Proposal MPPT Algorithm Using the Kalman Filter

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Abstract. Solar power is an abundant energy source on Earth. The photovoltaic technology employs photovoltaic panels to convert sunlight into electric energy. Photovoltaic panels themselves have very low efficiency, which means they provide little power compared to the maximum one. The power maximization is influenced by variables such as temperature and solar irradiation, and the variation of those values calls for an algorithm to identify the Maximum Power Point (MPP), which provides the maximum possible power given the environmental conditions and is known as Maximum Power Point Tracking (MPPT). This article proposes an MPPT algorithm based on Kalman filter, which is a widely applied computational method for engineering applications, in the environment MatLab/Simulink with the model of Advanced Solar Wind Power API 150 and simulated variations of temperature and solar irradiation. The achieved results show the efficiency of the proposed model, given that the relative errors were lower than 4%.

Keywords: Solar energy · Photovoltaic system · MPPT · Algorithms · Kalman filter

1 Introduction

Solar power is an abundant energy source on Earth. To convert the energy derived from the Sun, it is necessary to use technologies, which can be split into two groups: photovoltaic and thermal. Recently, the photovoltaic technology has been employing photovoltaic panels to convert sunlight into electric energy [1].

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However, photovoltaic panels themselves have very low efficiency, which means they provide little power compared to the maximum one. The power maximization is influenced by variables such as temperature and solar irradiation [2].

Abrupt changes in temperature and irradiation values impair photovoltaic panels' efficiency so they need a tracker called Maximum Power Point Tracking (MPPT) to identify an operation point that maximizes the power, which is known as MPP [2,3]. Over the years, many MPPT algorithms have been developed, being the following the most used by engineers and scientists: Perturb and Observe, Incremental Conductance, Hill Climbing Search, Fuzzy Logic Controller, Beta Method, System Oscillation, and Ripple Correlation [4,5].

The Kalman filter is widely employed in engineering applications. Being a recursive computational method based on the Least Squares technique, it can foresee future states by means of previous and current estimations [6]. In [7], the authors suggested that a Kalman filter could be used as an MPPT algorithm, but they did not vary the environment temperature and solar irradiation, and they did not measure the efficiency to identify the MPP either.

In contrast, research [8] presented the development of an MPPT algorithm based on a Kalman filter in MatLab/Simulink with abrupt changes in the environmental factors (temperature and irradiation) and measurement of the results' efficiency. Although [8] achieved satisfactory results, it used only the MX60 photovoltaic panel characteristics, so new studies are necessary to evaluate the proposed algorithm of MPPT based on Kalman filter with other models of photovoltaic panels.

Therefore, this work aims to validate the proposed algorithm (MPPT based on Kalman filter in MatLab/Simulink) with the Advanced Solar Wind Power API 150 model, performing changes in temperature and solar irradiation and measuring the consequent variation of efficiency.

2 Photovoltaic Panel

Figure 1 shows the equivalent circuit of a photovoltaic cell, containing two resistors and a current source [9]. Reference [10] describes the behavior of a photovoltaic cell through Eq. 1.

$$I = I_{ph} - I_d \left[e^{\frac{q(V+IR_s)}{nKT}} - 1 \right] - \frac{V + IR_s}{R_p} \tag{1}$$

According to [11], the elements of Eq. 1 are:

- I is the photovoltaic cell's output current;
- I_{ph} is the photo-current;
- I_d is the photovoltaic cell's dark saturation current;
- n is the P-N junction ideality factor;
- V is the photovoltaic cell's output voltage;
- q is the charge of the electron (1.6×10^{-19} C);

- K is the Boltzmann's constant (1.38×10^{-23} J/K);
- R_s is the cell's series resistance;
- R_p is the cell's shunt resistance.

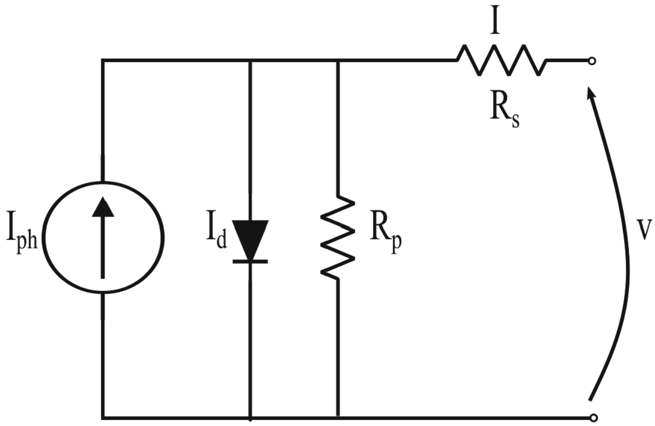

Fig. 1. Equivalent circuit of a photovoltaic cell.

To characterize the photovoltaic panel, the Advanced Solar Wind Power API 150 model was used with solar irradiation of 1000 W/m^2 and temperature of 25 °C. The specifications of this panel are the following:

- Maximum power: $P_{mp} = 150.075$ W;
- Open-circuit voltage: $V_{oc} = 41.8$ V;
- Voltage on the MPP: $V_{mp} = 34.5$ V;
- Temperature coefficient (voltage): $V_{oc} = -0.356\%/^\circ$ C;
- Short-circuit current: $I_{sc} = 5.05$ A;
- Current on the MPP: $I_{mp} = 4.35$ A;
- Temperature Coefficient (current): $I_{sc} = 0.037\%/^\circ$C.

Two different situations were simulated for this photovoltaic panel in MatLab/Simulink. In the first one, the temperature was constant (25 °C), and the solar irradiation received four values: 1000 W/m^2, 800 W/m^2, 600 W/m^2, and 500 W/m^2, as shown in Fig. 2. In the second situation, the solar irradiation was constant (1000 W/m^2), and the temperature received four values: 25 °C, 50 °C, 75 °C, and 100 °C, as shown in Fig. 3.

It can be seen in Fig. 2 that the photovoltaic power is inherent to the irradiation rise. On the other hand, Fig. 3 shows that the photovoltaic power decreases as the temperature rises.

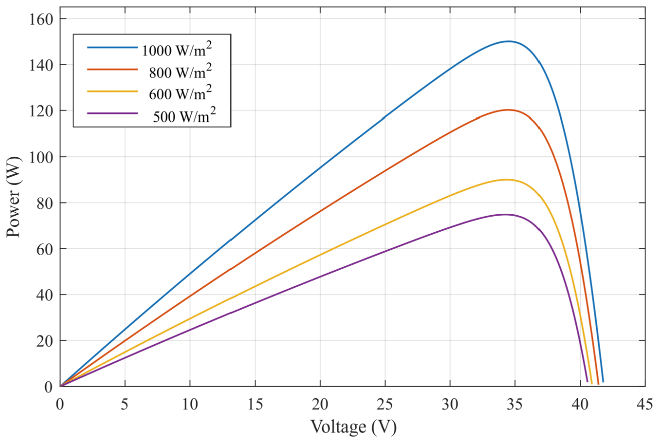

Fig. 2. PV power characteristic for different irradiation levels.

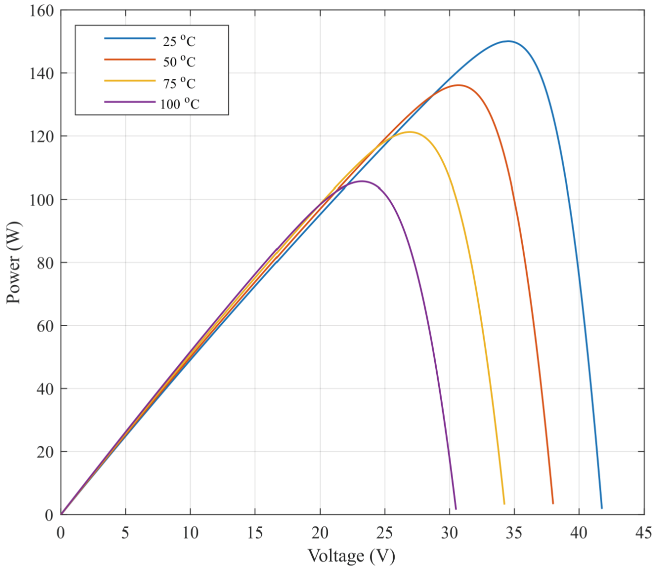

Fig. 3. PV power characteristic for different temperature levels.

3 MPPT

Since the characteristic curves of Figs. 2 and 3 change according to solar irradiation and temperature variations, an algorithm would be useful to identify the MPP for each circumstance. For this purpose, an MPPT algorithm such as the one presented in Fig. 4 is proposed.

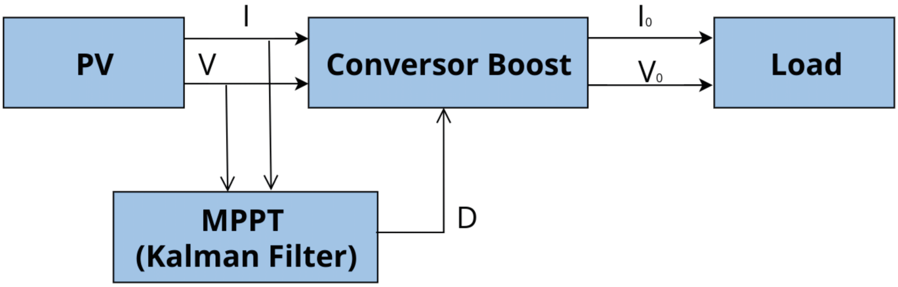

Fig. 4. PV system scheme.

Figure 4 represents the layout of a photovoltaic system. The boost converter is between the photovoltaic panels and the load and is controlled by the MPPT algorithm [5].

3.1 Boost Converter

Through Pulse Width Modulation (PWM), the boost converter in Fig. 5 operates continuously with the conversion of DC voltage (V) into another DC voltage (V_o). As one can observe, the converter has a MOSFET that is controlled by the PWM and operates as a switch, which affects the behavior of the other components. When it is switched on, the inductor stores the energy derived from the PV panel, the diode disconnects the load from the PV panel, and the capacitor supplies current to the load. Otherwise, when the MOSFET is switched off, the inductor discharges and the polarized diode connects the load to the PV panel, i.e., the output voltage is higher than the generated one since it is the sum of the input (PV panel) and the inductor voltages [12].

The boost converter equations are the following:

$$V_o = \frac{V}{1-D} \tag{2}$$

$$I_o = I(1-D) \tag{3}$$

The variables of Eqs. 2 and 3 are:

- I: Photovoltaic cell current (input);
- I_o: System's output current;
- D: Duty cycle.

Through Eq. 2, D, which is associated with V, is calculated, i.e., different values of V cause changes in the duty cycle.

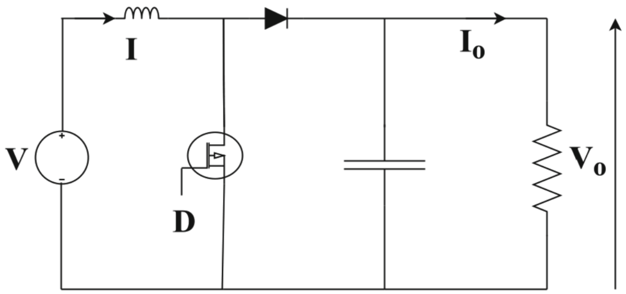

Fig. 5. Boost converter.

3.2 Kalman Filter

The Kalman filter can forecast, through the combination of the *propagation* and *assimilation* steps, a future state based on previous and current estimations.

The following equations define the *propagation* step:

$$x_{k+1}^{-} = Cx_k + Du_k \tag{4}$$

$$H_{k+1}^{-} = CH_kC^T + Q \tag{5}$$

where x_{k+1}^{-} is the estimation of the state in the iteration $k+1$ based on the previous iteration, and x_k is the corrected state in the iteration k achieved from the output measurement z_k. u_k is the process control of iteration k, C is a constant of the state transition model used for the previous state, D is a constant that depends on the model employed in the process control, and Q is the process covariance related to the matrix of noise states. H_{k+1}^{-} is the *a priori* covariance for iteration k, and H_{k+1} is the *a posteriori* covariance error for iteration $k+1$.

For the *assimilation* step, whose aim is to rectify the value predicted by the *propagation* step [6], the following equations are determined:

$$K_{k+1} = H_{k+1}^{-}E^T(EH_{k+1}^{-}E^T + R)^{-1}, \tag{6}$$

$$x_{k+1} = x_{k+1}^{-} + K_{k+1}(z_{k+1} - Ex_{k+1}^{-}), \tag{7}$$

$$H_{k+1} = (I_n - H_{k+1}E)H_{k+1}^{-}, \tag{8}$$

where x_{k+1} is the state that has undergone correction in iteration $k+1$ due to the output z_{k+1}, H_{k+1} is the *a posteriori* error covariance in iteration $k+1$, K_{k+1} is the Kalman gain, R is the noise covariance, z_{k+1} is the measurement, E is a constant related to the Kalman filter system and the observed space, and I_n is the identity matrix [6].

3.3 MPPT Algorithm Using Kalman Filter

To identify the MPP using the Kalman filter, it is necessary to design it to compute the voltage referent to the maximum power. According to [4], the power increases with a positive slop until the maximum power point and then decreases with a negative slope. Therefore, following the recommendations of [13] ($C = 1$ and $D = M$), the *propagation* equations become:

$$V_{k+1}^{-} = V_k + M\frac{\Delta P}{\Delta V} \tag{9}$$

$$H_{k+1}^{-} = H_k + Q \tag{10}$$

where V_{k+1}^{-} is the voltage value estimated by the proposed MPPT algorithm through the Kalman filter in iteration $k+1$ and corresponds to x_{k+1}^{-}. M is the equivalent to D, which is a scale factor. $\frac{\Delta P^{k-1}}{\Delta V^{k-1}}$ is the slope of the voltage-power curve in iteration $k+1$.

According to [13], the gain K can be computed by adopting $E = 1$ through the error covariance. The remaining equations (*assimilation* step) correct the measurement of the predicted covariance with the measurement of the photovoltaic cell voltage $V_{solar,k}$. Thus, the *assimilation* equations become:

$$K_{k+1} = H_k^{-}(H_k^{-} + R)^{-1} \tag{11}$$

$$V_{k+1} = V_{k+1}^{-} + K_k \times (V_{solar,k+1} - V_{k+1}^{-}) \tag{12}$$

$$H_{k+1} = (1 - K_{k+1}) \times H_{k+1}^{-} \tag{13}$$

4 Results

To evaluate the efficiency of the proposed MPPT algorithm based on the Kalman filter, two simulations were performed in MatLab/Simulink. For the first one, the temperature value was kept constant (25 °C), and the solar irradiation received values of 1000 W/m^2, 800 W/m^2, 600 W/m^2, and 500 W/m^2 during 3 s. The maximum power outputs achieved in each condition are depicted in Fig. 6.

In the second simulation, the solar irradiance was kept constant (1000 W/m^2), and the temperature varied: 25 °C, 50 °C, 75 °C, and 100 °C. The results achieved with these conditions are plotted in Fig. 7.

For better evaluation of the proposed MPPT algorithm through the Kalman filter, the achieved results were arranged in two tables. In Table 1, the output power of the photovoltaic panel is compared with the proposed method with constant temperature (25 °C). In Table 2, the same was done for the values achieved with constant solar irradiation (1000 W/m^2).

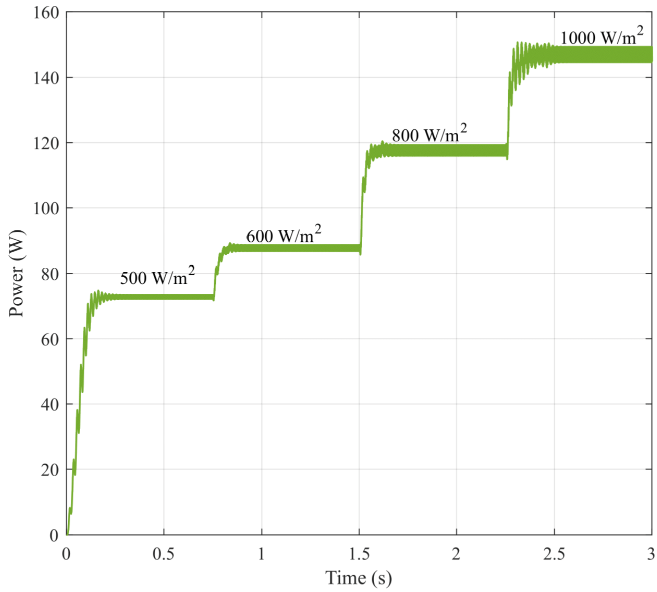

Fig. 6. Power obtained with the proposed MPPT Algorithm through the Kalman filter with constant temperature of 25 °C.

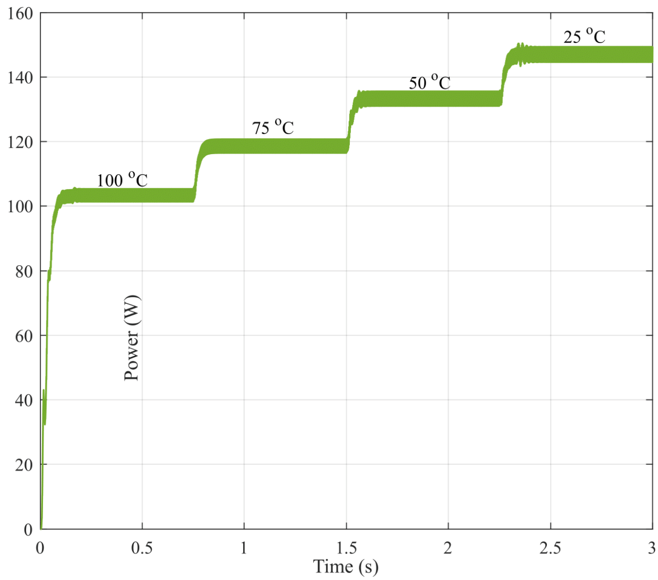

Fig. 7. Power obtained with the proposed MPPT Algorithm through the Kalman filter with constant solar irradiation of 1000 W/m^2.

Table 1. Comparison of the output power of the PV panel and the values obtained from the proposed MPPT algorithm using the Kalman filter at constant temperature of 25 °C.

Irradiation (W/m^2)	Maximum output power (W)	Maximum power using the MPPT with Kalman filter (W)	Relative error (%)
1000	150.075	145.700	3.344
800	120.333	118.309	1.612
600	90.048	88.644	1.567
500	74.859	73.977	1.183

Table 2. Comparison of the output power of the PV panel and the values obtained from the proposed MPPT algorithm using the Kalman filter with constant solar irradiation of 1000 W/m^2.

Temperature (°C)	Maximum output power (W)	Maximum power using the MPPT with Kalman filter (W)	Relative error (%)
25	150.075	147.466	1.744
50	136.108	134.117	1.463
75	121.253	119.823	1.181
100	105.620	104.511	1.081

By analyzing Tables 1 and 2, one can observe that the proposed MPPT with Kalman filter is efficient since the highest relative error is 3.344%.

5 Conclusion

The proposed MPPT algorithm based on the Kalman filter was implemented in the environment MatLab/Simulink with the aim of identifying the MPP and extracting the maximum power. The photovoltaic panels' P-V curves change when the temperature and solar irradiation vary, i.e., the Maximum Power Point (MPP) is not constant, and, for that reason, the MPPT algorithm must handle those variations.

Two simulations were performed in MatLab/Simulink. The first one considered a constant temperature of 25 °C and four values for solar irradiation (1000 W/m^2, 800 W/m^2, 600 W/m^2, and 500 W/m^2) during 3 s. In the second simulation, the solar irradiation was set to 1000 W/m^2, whereas the temperature received four values (25 °C, 50 °C, 75 °C, and 100 °C) during the same period. The MPPT algorithm with the Kalman filter was efficient in both scenarios since the highest relative error was 3.344%.

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