New Approach of Incremental Conductance Algorithm for Maximum Power Point Tracking Based on Fuzzy Logic

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Abstract

Tracking the maximum power point is an appropriate solution against climatic changes like the irradiance and temperature. The classic incremental conductance algorithm is one of the most widely used methods in commercial photovoltaic MPPT's (Maximum Power Point Tracking). A wide variation of climatic condition can degrade the produced energy. In this work we present our new approach based on fuzzy logic which can guarantee better performance. The studied system used to prove the efficiency of the proposed method is composed by a photovoltaic panel Kaneka K60 connected to a Sepic Converter which fed a resistive load. The All results quoted in this work are found using MATLAB-Simulink. We put the system in different working condition to highlight our new approach. All presented results are discussed.

Keywords: *Photovoltaic Panel, Sepic converter, MPPT, Incremental conductance algorithm, fuzzy logic.*

1. Introduction

The request on electric energy is increasing in recent years and the constraints related to its production, such as the pollution effect and global warming, lead research towards the development of renewable energy sources. In this context, photovoltaic (PV) systems offer a very competitive solution. To overcome the problems related to solar panels (such as adaptation) and get a maximum energy, it is necessary to optimize the design of all parts of the PV system. Furthermore, it is necessary to optimize the converters (DC-DC). This converter is used as an interface between PV generator and the load in order to extract maximum power and thus making the generator on its maximum power point (MPP). The DC-DC converter is controlled by an MPPT algorithm (maximum power point tracking) [1] [2]. Maximum power point tracking is a mechanism which can guarantee the maximal power permanently [3]. Several method of MPPT have been proposed in the literature, such as the Perturb and Observe algorithms [4] [5] [6], and incremental conductance algorithms [7] [8]. The Classical incremental conductance algorithms are based on the instantaneous incremental conductance to find the maximum power point [9] [10]. The main advantage of this algorithm is that it provides a good performance under changing climatic conditions. But a small increment value slows the search of the maximum power point. We must find a compromise between accuracy and speed, what makes this algorithm difficult to optimize. This work presents a new approach for incremental conductance method based on fuzzy logic in order to obtain better performances against climatic conditions change. First, we will present the model of the photovoltaic panel. Next, we will give the principle of operation of the Sepic

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converter used in this work. Then we will introduce the classical and the new method for tracking the maximum power point. We will finish by giving simulation results to illustrate the efficiency of the proposed method.

Nomenclature

PV	Photovoltaic system
MPPT	Maximum Power Point Tracking
I_{pv}	Output current of the solar generator
V_{pv}	Voltage of the solar generator
I_{ph}	Photovoltaic generator photocurrent,
I_s	Photovoltaic cell reverse saturation current diode $1.5024 \cdot 10^{-2}$ A
I_{cc}	Short Circuit current
K	Boltzman Constant $1.39 \cdot 10^{-23} \text{ m}^2 \text{ kg s}^{-2} \text{ K}^{-1}$
E_g	Gap energy $1.79 \cdot 10^{-19}$ J
n	ideality factor 630.97
K_i	Temperature coefficient in current
G	Irradiance
T, T_{ref}	Temperature and reference temperature 25°C
T_p	Junction temperature
R_s and R_p	the series and shunt resistance respectively,
G	the irradiance,
C	the number of cells (in series) per module,
V_{oc}	the open circuit voltage of the module,
q	the elementary charge in Coulomb.
V_{IN}	the input voltage of the Sepic convertre
V_{OUT}	the output voltage of the Sepic converter
I_{IN}	the input current of the Sepic converter
I_{OUT}	the output current of the Sepic converter
I_L	the current in the coil of the Sepic converter
V_D	the threshold voltage of the diode of the Sepic converter
f_{sw}	the switching frequency
C_s	value of the coupling capacitor of the Sepic converter
C_{in}	value of the input capacitor of the Sepic converter
C_{out}	value of the output capacitor of the Sepic converter
V_{Cs}	the voltage of the coupling capacitor
D	the duty cycle
D_{max}	the maximal duty cycle
V_t	the thermodynamic voltage
I_{mpp}	Nominal current at maximum power point
V_{mpp}	Nominal voltage at maximum power point
P_{mpp}	Nominal power at maximum power point

2. Photovoltaic Panel Modeling

The conversion of solar radiation into electricity by the photovoltaic process is one of the exploitation means of solar potential. A photovoltaic panel is mathematically modeled by the following equations [11]:

$$I_{pv} = I_{ph} - I_d - I_{sh} \quad (1)$$

$$I_d = I_s \left(\exp \left(\frac{(V_{pv} + R_s I_{pv})}{n C V_t} \right) - 1 \right) \quad (2)$$

$$I_{sh} = \left(\frac{V_{pv} + R_s \cdot I_{pv}}{R_p} \right) \quad (3)$$

$$I_{ph} = G(I_{sc} + K_i(T - T_{ref})) \quad (4)$$

$$I_s = I_{rs}(T - T_{ref}) \exp \left(\frac{E_g \cdot q^2}{K \cdot n} \left(\frac{1}{T} - \frac{1}{T_{ref}} \right) \right) \quad (5)$$

$$I_{rs} = \frac{I_{sc}}{\exp \left(\frac{q \cdot V_{oc}}{n \cdot KCT} \right)} \quad (6)$$

$$V_t = \frac{K \cdot T}{q} \quad (7)$$

R_s and R_p are the series and shunt resistors respectively, T_{ref} is the ambient temperature taken as reference, G is the irradiance, n is the ideality factor of the diode, T is the temperature cell, K is the Boltzmann constant, E_g is the gap energy, C is the number of cells (in series) per module, V_{oc} is the open circuit voltage of the module, I_{sc} is the short circuit current of the module, K_i is the coefficient of temperature and q is the elementary charge in Coulomb. The change of irradiance and temperature directly influences the power produced by the panel the following figures illustrate this effect.

Figure 1. The Irradiance and Temperature Effect on the Power Produced by the Kaneka K60

The photovoltaic panel used in this work is Kaneka K60 module. The electrical parameters of this module are shown in Table1:

Table 1. Characteristics of the Kaneka K60 at Optimal Conditions

Parameters	Value
Nominal Power	60w(+10%/-5%)
Voltage at maximum power	67V
Current at maximum power	0.9A
Open circuit voltage	92V
Short circuit current	1.19A

3. Sepic Converter

To obtain maximum energy for any weather condition, we should take care of the load's impedance. In buck operation this impedance should be as near as possible and less than R_{opt} ($R_{opt}=V_{mpp}/I_{mpp}$), V_{mpp} and I_{mpp} are respectively the voltage and current at maximum power point). In boost operation this impedance should be as near as possible as and larger than R_{opt} .

Sepic converter is one of the converters which are able to ensure optimal operation regardless of the load [12].

Sepic converter has many advantages:

- It can function as buck-boost converter without polarity reversal.
- The control of the transistor refers to the electrical ground.
- The ripple of the input current is limited.
- A good yield.

The SEPIC converter was designed in the late 1970s by Slobodan Cuk. The structure of SEPIC is deduced from that of capacitive Cuk by permuting the diode and the output inductor. It has similar features to the Cuk, but the input voltage is not inverted. The output voltage can be higher or lower than the input voltage. The SEPIC converter has two coils $L1$ and $L2$. The output voltage depends on the duty cycle applied to the switch K [13].

Figure 2. Sepic Converter Topology

When the duty cycle reached 50%, the input voltage will be equal to the output voltage. When higher, the output voltage will be lower than input voltage. And finally the output voltage will exceed the input voltage if lower. If we apply the Kirchhoff's voltage law the duty cycle will be given by [14]:

$$D = \frac{V_{OUT} + V_D}{V_{IN} + V_{OUT} + V_D} \quad (8)$$

With V_{IN} is the input voltage, V_{OUT} is the output voltage and V_D is the threshold voltage of the diode. For the desired output, the variation of the duty cycle will depend on the input voltage. Thus, the maximum duty cycle is [14]:

$$D_{MAX} = \frac{V_{OUT} + V_D}{V_{IN}(\min) + V_{OUT} + V_D} \quad (9)$$

To find the adequate value of the coil, we must fix the maximal accepted value of ripple. We have fixed empirically that a ripple of 40% of the maximum input current for the minimum input voltage is acceptable. The current ripple is defined by the following equation [14]:

$$\Delta I_L = I_{IN} \times 40\% = I_{OUT} \times \frac{V_{OUT}}{V_{IN(min)}} \times 40\% \quad (10)$$

Thus, the values of inductances are calculated by: (f_{sw} is the switching frequency)

$$L1 = L2 = L = \frac{V_{IN(min)}}{\Delta I_L \times f_{sw}} \times D_{max} \quad (11)$$

The value of the coupling capacitor is defined by [14]:

$$C_s = \frac{I_{OUT} \times D_{max}}{\Delta V_{Cs} \times f_{sw}} \quad (12)$$

To reduce the ripple at the input and the output, filter capacitors are used. We can remove C_{in} if there is no ripple in photovoltaic panel. C_{out} is dimensioned by [14]:

$$C_{out} \geq \frac{I_{OUT} \times D}{V_{ripple} \times 0.5 \times f_{sw}} \quad (13)$$

I_{OUT} is the current in the load, V_{ripple} is the voltage ripple.

4. Maximum Power Point Tracking Methods

The MPPT (Maximum Power Point Tracking) is a control law that provides an instantaneous adaptation of the operating point of the load at maximum power provided by the Photovoltaic generator. This can be achieved through the Sepic converter inserted between the generator and the load which is dynamically controlled by varying the value of duty cycle.

Figure 3. Synoptic of the Studied System

4.1. Classic Incremental Conductance Algorithm [15].

In this technique the term $\frac{dI_{pv}}{dV_{pv}}$ is compared to $-\frac{I_{pv}}{V_{pv}}$. The maximum power point is achieved when this difference is null.

$$\frac{dP_{pv}}{dV_{pv}} = I_{pv} \frac{dV_{pv}}{dV_{pv}} + V_{pv} \frac{dI_{pv}}{dV_{pv}} = I_{pv} + V_{pv} \frac{dI_{pv}}{dV_{pv}} = 0 \quad (14)$$

$$-\frac{I_{pv}}{V_{pv}} = \frac{dI_{pv}}{dV_{pv}} \quad (15)$$

dV_{pv} and dI_{pv} can be approximated by :

$$dV_{pv}(k) \approx \Delta V_{pv}(k-1) = V_{pv}(k) - V_{pv}(k-1) \quad (16)$$

$$dI_{pv}(k) \approx \Delta I_{pv}(k-1) = I_{pv}(k) - I_{pv}(k-1) \quad (17)$$

In results, to review the operation of the photovoltaic panel and the power at the load we use inequalities:

$$\frac{dP_{pv}}{dV_{pv}} > 0 \quad \text{For} \quad V_{pv} < V_{mpp} \quad (18)$$

$$\frac{dP_{pv}}{dV_{pv}} = 0 \quad \text{For} \quad V_{pv} = V_{mpp} \quad (19)$$

$$\frac{dP_{pv}}{dV_{pv}} < 0 \quad \text{For} \quad V_{pv} > V_{mpp} \quad (20)$$

This approach is easy to implement on programmable circuit such as microcontrollers. The organization chart presented on figure 4 resume the principle of the incremental conductance algorithm.

Figure 4. Diagram of Classical Incremental Conductance Algorithm

4.2. Proposed Method using Fuzzy Logic

Recently, the fuzzy logic control is used for maximum point tracking. This control offers the advantage of being robust. The design of a fuzzy controller requires three stages, which are: fuzzification, inference rules and defuzzification [16].

The preliminary step, which are the fuzzification, consist on defining the maximum range of variation allowed for the input variables. The purpose of the fuzzification is to transform input variables into linguistic variables. The second stage(the inference rules) is a step which can make a logical relationship between inputs and output. Indeed, membership rules will set for the optimal output related to the actual inputs. Table 2 presents all inference rules which allow toobtain optimal duty cycle (in results optimal power point).

The linguistic variables (fuzzy variables) are not understandable by the external environment. The defuzzification consists on computing the numerical values are from linguistic variables.

Based on the previously equations cited in paragraph (4.1). We have :

$$\frac{d(V_p * I_p)}{dV_p} = I_p + V_p * \frac{dI_p}{dV_p} \quad (21)$$

What will bring us to

$$\frac{dI_p}{dV_p} = -\frac{I_p}{V_p} \quad (22)$$

This equality means that the photovoltaic panel is at its maximum power point. We exploit this equality to design our fuzzy logic controller wich its input are:

$$E(k) = \frac{dI_p}{dV_p} + \frac{I_p}{V_p} \quad (23)$$

$$dE(k) = \frac{E(k) - E(k-1)}{T_e} \quad (24)$$

With T_e is the sample Time.

The inputs of the fuzzy controller include only three fuzzy subsets: Negative (N), Zeros (Z) and Positive (P).The N and P subset have a trapezoid shape. We applied the triangular shape for the Z subset. The choice of these shapes is empirical.

Figure 5.(a). Fuzzification Step of E(k)

Figure 5.(b). Fuzzification Step of $E(k)$ (Zoom In)

Figure 6. Fuzzification Step of $dE(k)$

Where $D(k)$ is the output of the fuzzy controller which includes five fuzzy subsets (numbered from 1 to 5). It allows obtaining the maximum precision of the duty D which can reduce the time to achieve the maximum power point.

Figure 7. Defuzzification Step of $D(k)$

Related to the choice adopted for the fuzzification of input and the defuzzification of the output, there are nine inference rules on the data base of the fuzzy controller. We use Mamdani's method with Max–Min for fuzzy combination. The fuzzy controller rules are based on Table 2:

Table 2. Basic Inference Rules for the Fuzzy Controller

Rules	E	$dE(k)$	D
1	Z	N	2
2	Z	P	4
3	Z	Z	3
4	P	P	1
5	P	Z	1
6	P	N	1
7	N	N	5
8	N	Z	5
9	N	P	5

5. Simulation Results and Discussion

In order to highlights the performance of the designed controller, we have simulate the structure presented by figure 3. In this structure, we have used the proposed controller based on fuzzy logic and the classical incremental conductance to compare its results. Both controllers are simulated with the same climatic condition variations shown on Table 3.

Table 3. Irradiance and Temperature Variation According to the Simulation Time

Simulation time	$G(w/m^2)$	$T(^{\circ}C)$
[0,2]	800	25
[2,4]	1000	18
[4,6]	1000	40
[6,8]	800	18
[8,10]	1000	20
[10,12]	1000	35
[12,14]	900	20

Numerical simulations shown on Figure 8 describe the power behaviors related to proposed controller based on fuzzy logic and classical incremental conductance algorithm.

Figure 8. General Power Behaviour

The following figures zoom the behaviour of each controller for several times.

Figure 9. Power Behavior at [0,1] Second of Time Simulation

Figure 10. Power Behavior at [2,3] Second of Time Simulation

Figure 11. Power Behavior at [8,10] Second of Time Simulation

Despite these disturbances, we note that the system converges to its point of maximum power and it remains stable with a near-zero ripple factor. The rise time

about 0.5s for classical MPPT control and 0.4s for the proposed controller based on fuzzy logic which are both a moderate transient time.

At this level we can say that both presented algorithm provide satisfying results. But the proposed method tracks the Maximum power point more quickly than the classical method especially when there is a wide variation of climatic condition. The small divergence seen on the curve of the proposed method (at the start of each tracking caused by the variation of climatic conditions) is related on the strong correlation between membership functions. The elimination of this small divergence causes the lost of the obtained advance at the level of speed compared to classical method.

6. Conclusion

We presented a new incremental conductance method based on fuzzy logic. We have used a system which is composed by photovoltaic panel, Sepic converter which is controlled by the MPPT algorithm and a resistive load. The results prove that the proposed method gives better performance than the classical method.

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Appendix:

Specifications of PV generator

Electrical Data	Value
Nominal output $P_{mpp}(W)$	60
Nominal Voltage V_{mpp}	67
Nominal current $I_{mpp}(A)$	0.9
Open circuit voltage $V_{oc}(V)$	92
Short circuit current $I_{sc}(A)$	1.19

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