A Power Electronic Controller Based Algorithm for Output Power Prediction of a PV Panel.

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Abstract- The utilization of renewable energy sources, such as solar and wind power, has gained significant momentum in recent years due to concerns about the environmental impact of traditional fossil fuels and the desire for energy independence. Governments, organizations, and individuals around the world are investing in and implementing renewable energy systems at an increasing rate. One such issue is the uneven power generation in large solar panel farms, where different zones are affected by varying weather and sun irradiance conditions. This results in a disparity in power generation between zones. In order to address this problem, this paper proposes a solution of incorporating small PV panels that will act like a PV detector in each zone, which are affected by the same weather and irradiance conditions and have the same azimuth and tilt angles to estimate the output power of PV panels. The PV detector will be loaded to their maximum capacity using a Power Electronic Controller (PEC) of MPPT algorithms cascaded with a well-designed topology that maintains the MPPT is working at its maximum load in all cases. By comparing the instantaneous power generated and the maximum power that can be delivered by the PV detector to the PEC, the power of the zone can be accurately determined. In addition, our MATLAB simulation allows us to implement in real life our theory and being industry applicable with results approximately equal to results shown in MATLAB.

Keywords Renewable Energy, Power Generation, Photovoltaic, Sustainability.

1. Introduction

Globally, the use of renewable energy sources such as solar and wind power has increased significantly. This increase has brought about several challenges, including power quality problems in photovoltaic (PV) systems, such as voltage sags, flicker, and harmonics, which impact the stability of the grid [1][2][3][4]. However, a major issue that still affects the performance and efficiency of solar farms is the uneven power generation between different zones caused by varying weather and sun irradiance conditions. This leads to not having an accurate estimation of the overall power of the whole grid [5]. The goal of this paper's research is to create a solution to this problem by incorporating small PV detector connected to a well-designed Power Electronic Controller (PEC) in each zone to detect the power generated by each zone and estimate the power generated by the entire grid by adding the power estimation of each zone. The proposed methodology entails installing PV detectors in each zone and connecting them to an MPPT cascaded with a power electronic circuit topology; the first follows a P&O algorithm, while the power electronic circuit follows an algorithm that keeps the MPPT operating at maximum capacity in order to track the maximum power point and keep the MPPT operating at maximum load this PEC will lead us to estimate the power of each zone especially for the off grid system where the PV generation is dependent on the load it itself. The power of the zone can be calculated by comparing the instantaneous power generated to the maximum power that the PV detector can deliver while accounting for the efficiency of the two MPPTs. Implementing this proposed solution could result in more efficient and effective use of renewable energy, as well as a better understanding of the power generated by each zone in a solar farm.

Referring to previous work in PV power prediction we can see that some papers during time are released to clarify this problem statement we can see that a lot of studies was conducted with the goal of forecasting the AC power output of a PV plant using meteorological data [6][7][8]. In 2015, The authors proposed a methodology that employs a nonparametric PV model with several forecasts of meteorological variables from a Numerical Weather Forecast model as inputs, as well as actual AC power measurements from PV plants. Collecting previous AC power measurements from a PV plant, forecasting a set of Weather Research and Forecasting variables such as solar radiation, cloud cover, temperature, and wind speed, and then training a machine learning tool are all part of the methodology. The study's findings show that this approach views the PV system as a black box and does not assume any knowledge of the system's internal characteristics and processes. It was also discovered that increasing the number of Weather Research and Forecasting variables does not necessarily improve forecast accuracy, and the overall cvMAE measure of the goodness of predictions for applications requiring hourly predictions over a 24-hour period) was less than 9.5% [9]. Furthermore, in 2018, a study was conducted with the goal of determining the most effective data collection and model building scenario to support reasonably accurate prediction of solar PV power output. The study's methodology included two scenarios for data collection and modeling of solar PV performance. Predicting PV module power output using measured cell/module temperature and climatic data such as irradiation on POA, ambient temperature, and wind velocity is the first scenario. The second scenario involves only using climatic data to predict PV module power, such as solar irradiation on a horizontal or tilted surface, ambient temperature, and wind velocity. The study's findings revealed that predicting field PV module power requires measurements of solar irradiation on the plane of the array [10]. Moreover, in 2020, a study was conducted with the goal of forecasting PV solar output power using meteorological variables. The authors used machine learning-based regression methods to analyze the correlation and interdependence among meteorological variables using three years of input meteorological data and PV output power data from multiple prosumers in two case studies, one in the United States and one in the Netherlands [11]. We can notice that studies that uses meteorological variables and forecasting power using techniques like calculations or machine learning suffering from limitations and drawbacks like errors in sensors and there life time that are sensing irradiance, temperature and other needed parameters in addition to processors limitations that is performing the calculation also the higher the data acquisition performance the higher the price in plus the major limitation is the global warming that is affecting the planet and change in climate where the weather from 3 years in different from nowadays weather [12].

In addition, in 2017, the authors use a Long Short-Term Memory (LSTM) network to model and predict solar power output. The authors found that the LSTM network is an efficient technique with acceptable accuracy for predicting short-term photovoltaic (PV) power output. However, the results of the study are limited by the use of only one year of meteorological data, and the effects of global warming on the weather patterns. All these conditions increase the importance of proposing a new accurate and industry applicable method [13].

In addition, in 2018 where a study published that aim to investigate the reliability of a Generalized Regression Neural Network (GRNN) algorithm for the power prediction of a PV panel in order to minimize the effect of fast-changing meteorological conditions. They use a GRNN algorithm which is a type of neural network that is used for function approximation, it can be used for nonlinear and complex systems, it's suitable for a large set of data, and it doesn't require much calculations. In their methodology, they use PV panels and electrical load with sensors that read current, voltage, temperature, and pyranometer data, these data are entered into an NI 6212 board for data acquisition. The results of the paper show that the algorithm is able to predict the output power of the panel based on available solar irradiance and temperature [14]. We can notice that drawback of sensor measurements errors and life time is also available in this study in addition to high price of the used board.

Also, we can see that there are more techniques in 2020 to increase the efficiency and estimating the PV output power as we are seeing in this paper by Francesco Nicoletti et al. which aimed at estimating the PV electrical power and temperature profile along the panel thickness. They introduced a methodology to estimate the cloudiness of the sky, which affects radiative heat exchange and used it to infer the PV Electrical Power and Temperature Profile. The results of the study shows that this model was able to predict the temperature of the back of PV panels with small number of acceptable errors. However, the model has markable limitations, such as the assumption of homogeneous temperature for the faces [15].

Finally, referring to the limitations of existing techniques for predicting the maximum power output of a solar farm and considering the recommendation of most of researchers in their future work on the importance of using additional parameters to increase the sensitivity and accuracy of power prediction [16]. Also, an accurate and effective method to predict output power for PV panels is needed[17][18]. We propose the use of a PEC based algorithm for instantaneous power prediction. This method offers a notably lower cost compared to alternative approaches and is highly reliable due to its closed-loop integration with the power circuit. Additionally, it is versatile and can be used with any PV panel model available on the market, while also being relatively simple to implement and use.

2. Proposed Methodology

In order to predict the output power of a photovoltaic (PV) panel in an off-grid system, I propose a new method that utilizes a PEC board connected to a PV detector. This board is composed of a Maximum Power Point Tracking (MPPT) algorithm, which is cascaded with a well-designed topology to ensure that the MPPT is operating at its maximum load. The topology is formed by a RC passive low-pass filter and a Buck-Boost circuit. The gating of the Buck-Boost circuit is controlled by an algorithm that takes the power delivered by the MPPT as input and controls the gating to maintain that the MPPT is at its maximum in all weather conditions. The PEC will track the maximum power that can be delivered by the PV detector, and by considering the efficiency of the PEC and comparing the instantaneous power consumed by the PEC and the maximum power that can be delivered by the PV detector, we can deduce a percentage. Using this percentage, we can determine how much the zone where the PV detector is placed can be delivering instantaneously. This can be done by multiplying the percentage with the maximum power that can be generated by this zone in typical conditions, while considering losses. This algorithm will be implemented in a closed-loop control circuit, where it takes feedback from the inverter to increase the accuracy of the prediction. Also, regarding the inverter the AC output that is feeding the load and the DC terminal that is connected to battery bank will be measured and added to the algorithm to ensure that the methodology is working in a closed loop with fast response time. The proposed system has several advantages in off-grid systems, as it allows for accurate prediction of power output, enabling the user to manage load consumption, battery usage, and charging in real-time. This, in turn, allows the user to benefit from excess power and optimize their energy usage. Figure 1 below describes the proposed methodology.

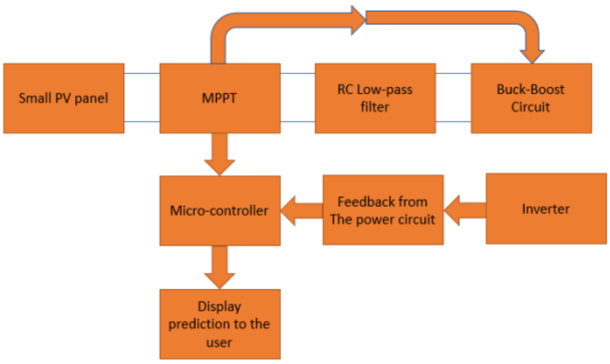

Fig. 1. Methodology single line diagram.

3. Mathematical Model

To prove our methodology, we made it mathematical model of the PEC board, starting by:

- ❖ MPPT that follow the P&O (perturb and observe) algorithm:
- Acceptable switching frequency [20Khz;60Khz] we will choose 50Khz.
- Maximum input voltage= 19V.
- Minimum input voltage= 10V.
- Maximum output voltage= 21V.
- Minimum input voltage= 20V.
- Output current= 0.5A.
- Ripple= 0.1V.

Referring to this given we can design a well DC-DC converter:

$$Dmin = 1 - \frac{Vin(Max)}{Vout(Min)} \quad (1)$$

$$Dmax = 1 - \frac{Vin(Min)}{Vout(Max)} \quad (2)$$

$$Lmin = D \times Vin \times \frac{1-D}{2\times f\times Iout} \quad (3)$$

$$Ipeak = \frac{Vin(Max)\times D}{f\times L} \quad (4)$$

$$Cmin = \frac{Iout}{Vripple\times f} \quad (5)$$

We will select the value of inductor and capacitor depending on our calculations and the availability in the market as per Table 1.

Table 1. Inductor and Capacitor parameters 1

Inductor	$L = 100\mu H;\ I = 4A$
Capacitor	$C = 200\mu F; V = 40V$
MOSFET	$Power = 1700W$

We chose a high speed MOSFET due to high switching frequency. In addition, a 7 K/W heat sink is designed to maintain high switching frequency.

- ❖ RC Low-pass filter:

$$Xc = \frac{1}{2\times \Pi \times f \times C} \quad (6)$$

With $C = 4700\mu F$

$$Vout = Vin \times \frac{Xc}{\sqrt{R^2+Xc^2}} \quad (7)$$

With $R = 50\Omega$

- ❖ Buck-Boost Circuit:
  - Switching frequency=5Khz.
  - Maximum input voltage= 1.5V
  - Output voltage=1V
  - Resistance= 10Ω

Referring to this given we can design a well DC-DC converter:

$$Vout = -Vs \times \frac{D}{1-D} \quad (8)$$

$$Lmin = \frac{(1-D)^2\times R}{2\times f} \quad (9)$$

$$Cmin = \frac{D}{R\times r\times f} \quad (10)$$

We will be select value of inductor and capacitor depending on the availability in the market as in Table 2.

Table 2. Inductor and Capacitor parameters 2

Inductor	$L = 2.8\mu H;\ I = 1A$
Capacitor	$C = 2.2\mu F; V = 16V$
MOSFET	Power=1700W

Then dividing the instantaneous power (P_i) delivered that we are measuring at the input of the proposed topology circuit by the maximum power (P_m) that can be delivered by the PV detector considering the efficiency of the PEC multiplying by one-hundred will give us a percentage (P) that we will use later on to predict the maximum instantaneous power that can be delivered by the zone (P_{zi}) where this PV detector is placed:

$$P = \frac{Pi}{Pm \times \eta} \times 100 \quad (11)$$

$$Pzi = \frac{P}{100} \times (Pm \times \eta) \quad (12)$$

4. Matlab Simulation

A. Testing the PEC on Matlab:

To show the validity of implementing our proposed methodology in real life and prove our mathematical model a simulation on MATLAB is made with same calculated value and methodology. Figure 2 below shows the circuit implemented on MATLAB for the PEC board connected to a small 9.72 Watts PV panel and tested at different weather and irradiance conditions.

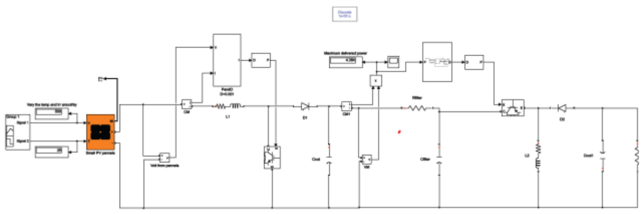

Fig. 2. PEC circuit.

B. Simulation results:

Results of the simulation under different weather and irradiance conditions as shown in figure 3.

Our proposed methodology and mathematical model are both valid through simulation results made on MATLAB [19] for predicting the maximum power output of solar strings in a specific location, regardless of weather conditions, irradiance temperature, or the specific PV modules used. As demonstrated in Figure 4, our methodology closely follows the instantaneous maximum power output of the PV detector under various weather and irradiance conditions. Furthermore, the proposed methodology can be implemented

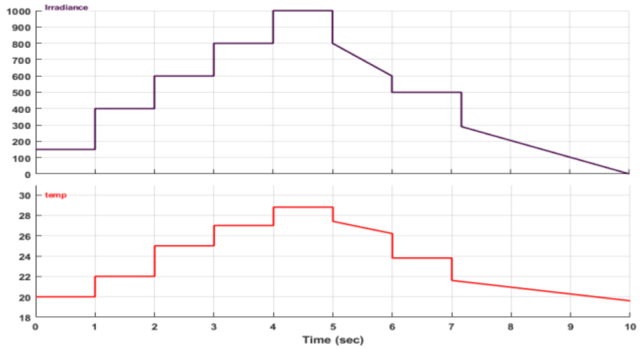

Fig. 3. Variation of irradiance and temperature with respect to time

in real-life scenarios, making it a reliable tool for predicting the maximum power output of solar farms.

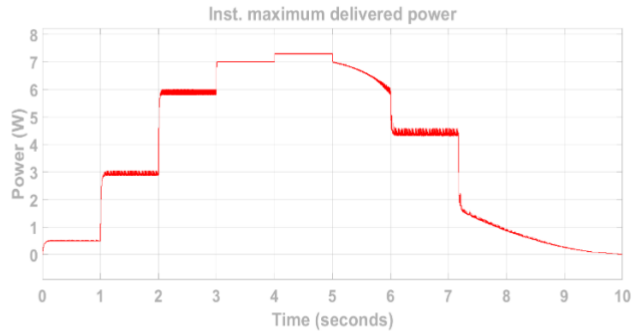

Fig. 4. Instantaneous maximum delivered power of PV detector.

After analyzing the result obtained, we can deduce that the PEC proposed topology is giving us the desired output by tracking the maximum power that can be delivered by the PV detectors connected, with small oscillations as shown in figure 5. These small oscillations appears when the PEC board is working on the maximum output power where the average between the maximum and minimum point of these small oscillations represents the maximum output power point that PV detector can deliver instantaneously.

Fig. 5. zoom in for instantaneous maximum delivered power of PV detector.

In addition, our PEC board is evaluated in a 3.2KW grid composed of two parallel 1.6KW each string. Where these two strings are placed in two different zones on the same building roof and PV detectors are placed in the middle of each string. The 3.2KW is set to work at its maximum and the

PEC board is predicting the output of the grid as shown in figure 6.

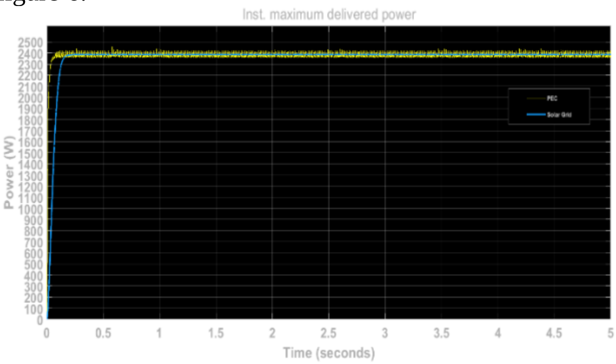

Fig. 6. Output power prediction of PEC board for a solar grid

5. Conclusion

The proposed method for predicting the output power of a photovoltaic (PV) panel in an off-grid system utilizes a PEC board. The PEC board is composed of a Maximum Power Point Tracking (MPPT) algorithm, which is connected to a well-designed topology that continuously measures the power and varies the control of the gating. The instantaneous maximum delivered power by the PV detector is measured and entered a microcontroller, which considers the efficiency of the PEC board, as well as the efficiency of the PV module and any losses. The system operates in a closed loop, as it takes feedback from the power circuit, and the results are displayed on a screen. One of the primary advantages of this method is its low cost and adaptability to any solar farm, regardless of the PV panel specifications. Furthermore, the proposed system enables accurate power output prediction, allowing the user to manage load consumption, battery usage, and charging in real-time, allowing the user to benefit from excess power and optimize their energy usage. The PEC board will be integrated with a user-friendly interface that will display the instantaneous maximum delivered power by the PV detector in the future vision of this proposed method. This enables the user to easily manage their electricity consumption and make informed decisions about how to use the PV panel's power. The user will have the option of using all the power delivered by the panel, using some of the power to charge a battery, or even benefiting from excess power by turning on home equipment or powering a smart water heater. The smart water heater that we envision in the future will be able to read the amount of excess power being generated by the PV panel and adjust its heating operations, accordingly, allowing the user to benefit from the excess power generated by the panel. This will not only increase the efficiency of the system, but also provide the user with more control over their energy usage.

Overall, the proposed method for predicting the output power of a PV panel in an off-grid system has the potential to be integrated with other smart energy management systems, such as the smart water heater, to provide users with more control over their energy usage and increase the overall efficiency of the system. The use of a PEC board, MPPT algorithm, and a well-designed topology allows for accurate predictions of power output, making it a cost-effective solution that can be used in any solar farm. Figure 5 is illustrating 3D drawing about how PV detectors is placed in the middle of each string with different zones that are affected by irradiance conditions.

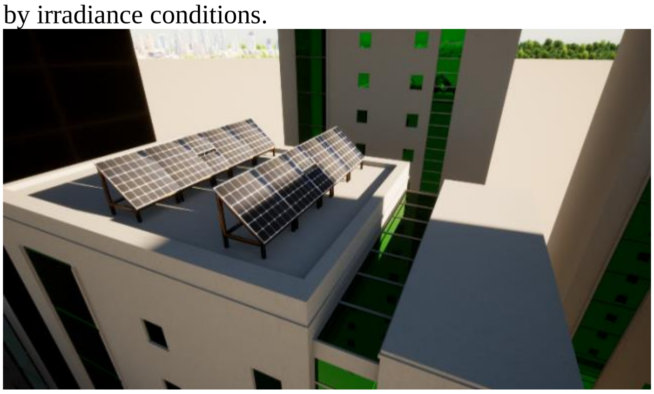

Fig. 7. PV detectors placed in different zones.

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