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Implementation of Maximum Power Point Tracking Using Kalman Filter for Solar Photovoltaic Array on FPGA

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Abstract

This paper proposes FPGA implementation of a novel approach to track maximum power point of a solar photovoltaic array. The approach uses Kalman filter algorithm to track maximum power point. Using this approach tracking becomes much faster than using the generic Perturb & Observe algorithm in case of sudden weather changes. In this paper output of the proposed algorithm on FPGA is provided. Experimentation was performed under optimal conditions as well as under cloudy conditions i.e. falling irradiance levels. Using the proposed technique the maximum power point of a solar PV array is tracked with an efficiency of 97.11%. Moreover, the maximum power point has been tracked at a much faster rate i.e. 4.5 ms using the proposed algorithm compared to the existing generic Perturb and Observe approach.

Keywords: Maximum power point tracking, Kalman filter, perturb and observe, photovoltaic, FPGA

1. Introduction

Solar energy is one of the most widely used sources of renewable energy and is available in abundance. Solar radiation is converted to electrical energy by using solar cells which exhibit photovoltaic effect. Photovoltaic power is used in a variety of applications such as power generation, mobiles, computers and transportation applications. These PV solar panels exhibit non linear V - I characteristics as their output supply depends mainly on the nature of connected load. Moreover there exist multiple maxima in the output characteristics of a solar PV array under partially shaded conditions. Hence, it is essential to find optimal power point of the panel so as to increase the overall efficiency of the photovoltaic system. Hence, Maximum Power Point Tracking (MPPT) algorithm is used for extracting maximum power available from a PV module under different conditions [1]. Various MPPT techniques have been used in past but Perturb & Observe (P&O) algorithm is most widely accepted and preferably used by industry. Using P&O algorithm the controller adjust voltage and measures power and if this measured power is greater than the previous value of power, adjustments are made in the same direction until there is no more increment in power [2]. Fig. 1 shows how power is calculated using P&O algorithm. P&O is also called as hill climbing method because it checks the rise of the curve till MPP and the fall after that point. This method is easy to implement but can cause oscillations in power output and can sometimes show tracking failures in rapid environmental changes [3] i.e. locates operating point away from MPP when there is a sudden change in voltage characteristics.

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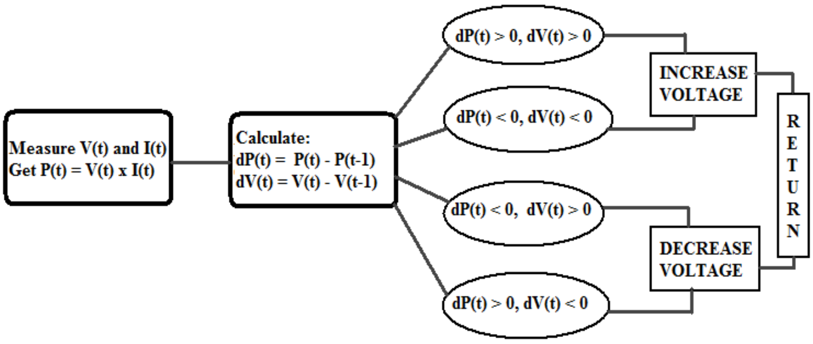

Fig. 1. Flowchart depicting the Perturb & Observe algorithm.

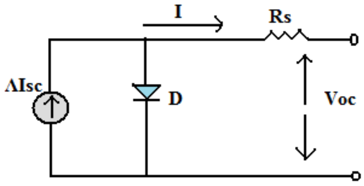

Fig. 2. Solar cell equivalent circuit.

This paper proposes implementation of a new MPPT technique using Kalman Filter. A linear state space representation is used to apply the Kalman Filter algorithm to track the maximum power point of a PV array. The algorithm has been implemented on Altera Cyclone II EP2C20F484C7 FPGA board [4].

Section 2 describes the characteristics of a PV array. Section 3 describes the proposed Kalman filter approach for tracking maximum power point. Section 4 describes the system configuration and setup. In section 5 the results of MPPT using Kalman filter on FPGA are discussed. Section 6 gives the conclusion.

2. Characteristics of PV Array

PV array consists of collection of numerous solar cells in series or parallel. Fig. 2 shows the circuit model of a solar cell. The shunt resistance is ignored just for simplicity which is good enough to make fairly accurate models. The simplified equation [4] is given as

$$I = I_{SC}\left\{\lambda - \frac{1}{\exp\left(\frac{qA}{kT}\right)}\left(\exp\left(\frac{qAV}{kTV_{OC}}\right) - 1\right)\right\} \tag{1}$$

where V_{oc} and I_{sc} are open circuit voltage and current values at 1 kW/m^2 and 25 °C. V and I are the array output voltage and current, q is the elementary charge, k is the Boltzmann constant, T is the temperature of array in °C, λ is irradiance in kW/m^2 and A is a constant, generally taken as 0.2464 [5].

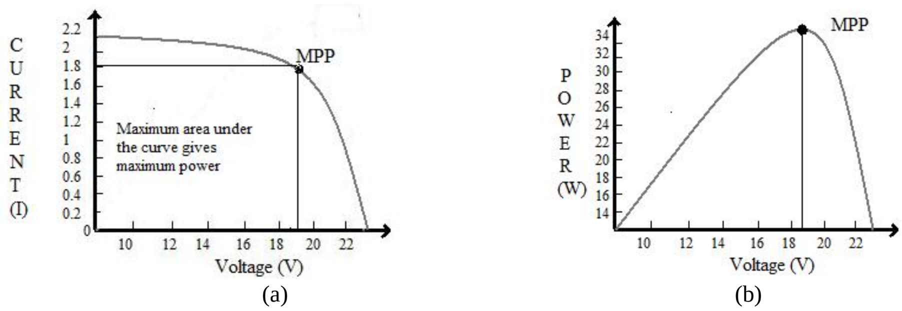

Fig. 3. (a) Generic Current vs. Voltage curve; (b) Generic Power vs. voltage curve.

Characteristics of a PV array is described by *I-V* curve and taking value of *A* as 0.2464 makes the behavior of the equation similar to ideal behavior of the *I-V* curve. A general *I-V* curve is shown in the Fig. 3 (a) under given conditions i.e. irradiance of $1kW/m^2$ and temperature of 25 °C there is one point on the *I-V* curve which gives Maximum Power Point because it maximizes the area under the curve. A general *P-V* curve is shown in Fig. 3 (b) the PV panel considered has V_{oc} = 22 V and I_{sc} = 1.3 A at $1kW/m^2$ and 25°C.

3. MPPT using Kalman Filter

3.1. Kalman Filter

Kalman filter provides stochastic estimation in noisy environment. The kalman filter operates on estimating states by using recursive time & measurement updates over time. Noise effect in the system is decreased due to recursive cycles which finally lead to the true value of measurement [6]. Fig. 4 shows the generic block diagram of Kalman Filter.

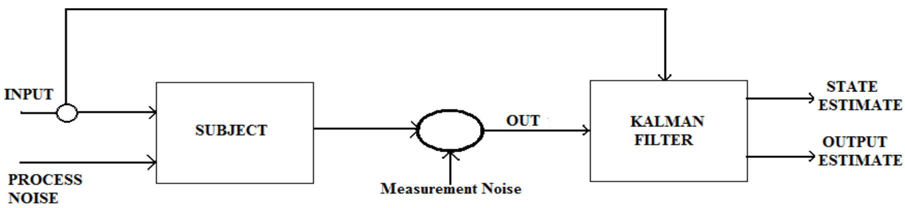

Fig. 4. Generic block diagram to describe Kalman Filter algorithm

Let the input be x_t at iteration t, control process be u_t at iteration t, *w* be the added process noise and *v* be the added measurement noise. The Kalman filter equations are given as follows:

A. Time Update – (Prediction state)

$$\hat{x}_t^- = A\hat{x}_{t-1} + Bu_{t-1} \tag{2}$$

$$z_t^- = Az_{t-1}A^T + Q \tag{3}$$

Here Q is the process noise covariance, $\hat{x}_t^-$ be the state estimate at iteration *t* given by the results from former iterations, $\hat{x}_{t-1}$ be the state estimate at iteration *t* given by the measurement output y^t , z_t^- be the priori error covariance and z_t or z_{t-1} be the posteriori error covariance**.** *A* & *B* are constants.

B. Measurement Update – (Correction State)

$$K_t = z_t^- C^T (Cz_t^- C^T + R)^{-1} \tag{4}$$

$$\hat{x}_t = \hat{x}_t^- + K_t(y_t - C\hat{x}_t^-) \tag{5}$$

$$z_t = (I - K_t C)z_t^- \tag{6}$$

R is the measurement noise covariance, K_t is the Kalman gain & *C* is constant.

The above equations [7] represent Kalman filter implementation for a generic linear discrete system. The time update predicts forward state estimate and error covariance. The estimates are then put into measurement update which acts as correction mechanism and correct the estimated values. As the above cycle takes place multiple times turn by turn the noises are reduced and the error covariance z_t becomes closer and closer to zero.

3.2. MPPT using proposed equations

According to the P – V curve power increases with a gradual positive slope until reaches one optimal point and decreases after that steeply. Based on that feature the MPPT algorithm is governed by the given state equation [8] where V_{actual}^{t+1} is the value of voltage updated by the MPPT controller at iteration t+1.

$$V_{actual}^{t+1} = V_{actual}^{t} + M\frac{\Delta P^t}{\Delta V^t} + w, \quad (A=1 \text{ and } B=M) \tag{7}$$

M is the step size corrector and $\Delta P^t / \Delta V^t$ denotes the slope of the P – V curve at instant t of solar array. The slope $\Delta P^t / \Delta V^t$ is same as control unit u_t and on adding process noise w into the system a similar one dimension linear state space equation can be formed.

The measurement equation is dependent on V_{actual}^{t} and measurement noise v.

$$y^t = V_{actual}^{t} + v, \ (C=1) \tag{8}$$

Considering y^t as the reference voltage at given instant we get the updated measurement equation [9] as

$$V_{ref}^{t} - V_{actual}^{t} = v \tag{9}$$

Two known values, V_{ref}^{t} and $\Delta P^t / \Delta V^t$ are used for Kalman filter estimate.

3.2.1. Time update

Based on voltage estimate V_{actual}^{t-1} & error covariance z_{t-1} of the previous state we predict new estimate

$$\begin{aligned} V_{actual}^{t^-} &= V_{actual}^{t-1} + M\frac{\Delta P^{t-1}}{\Delta V^{t-1}}, \quad (V_{actual}^{t^-} \text{ is analogous to } \hat{x}_t^-) \\ z_t^- &= z_{t-1} + Q \end{aligned} \tag{10}$$

3.2.2. Measurement Update

From the error covariance update in prediction (time update) state we calculate the Kalman gain first:

$$K_t = z_t^-(z_t^- + R)^{-1} \tag{11}$$

Now K_t updates the estimate of V_{actual}^{t} and z_t by using $V_{actual}^{t^-}$ and z_t^- from the prediction state & K_t from equation (11)

$$V_{actual}^{t} = V_{actual}^{t^-} + K_t(V_{ref}^{t} - V_{actual}^{t^-}) \tag{12}$$

$$z_t = (1 - K_t)z_t^- \tag{13}$$

As the above steps occur turn by turn the estimated result is expected to be closer to the maximum power point.

4. System Configuration and Setup

As shown in Fig. 5, solar array is initially connected to current and voltage sensor which gives the voltage and current value at that instant of time, the voltage will be reduced between 0 – 5 V by using resistances so that it can be passed by a low pas filter to ADC (which works between 0 – 5 V). The digital output of ADC is sent to the FPGA running the MPPT algorithm for floating point values. The output from FPGA is sent to a Digital to Analog converter in form of the PWM wave, the Pulse width is decreased till one move closer to MPP and as one starts moving away from MPP the width of PWM is increased. The analog output is sent to DC - DC boost converter which converts voltage at levels 0 V – 5 V to appropriate level between 18 V – 24 V and thus final output is sent to the load connected. Fig.6. displays the circuit setup with the ICs used.

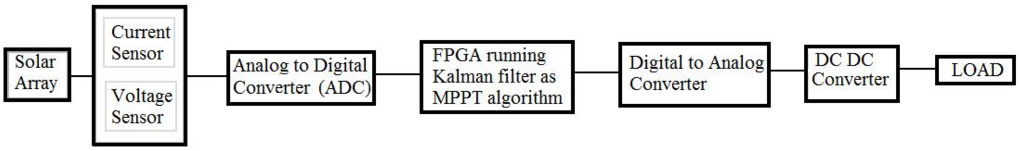

Fig. 5. System setup (Block level)

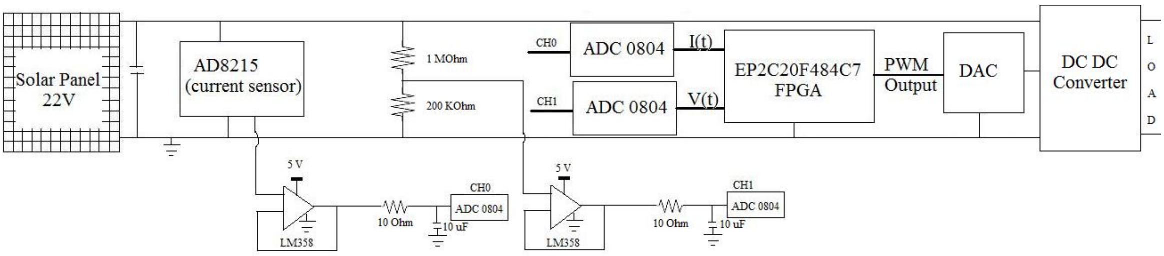

Fig. 6. System setup with configuration (circuit level)

5. Simulation and Results

For implementation purpose a 22 V (open circuit voltage) & 1.3A (short circuit current) solar panel is used. It produced 29 W at 25^0C and 1kW/m^2 irradiance. MPP varies from 18 V - 22 V depending upon environment conditions. The error approximation of current sensor is around $\pm 0.3\%$ so an error of approximately 0.3% is considered from this when measuring current values. Voltage sensor has small accuracy issue but major accuracy issue comes with ADC which has error approximation of $\pm 2\%$. So, we take the measurement noise v to be around 2%. M is selected on the basis of voltage change limitation and slope of the P – V curve. According to calculation M comes out around 0.05. The algorithm has been realized on EP2C20F484C7 as implementation on reconfigurable architecture like FPGA ensures hardware based flexibility.

Fig. 7 depicts the convergence of proposed MPPT algorithm at optimal conditions (i.e. 25^0C and 1kW/m^2) with the time of convergence around 4.5 ms which is much less than time of convergence by generic P&O algorithm (executed under same ambient conditions) which is around 15ms [10].

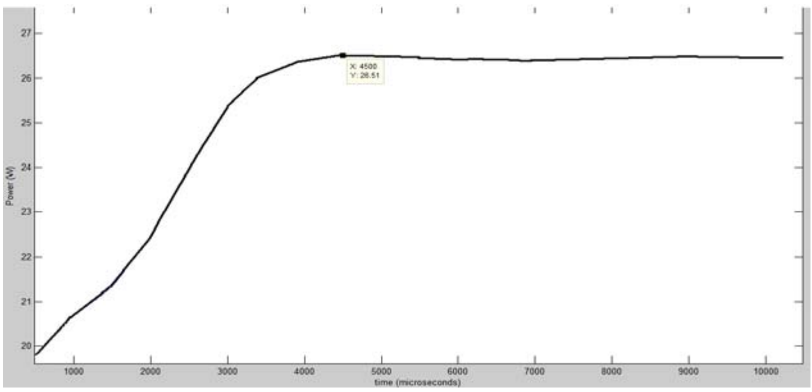

Fig. 7. Convergence of proposed algorithm at 1kW/m^2 irradiance and T = 25^0C (Simulation carried using MATLAB 2009).

Using the proposed algorithm tracking of MPP under falling irradiance level is reported in Table 1. Table 2 reports the results of the MPPT using kalman filter technique under optimal conditions. From the table it can be observed that efficiency of as high as 97.11% can be achieved using this proposed technique. This is improvement over the tracking efficiency of 96.13 that has been achieved using P&O algorithm under similar conditions.

Table 1. Voltage and Power at falling irradiance level (Implementation done on a cloudy day)

Voltage		Current	Power
Actual(V)	MPPT(V)	A	MPPT(W)
20.61	20.76	0.94	19.52
20.33	20.62	1.00	20.62
20.20	20.43	1.03	21.05
19.97	20.30	1.06	21.52
19.85	20.21	1.05	21.22
19.66	20.10	0.82	16.48
19.52	20.02	0.68	13.62
19.46	19.97	0.55	10.98
19.30	19.88	0.52	10.34

Table 2. Result of the proposed MPPT algorithm under optimal conditions

Voltage		Current	Power		Efficiency
Optimal(V)	MPPT(V)	A	Optimal(W)	MPPT(W)	%
21	21.38	1.19	27.3	25.44	93.19
	21.44	1.20		25.73	94.25
	21.48	1.22		26.21	96.01
	21.38	1.24		26.51	97.11
	21.44	1.22		26.16	95.82
	21.36	1.21		25.41	93.08

Table 3. Resource utilization summary of the MPPT controller.

Resource	Usage
Total Logic Elements	3723 / 18,752 (20%)
Total combinational functions	3058 / 18,752 (16%)
Dedicated logic registers	2,882 / 18,752 (15%)
Total registers	2882
Total pins	240/315 (76%)
Total memory bits	1030 / 239,616 (<1%)
Embedded multiplier 9-bit elements	50/52 (96%)

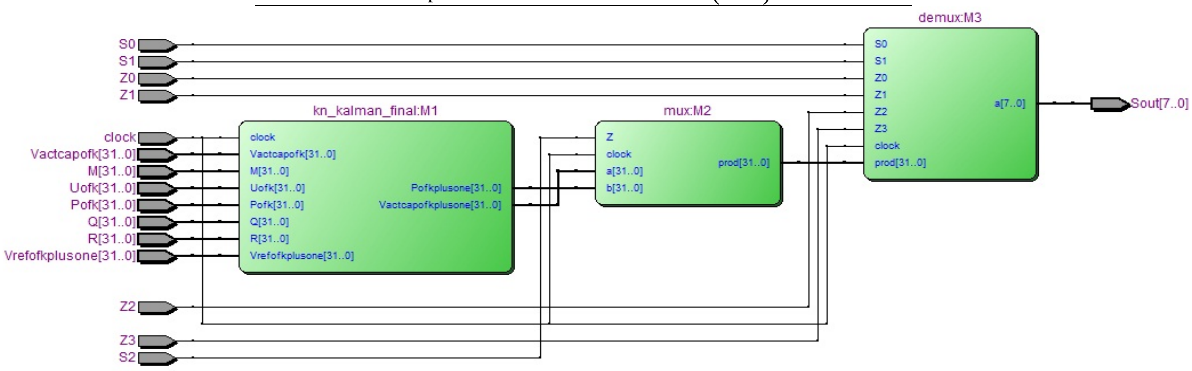

Fig. 8. Post mapping RTL of proposed algorithm

Fig.8 depicts the overall RTL of the proposed MPPT algorithm. The 8 bit S_{out} from the output is send to PWM generating module. Table 3 reports the resource utilization summary of MPPT controller when the VHDL code is simulated using Quartus II.

6. Conclusions

In this paper maximum power point tracking algorithm using Kalman filter is implemented on FPGA. The proposed method performs estimation as fast as the clock rate of FPGA. Also, the FPGA implementation is very useful due to the fact that FPGA are reconfigurable and are becoming economical, faster and power efficient day by day. The Kalman filter technique utilizes 3,723 logic elements which is only 20% of the total logic elements. The time required for convergence to the maximum power point comes around 4.5 ms using the proposed technique which is much less than that using the generic P&O algorithm. Moreover the Maximum power point has been tracked with efficiency of 97.11% using the new proposed MPPT algorithm which is an improvement over the tracking efficiency of 96% that has been obtained using generic P&O algorithm under similar experimental conditions. Further works are going on to improve the convergence rate and also the tracking efficiency under partially shaded conditions.

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