiftness, smoothness, and flexibility via performance analysis using overshoot, peak time and settling time, following existing applications on DC motor control [11]. In this article: Section 1 presents the introduction to the advantages of photovoltaics. Section 2 briefly shows the architecture, I-V, and P-V characteristics of a photovoltaic cell, module, and array being constructed. Section 3 comprises the MPPT algorithms and PV systems design and waveform signal behavior of the P&O algorithm vs the INC algorithm with specified gain values. Section 4 depicts the performance analysis between the P&O algorithm vs INC algorithm. Finally, section 5 provides the conclusions.

2. Photovoltaic characteristics

2.1. Photovoltaic cell architecture

The cell is composed of micro crystalline Silicon Dioxide. The unit of charge for each cell is from 0.4-0.5 volts. The modules are composed of interconnected cells in series and parallel configuration. The array (solar panel) is composed of modules in series and parallel strings producing a Voc & Isc output for the rated PV panel. Photovoltaic modules are composed of interconnected solar cells which are configured in series and / or parallel topology to make up an array. Modules are interconnected to form photovoltaic arrays better known as solar panels. The fundamental parameters that are associated with solar cells are short circuit current (Isc), open circuit voltage (Voc), and maximum power point (MPP) which are used for design (Figure 1).

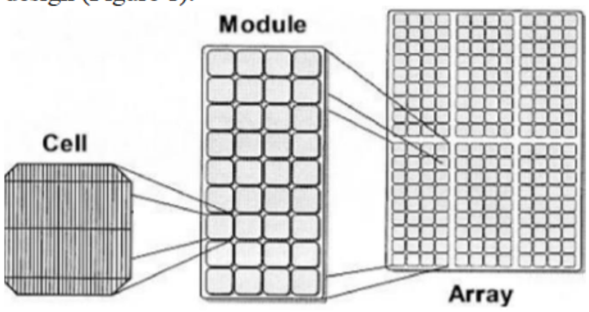

Figure 1: Photovoltaic structure

Sunlight delivers photon energy into the photodiode creating a current through a shunt resistor parallel to the load and series resistor interfaced with to the load producing output voltage. Irradiance (G) is rated in units of 1000W/m^2. Monocrystalline and polycrystalline technologies are based on the microelectronic manufacturing technology (Figure 2).

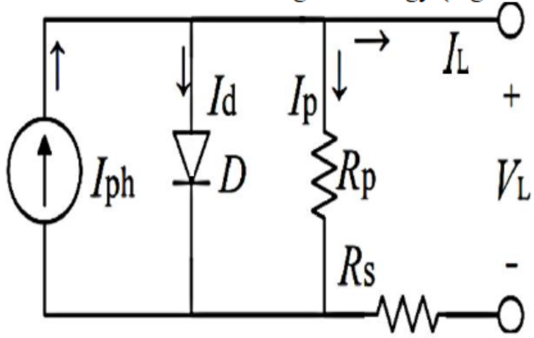

Figure 2: Equivalent PV model

$$Pmp = Vmp \times Imp \quad (1)$$

$$FF = Vmp \times Imp \;/\; Voc \times Isc \quad (2)$$

$$\eta = {}^{Pm}/_{Pin} * 100\% \quad (3)$$

$$\eta pv = Voc*Isc*FF/Pin \quad (4)$$

In equations (1-4), Isc is the maximum current in the power quadrant. When the voltage is equal to zero the short circuit current (Isc) condition is reached dependent on low impedance. Voc is the maximum voltage in the power quadrant. When the current is equal to zero the open circuit voltage (Voc) condition is reached. Pmp is the maximum operating point across the load. Vmp is defined as maximum voltage and Imp is the maximum current. Fill Factor is the ratio of the maximum power from the solar cell to the product of Voc and Isc. Efficiency (η) is basically the power output divided by the power input.

2.2. Photovoltaic characteristics

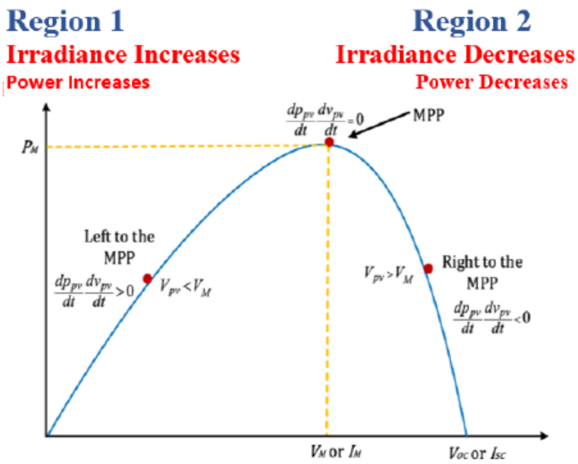

Figure 3: P-V P&O MPPT characteristics

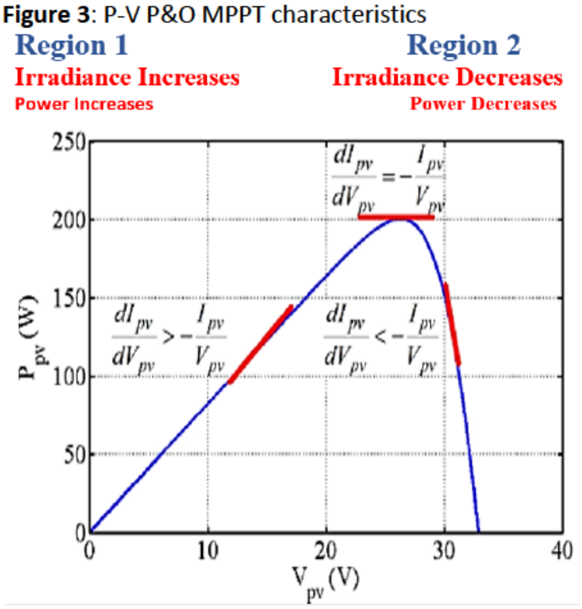

Figure 4: P-V INC MPPT characteristics

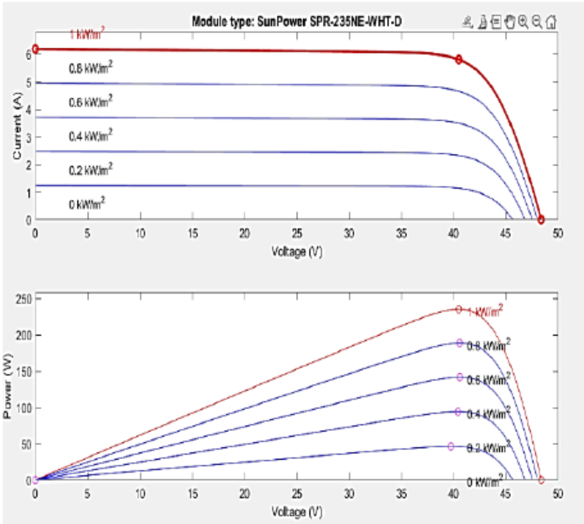

Figure 5: Simulink I-V & P-V characteristics plots

The P-V P&O MPPT Characteristics, P-V INC MPPT Characteristics and Simulink I-V & P-V Characteristics are plotted below in Figures 3-5. The I-V characteristic graph below illustrates the current vs voltage level at irradiances from 0 to 1000 W/m^2 in increments of 200 W/m^2. The temperature is fixed at a value of 250°C. the irradiance increases the current remains constant while the voltage increases. The maximum power point is located at the knee of the plot. The P-V characteristic plot illustrates the power vs the voltage illustrating direct proportionality of the irradiance, power, and voltage. The power remains constant for varying irradiances.

3. Simulink models and flowcharts of two typical MPPT algorithms

3.1. Perturb and observe (P&O) MPPT algorithm

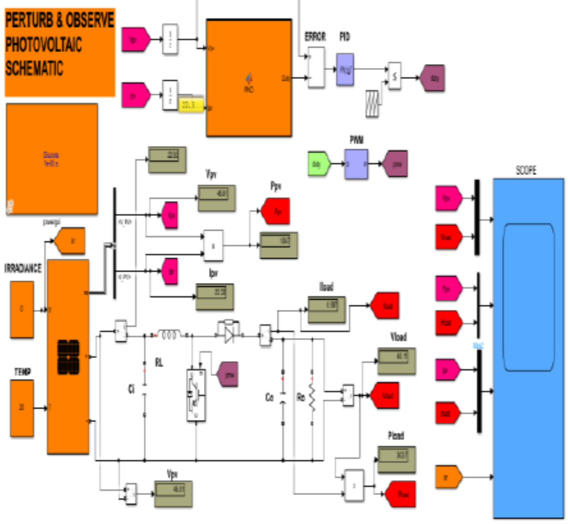

Figure 6: PV with (P&O) MPPT Simulink model

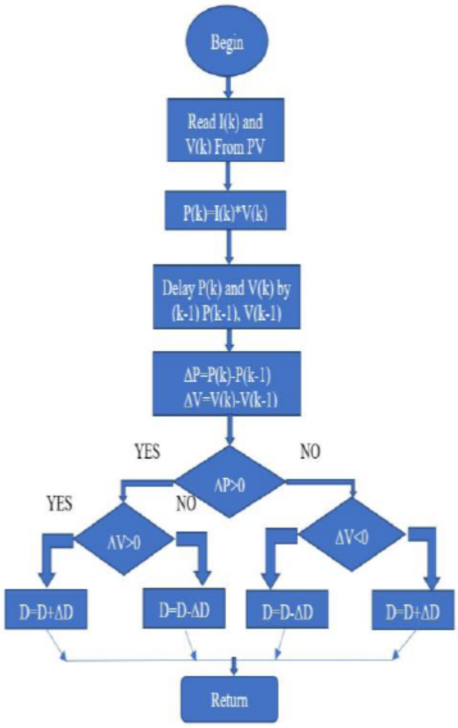

Figure 7: Perturb & observe (P&O) MPPT algorithm

This algorithm is used to develop the source Matlab/Simulink/Simscape code for the control system by adjusting the duty cycle of the switching device. The software has a function block where the code is stored and compiled to the control system. The Matlab code has been slightly adjusted to achieve the appropriate response for step voltage application. The duty cycle has a preselected parameter for the initial input, minimum, and maximum value, which are compared enabling the switching response of the inverter.

3.2. Incremental conductance (INC) MPPT algorithm

The Incremental Conductance Boost Converter Simulink model is interfaced with a Boost Converter. The Boost Converter topology displays an input and output capacitor to regulate the input current from the PV array. An inductor is coupled in series to regulate the voltage and a diode is forward bias in series with the load resistor. The Boost converter will step up the input voltage from the PV array. The control scheme is composed of a PID controller to regulate the proportion and integral gain while the PWM will distribute the duty cycle to the IGBT MOSFET for appropriate on/off switching response. The error function block is coupled to the Matlab function block to track the closed loop line signal to reference signal. Matlab INC source with produce the logic for the on/off duty cycle response. Incremental Conductance method involves tracking voltage and current.

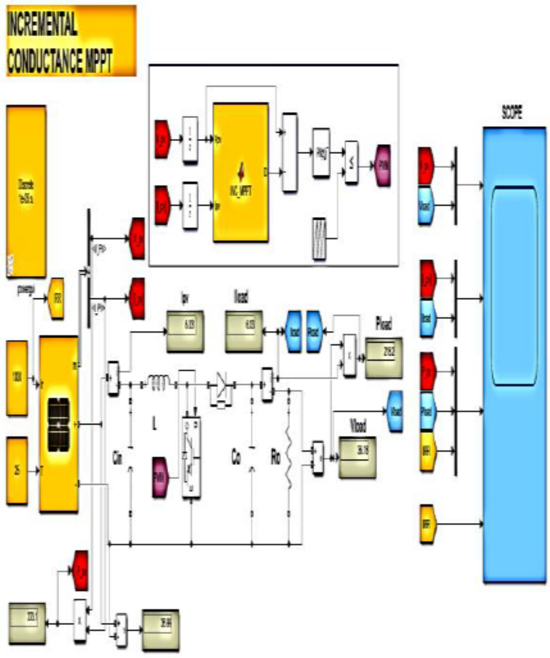

Figure 8: PV boost converter schematic (INC) MPPT

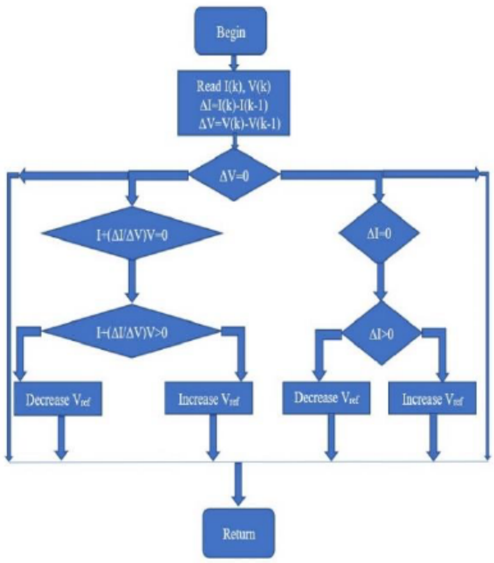

Figure 9: Incremental conductance MPPT algorithm

3.3. Photovoltaic specifications

Table 1

Photovoltaic specifications

Module Data	SunPower SPR-235NE-WHT-D
Maximum Power (W)	234.9
Cells Per Module (N-cell)	72
Open Circuit Voltage (Voc)V	48.4
Short Circuit Current (Isc)A	6.18
Vmp (V) @ Max Power Point	40.5
Imp (A) @ Max Power Point	5.8
Temperature Coefficient of Voc (^{0}C)	-0.254
Temperature Coefficient of Isc (^{0}C)	0.038997

Module Parameters	PV Circuit Parameters
Light Generated Current I_L (A)	6.1883
Diode Saturation Current I_o (A)	2.6227e-12
Diode Ideality Factor	0.91919
Shunt Resistance Rsh (Ω)	320.9611
Series Resistance Rs(Ω)	0.43359

PV Array Data	Connection Configuration
Series Connection	1 module per string
Parallel Connection	5 parallel strings

Photovoltaic specifications (PV Array Data, Module Data, Module Parameter) are listed in Table 1.

4. Performance simulation results

A standard boost converter model is implemented and simulated to gather a base model to compare with the other PV systems. The numerical measurements were conducted to illustrate the operation characteristics of the PV system under various irradiation levels. The power and voltage gains were evaluated to determine if the system operates as expected. The data recorded from the simulations gave a base to compare with MPPT methods. There were six simulations conducted with irradiances of 0, 200, 400, 600, 800, and 1000 W/m^2. The voltage, current, and power levels at the PV panel were measured and recorded, while the boost voltage, current, and power were measured to evaluate the robustness of the base model for the implemented MPPT method. The maximum power point tracking response will be analyzed for increased and reduction in irradiance levels. Voltage, current, and power will be evaluated to determine potential gains and losses during the simulations. The power gain and performance will be compared between the P&O MPPT vs INC MPPT tracking capabilities.

4.1. Simulink P&O simulations

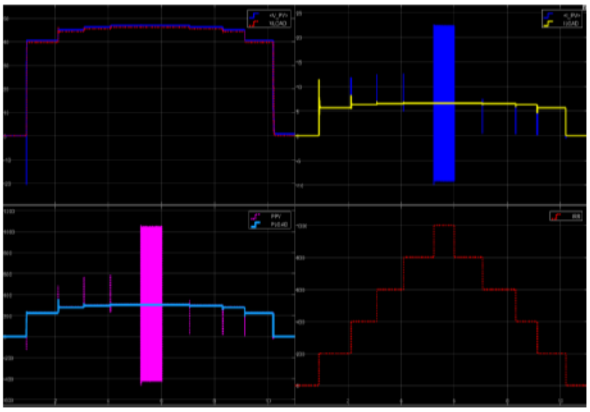

Figure 10: PV system with P&O MPPT rise/sunset cycle irradiances W/m^2

Table 2

PV with perturb & observe MPPT model data

Irr W/m^2	Vpv (V)	V_{load} (V)	Ipv (A)	I_{load} (A)	Ppv (W)	P_{load} (W)
0	0	0	0	0	0	0
200	40.51	39.7	5.67	5.671	229.7	225.2
400	45.04	44.23	6.319	6.319	284.6	279.5
600	46.22	45.41	6.487	6.487	299	294.6
800	46.91	46.1	6.586	6.586	308	303.6
1000	46.91	46.1	22.32	6.587	703	303.7

Simulink P&O simulation results are plotted in Figure 10 and PV with Perturb & Observe MPPT model data are listed in Table 2.

4.2. Simulink INC simulations

Simulink INC simulation results are plotted in Figure 11 and PV with INC model data are listed in Table 3.

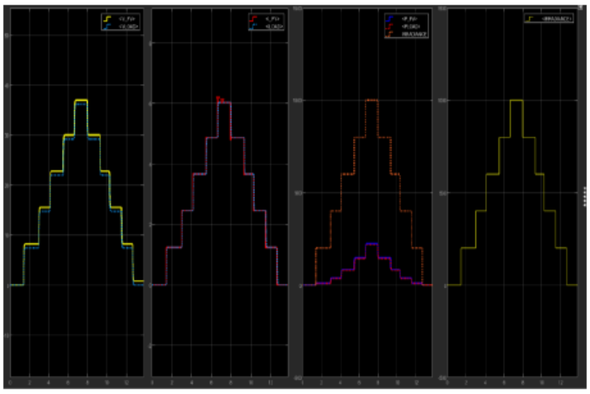

Figure 11: Simulink INC waveform irradiance rise/sunset cycle W/m^2

Table 3

PV with INC model data

Irr W/m^2	Vpv (V)	V_{load} (V)	Ipv (A)	I_{load} (A)	Ppv (W)	P_{load} (W)
0	0	0	0	0	0	0
200	8.19	7.39	1.23	1.32	10.1	9.109
400	15.5	14.7	2.45	2.45	38.1	36.15
600	22.6	22	3.66	3.66	83.6	80.69
800	30.0	29.2	4.87	4.87	146	142.3
1000	36.9	36.2	6.03	6.03	223	218.2

4.3. Performance comparisons

Table 4

PV with P&O performance sunrise/sunset cycle irradiance

Response	V_{load} (V)	I_{load} (A)	P_{load}(W)
Average	36.89	5.27	234
Overshoot (%)	21.1	12.54	24.9
Undershoot (%)	3.08	11.10	6.04
Rise Time (s)	4.55ms	30ms	24ms

Table 5
PV with INC performance data sunrise/sunset cycle irradiance

Response	V_{load} (V)	I_{load} (A)	P_{load}(W)
Average	**18.25**	**3.04**	**81.4**
Overshoot (%)	**0.480**	**0.418**	**0.42**
Undershoot (%)	**1.666**	**1.666**	**1.666**
Rise Time (s)	**34ms**	**34ms**	**40ms**

The PV system with the P&O algorithm had a faster rise time, less overshoot, less undershoot, and more average voltage and power gain than the PV system with the INC algorithm.

5. Conclusions

The objective of this research is to design, analyze and improve on the performance of a DC photovoltaic system. Perturb & Observe and Incremental Conductance MPPT algorithms were compared using the Matlab/Simulink/Simscape simulation software. In each system, a Boost converter was coupled to the PV array to step up the voltage and power to the load resistor. Power at the output terminal was highest for the PV with P&O MPPT algorithm. The tracking system for PV system with INC MPPT performed the best, displaying less attenuation in the signal than the others. Each system maintained constant voltage regulation throughout the irradiance change cycle. The major components to design the PV system needed to be sized for the Boost converters to operate properly. Standard converter equations are design for ideal conditions whereas solar generation is dependent on variable irradiance levels which creates a nonlinear signal response. The rating for the capacitors, inductor, and resistor is key to design robust Boost converter. Comparisons between the Perturb & Observe and Incremental Conductance algorithms were made to reveal the pros and cons of each. The Perturb & Observe method for power point tracking doesn't perform well under rapid changing irradiance levels while the Incremental Conductance method does. When various level of irradiation was injected into the PV array in increments 200W/m^2, both algorithms worked. The P&O algorithm produced signal distortion while the INC PV system produced less signal distortion. Thus the system needed additional tuning by increasing the input capacitor rating to smooth out the current ripples. Changing the proportional gain to 0.45 and the integral gain to 5 helped to reduce the rise time response of the output signal. The PV system with P&O algorithm outperformed the PV system with the INC algorithm by achieving a faster rise time, less overshoot, and more power gain, but the PV system with the INC algorithm had less signal attenuation.

6. References

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