Design and Implementation of a Digitally Controlled Photovoltaic System Using Series Connected Buck Converters

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Abstract: In PV (photovoltaic) power systems, a MPPT (maximum power point tracking) algorithm is vital in increasing their efficiency. But it is also vital to take into account the non ideal conditions resulting from complex physical environments in such PV power systems. To minimize the degradation of performances caused by these conditions, and therefore adding reliability and robustness, this paper presents an implementation of a digitally controlled system using a topology based on series connected DC-DC buck converters for a stand-alone PV power system applications, operating with local and autonomous controls, to track the maximum power points of PV modules in non ideal conditions. Simulations are carried out by using C-MEX S-functions under MATLAB-SIMULINK environment. A PV system of 1.44 kWc is described and simulation results are presented.

Key words: Buck converter, boost converter, MPPT control, photovoltaic power system, solar energy.

1. Introduction

A PV (photovoltaic) solar array can convert the solar energy directly into electricity in a clean and safe manner, without generating any air or water pollution.

Nowadays, and more than ever, solar electricity has become a very promising source of energy, and could soon be a competitive alternative to conventional retail power in many regions. The trend around the world suggests increasing interests in this renewable form of energy. Indeed, big parks of PV power systems have been installed in recent years [1] around the world and many ambitious plans have been drawn up to tap the potential for generating solar power.

The performances of any PV array are significantly affected by four main factors: cells materials and temperature, solar irradiance, and load. For a maximization of the PV array output power, a considerable amount of control algorithms, known as

MPPT (maximum power point tracking), has been developed on the issue during the last three decades [1-3]. Each of these methods has its own advantages and limitations. Namely there are three most commonly used ones that are well suited for digital implementation: Perturb and Observe method (P&O), Incremental Conductance method (IncCond), and Constant Voltage method (CV). A comparative study carried out by Hua et al. [4] shows that the incremental conductance algorithm has advantages over other control algorithms. The primary advantage of such incremental conductance algorithm over many others methods lies especially on the facts that it can calculate the direction in which to perturb the PV array's operating point to reach the MPP (maximum power point), and can determine when it has actually reached the MPP. Thus, under rapidly changing conditions, it should not track in the wrong direction, as others methods can, and it should also not oscillate about the MPP once it reaches it.

Furthermore, the sunlight is only available for a

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limited time, and depends heavily on weather conditions. So the PV interface must take full advantage of the available solar energy. Moreover, in powerful photovoltaic systems, PV modules are often connected in strings, arrays or both. But, this direct association does not always lead to a better exploitation of available solar energy. Indeed, it suffices that one or more modules receive less insolation than others that the whole system is affected. Besides, different and complex physical conditions, such as shadowing, load conditions, low solar radiation, bad orientation of modules, dust and snow collection, photovoltaic ageing processes, etc., may degrade the performances of the system.

This paper describes an application of power electronics in designing and implementing a digitally controlled photovoltaic power system using series connected buck converters, with the purpose of to more efficiently use the available solar energy and ensure that the operating characteristics of the load and the PV array match at the maximum power available, no matter what the non ideal conditions. All of this work is carried out in the environment MATLAB/SIMULINK.

2. Electrical Model of a PV Cell

A PV cell can be represented by its simplest equivalent circuit as shown in Fig. 1.

The I_{pv} - V_{pv} characteristic is described by the Eq. (1) [5]:

$$I_{PV} = I_{CC} - I_S \left[\exp \left(\frac{q(V_{PV} + R_S I_{PV})}{mkT} \right) - 1 \right] - \frac{V_{PV} + R_S I_{PV}}{R_P} \quad (1)$$

where

$$I_{CC}(T) = I_{SC}(T_{ref}) \frac{G}{G_{ref}} + \alpha(T - T_{ref}) \quad (2)$$

$$I_S(T_{ref}) = \frac{I_{SC}(T_{ref})}{\left[\exp \left[\frac{qV_{OC}(T_{ref})}{mkT_{ref}} \right] - 1 \right]} \quad (3)$$

$$V_{OC}(T) = V_{OC}(T_{ref}) + \beta(T - T_{ref}) \quad (4)$$

where

I_S : saturation current (A);

I_{CC} : light-generated current (A);

K : Boltzmann's constant (J/K);

T : absolute temperature (K);

R_S : series resistance (Ω);

R_P : shunt resistance (Ω);

m : ideality factor of the junction ($1 < m < 2$);

I_{SC} : short circuit current (A);

V_{OC} : open circuit voltage (V);

G : insolation (W/m^2);

A : temperature coefficient of the current;

B : temperature coefficient of the voltage.

The subscript ref refers to the standard tests conditions (for example, $T_{ref} = 25^\circ C$, $G_{ref} = 1 \text{ kW}/m^2$).

These current-voltage characteristics (I_{pv} - V_{pv}) may represent the output of any PV generator from a unique cell to the largest array.

Eq. (5) gives the output power P_{PV} of the PV generator:

$$P_{PV} = V_{PV} \times I_{PV} \quad (5)$$

The market available Mitsubishi UD180MF5 PV module has been selected in this study. The electrical characteristics of a PV module, given by manufacture's data sheet at the nominal temperature of $25^\circ C$, are shown in Table 1.

From the model (1) and the provided data, MATLAB/SIMULINK based simulations are carried out to plot the current-voltage (I_{pv} - V_{pv}) characteristics (Fig. 2) respectively at many different solar insulations

Fig. 1 Equivalent circuit of a PV cell.

Table 1 Electrical characteristics of the Mitsubishi UD180MF5 PV module.

Parameter	Value
Number of cells	50 in series
Maximum power rating	180 Wp
Open circuit voltage (V_{oc})	30.4 V
Short circuit current (I_{sc})	8.03 A
Maximum power voltage (V_{mp})	24.2 V
Maximum power current (I_{mp})	7.45 A

Fig. 2 Current-voltage (I_{pv} - V_{pv}) characteristics of the UD180MF5 PV solar panel for many different ambient irradiances G at $T = 25^\circ\text{C}$.

G . Five levels of irradiation G within a range of 200 to $1,000\text{ W/m}^2$ were used.

3. Matching the PV Array to the Load

When a PV array is directly connected to a load, the operating point of the system will be located at the intersection of the I_{pv} - V_{pv} curves and load line as shown in Fig. 2. In general this operating point is not systematically located at PV array's maximum power points. Moreover, there is a unique point on each curve, called the MPP (maximum power point), at which the array operates with maximum efficiency and produces maximum output power. These maximum power points are located close to the knees of the curves (Fig. 2).

It must emphasize that the location of the PV array MPP is not known a priori, and the situation is furthermore complicated by the highly nonlinear behavior of the PV array's I_{pv} - V_{pv} curves on irradiance G or temperature T , as shown in Fig. 2. So, to ensure

that power requirements of the load can be provided, the PV array must usually be oversized, although this may lead inevitably to an overly expensive system.

To overcome this difficulty, a switch mode DC-DC power converter system, called maximum power point tracker (MPPT), can be inserted between the load and the PV array in order to maintain the operating point of the latter at the MPP, by controlling its voltage or current independently of those of the load. Thus, this MPPT can maximize the power output from a PV array system under varying conditions (irradiance, temperature and load). For a given solar insolation and temperature namely, the tracking algorithm computes the duty ratio of the converter so that the PV array voltage equals the voltage corresponding to its MPP. If the matching system is carefully designed, it can lead to maximum power transfer, and therefore it can maximize the PV array efficiency and minimize the overall system cost.

4. Proposed System

Several works have initiated the idea of connecting in series the DC-DC converters that are supplied by a photovoltaic generator. It is shown that this configuration allows many advantages [6-14].

Figs. 3 and 4 show the block diagram of the proposed PV system and the block diagram of its digital system control respectively. The MPPT algorithm control used here is the incremental conductance method.

Fig. 3 Block diagram of the proposed system.

Fig. 4 Block diagram of the digital system control.

It is used a topology that consists of four DC-DC series connected buck converters. Each buck converter is driven by two photovoltaic panels mounted in parallel. This will be referred in the following as a PV module. This subsystem is equipped with its own local and autonomous MPPT control to track the maximum power point of PV modules, whatever the environment conditions of the corresponding panels. Indeed, this topology allows the system to accommodate its changing load and complex physical environments, and therefore, to provide optimal conversion efficiency for both the individual subsystems and the entire system.

The control unit of the digital system consists mainly of MPPT algorithm blocks that are implemented in C language using C-MEX S-functions under MATLAB-SIMULINK environment. Obviously, this algorithm uses I_{PV} and V_{PV} that represent respectively the sensed current and voltage at the PV modules output (Figs. 3 and 4). Furthermore, for each subsystem, the provided optimal duty cycle allows to generate the necessary PWM signal to drive the gate of the DC-DC converter switch MOSFET.

The four DC-DC series connected buck converters supply six batteries. These are series mounted to ensure a total capacity of 690 AH (the batteries stack, Fig. 3). The whole system can provide a total power of 1,440 W under a voltage of 82.8 V. It is also used a DC-DC boost converter with PWM voltage control to boost this latter voltage to 350 V for DC-AC inverter purposes.

This DC-DC boost converter uses a PI (Proportional-Integrator) controlled feedback loop voltage regulation to maintain its output voltage at the desired value, i.e. 350 V, when its input voltage is subject to variations. In addition, this system is designed with the aim to be used as a modular unit. So, by choosing the suitable DC-AC inverter, several units can be coupled in parallel if the needed power is greater than 1,440 W. It is worth to mention that during the day time, the batteries and the inverter are connected to the photovoltaic power system, while during the night time, the latter is switched off and the batteries become responsible of supplying the inverter. On the other hand, it goes without saying that the DC-DC boost converter is switched on during the day time only when its input voltage is between 82.8 V and 74.52 V ($82.8 - 82.8 \times 10\%$).

It can point out that the DC-DC boost converter with its PI controller as well as the DC-AC inverter are not developed in this paper. It will be presented in a future paper. It will be also mentioned in the following. The term load is relative to the series connected buck converters, e.g., here, the load can be either the batteries stack or a resistor that simulates all the circuits located downstream of the system (the DC-DC boost and the DC-AC inverter, Fig. 3).

5. Analysis of the DC-DC Converters—The Control Laws

For the DC-DC converter, the buck and the boost converters are shown to be the most efficient topologies for a given cost, with the buck best suited for long strings and the boost for short strings. In general, the PWM (pulse width modulation) techniques are used to provide the control of the power converter, responsible for the transfer of energy from the PV array to the load.

5.1 DC-DC Buck Converter

The basic circuit topology of the DC-DC buck converter is given in Fig. 5.

Fig. 5 Module integrated DC-DC buck converter for a PV system.

Here, the switch Q1 is operated at the switching frequency $F = 1/T$, with a duty ratio D_{MPP} defined as a ratio of the switch on time t_{on} to the sum $T = t_{on} + t_{off}$ of the on and off times:

$$D_{MPP} = \frac{t_{on}}{t_{on} + t_{off}} = \frac{t_{on}}{T} \quad (6)$$

Neglecting losses and using Faraday's law for the buck inductor L , it can easily show that the average value of the output voltage, V_s , is:

$$V_s = D_{MPP} \times V_{PV} \quad (7)$$

Taking into account the converter's efficiency η_{BUCK} defined as the ratio of output power to input power:

$$\eta_{BUCK} = \frac{P_s}{P_{PV}} = \frac{V_s I_s}{V_{PV} I_{PV}} \quad (8)$$

The average output current I_s is then given by:

$$I_s = \eta_{BUCK} \frac{I_{PV}}{D_{MPP}} \quad (9)$$

From the above equations, it can now express D_{MPP} as a function of η_{BUCK} , load resistor R_{IN} , and PV module's internal resistor R_{PV} :

$$D_{MPP} = \sqrt{\eta_{BUCK} \frac{R_{IN}}{R_{PV}}} \quad (10)$$

But since D_{MPP} and η_{BUCK} are less than 1, the matching condition requires:

$$R_{IN} < R_{PV} \quad (11)$$

So, for a high converter's efficiency, the optimum duty cycle $(D_{MPP})_{opt}$ is expressed as a function of the optimum PV array internal resistor $(R_{PV})_{opt}$:

$$(D_{MPP})_{opt} = \sqrt{\frac{R_{IN}}{(R_{PV})_{opt}}} \quad (12)$$

This latter equation gives the control law that must be generated by the MPPT system to make the PV module operate at its MPP, for given resistive load R_{IN} , insolation and temperature.

In case of the DC-DC buck output converter is directly connected to the battery stack, R_{IN} is simply the internal of such battery stack (Fig. 3).

5.2 DC-DC Boost Converter

The basic circuit topology of the DC-DC boost converter is given in Fig. 6.

By following the same reasoning as for the buck converter, it can show easily that:

$$V_o = \frac{V_s}{(1 - D_{REG})} \quad (13)$$

$$I_o = \eta_{BOOST} (1 - D_{REG}) I_s \quad (14)$$

and

$$R_{IN} = \eta_{BOOST} R_o (1 - D_{REG}) \quad (15)$$

This leads to the following important condition:

$$R_o > R_{IN} \quad (16)$$

Then, for such a converter and for a maximum power transfer, the PWM control signal must have an optimum duty cycle. $(D_{REG})_{opt}$ is given by:

$$(D_{REG})_{opt} = 1 - \sqrt{\frac{(R_{IN})_{opt}}{\eta_{BOOST} R_o}} \quad (17)$$

At this level, it must be underlined that when the photovoltaic series string is directly connected to the DC-DC boost converter, without using battery stack, the control law that must implemented is obtained from Eq. (12), where R_{IN} is given by Eq. (15). Thus, for high converters' efficiencies, it can easily show that:

Fig. 6 DC-DC boost converter for a PV system.

$$(D_{MPP})_{opt} = (1 - D_{REG}) \sqrt{\frac{R_O}{(R_{PV})_{opt}}} \quad (18)$$

6. Simulation Results and Discussion

To test the effectiveness of the controls adopted in the proposed PV system, simulations by considering the two following physical conditions were carried out:

(1) The photovoltaic system is loaded either with a batteries stack or with a constant resistive load, but it undergoes abrupt changes in insolation.

(2) The photovoltaic system is fed with constant insolation but undergoes abrupt changes in resistive load.

6.1 Abrupt Changes in Insolation Value

6.1.1 The Load Is a Fixed Resistor

The photovoltaic system is loaded by a fixed resistor of 4.7Ω and fed with a changing insolation. The insolation varies abruptly from $1,000 \text{ W/m}^2$ to 600 W/m^2 and then from 600 W/m^2 to $1,000 \text{ W/m}^2$. The changes in insolation occurs at times 5 ms and 15 ms (Fig.7a). The effect of this abrupt changes is observed through simulation results when considering the following important quantities, e.g., the output voltage, the output current, the transmitted power at the level of the batteries stack, and the optimal duty cycle (Fig. 7).

At first glance, simulation results show that in steady mode, the previous electrical quantities depend closely on the variations of the incident insolation.

Indeed, initially and before any change in insolation, the optimal operation point is found in a time less than 2 ms, with a duty cycle equals to 0.82. This point is tracked and locked until the occurrence of a change in insolation.

At the first change in insolation, which took place at 5 ms (Figs. 7b, 7c and 7d), the PV system loses momentarily the optimum operating point. At the same time, the duty cycle control signal drops to a lower value, and the voltage across the PV module terminals evolves into short-circuit voltage. This effect is marked by the presence of a negative peak on the graphs of the

Fig. 7 Different electrical quantities of the PV system with a fixed load and changing insolation ($1,000 \text{ w/m}^2$ - 600 w/m^2).

electrical quantities (voltage, current, and power, Fig. 7). After this transient event, the control system carries out a new research for a new optimum operating point which is quickly reached. Indeed, the electrical quantities, i.e., the output power, the output voltage, the output current, and the duty cycle are kept stabilized respectively at 807 W, 62.5 V, 13 A and 0.65.

During the second abrupt change in insolation, which took place at 15 ms (Fig. 7), the PV system loses again its optimal operation point. But the control system provides a duty cycle signal that increases and slightly exceeds the optimal value. This means that the PV module evolves to the open circuit voltage. Then the control system cuts this progression and performs the research of a new optimal operation point that is quickly reached. New values of electrical quantities cited above are tracked and stabilized respectively at 1440 W, 82.8 V, 17.3 A and 0.82.

For more clearness, the voltage across the PV module to exemplify these events was picked (Fig. 8).

6.1.2 The Load Is a Battery Stack

Similar simulation tests are carried out, where the fixed resistor is replaced by a batteries stack. Fig. 9 gives the simulation results that show the same

Fig. 8 Input voltage of any buck converter (output voltage of any PV module).

Fig. 9 Different electrical quantities of the PV system with changing insolation (1,000 w/m²-600 w/m²) and the batteries stack as a load.

behaviour as the previous case, except that the duty cycle provided by the control system (Fig. 9d) doesn't have the same form compared to the previous case where the load was a fixed resistor. The control system acts properly, since it can track the occurred changes in insolation and it always moves to the good direction.

Here, one should notice that the output voltage of any DC-DC buck converter is imposed and maintained

constant (82.8 V) by the batteries stack in spite of the insolation changes. But the output current provided to the batteries stack is optimally imposed by the MPPT control system, taking into account the state of insolation.

6.2 Abrupt Changes in the Load Value

In this subsection, it presents the result of simulation tests carried out on the proposed PV system with constant insolation ($1,000 \text{ W/m}^2$), constant temperature (25°C), and abrupt changes in the load value. Indeed, two values are selected for the value of the resistive load, namely 4.7Ω and 3.3Ω . The results are shown in Fig. 10. The behavior of the photovoltaic system in terms of variations electrical quantities is somewhat similar to the cases presented in the previous subsections. Once again, these results show the effectiveness of the control system that was used.

Fig. 10 Different electrical quantities of the PV systems with fixed insolation ($1,000 \text{ W/m}^2$) and changing load.

7. Conclusion

In this paper, it proposed a 1.44 kW digitally controlled PV power system for stand-alone PV power system applications, using four series connected DC-DC buck converters. Each buck converter is driven by a pair of PV panels connected in parallel, operating in complex physical environments with local and autonomous controls, to track the maximum power points of PV modules. The control unit of the digital system is based on the MPPT algorithm which is implemented in C language using C-MEX S-functions under MATLAB-SIMULINK environment.

To test the performances of the control unit, it carried out simulations under brutal changes in insolation and load, in order to explore their influences on the electrical quantities of such a PV system. Simulation results show that, in these complex conditions, the control unit tracks can quickly find the optimal operation point, insuring a maximum power transfer from the PV modules to the load.

According to the all simulations carried out in the conditions mentioned above, this PV system exhibits some important performances, compared to the literature results, namely:

- a good dynamics in term of the response time which is less than 2 ms;
- a very good precision, since the optimal operation point is found quickly, tracked and locked without any oscillations;
- a very good stability; indeed, once the steady state is reached, the system presents no risk of divergence.

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