Design and realization of an autonomous solar system

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Abstract. The aim of this work is the design and realization of an autonomous solar system, with MPPT control, a regulator charge/discharge of batteries, an H-bridge multi-level inverter with acquisition system and supervising based on a microcontroller. The proposed approach is based on developing a software platform in the LabVIEW environment which gives the system a flexible structure for controlling, monitoring and supervising the whole system in real time while providing power maximization and best quality of energy conversion from DC to AC power. The reliability of the proposed solar system is validated by the simulation results on PowerSim and experimental results achieved with a solar panel, a Lead acid battery, solar regulator and an H-bridge cascaded topology of single-phase inverter.

1. Introduction
An autonomous solar system is a photovoltaic solar power plant which is not connected to the grid. The extraction of the maximum power from solar panels called 'MPPT technique' (Maximum Power Point Tracking) provides an effective method to solve the optimization problem. A multi-junction solar cells are different from silicon PV cells as they are capable of converting solar irradiation into energy at high efficiency. PV array represents the essential power conversion unit of a photovoltaic system. The output characteristics of PV array depend on the irradiation, the temperature and output voltage of PV array. Among the MPPT strategies which are the most used: the method of incremental conductance (I.C.), the Perturbation and observation (P&O), and fuzzy logic.
The performance of a standalone photovoltaic system depends mainly on the technical regulation and control adopted. In fact, there are many methods for estimating charging status 'State Of Charge: SOC'. The simplest method is the use of coulomb metric measurement.
The objective of this work is the realization of a complete solar system based on a microcontroller intended for the MPPT control and monitoring the state of charge of the batteries to protect them. We are implementing the P&O algorithm for MPPT control. For the determination of 'SoC' in the storage system, we are implementing a specific coulomb metric method with an understandable and reliable user display which increases the performance and reliability of the battery.
We are implementing the algorithm control of the five level inverter to achieve an output voltage that resembles a sinusoidal voltage. For the implementation of the whole process, an innovative control application is developed on Labview environment that gives the system a flexible and scalable structure for controlling, monitoring and supervising the complete system in real time.

2. Photovoltaic generator
The principle operation of a photovoltaic generator is based on the photovoltaic effect of semiconductor PN junction. When exposed to sunshine, a DC current is generated; this current varies linearly with the solar radiation [6].

![Figure 1. Characteristic of a solar panel.](image)

The current-voltage characteristic depends on the irradiation and temperature conditions on the surface of the photovoltaic cell. Figure 1 shows the influence of irradiation on the current-voltage characteristics and power-voltage of a photovoltaic module with a constant temperature [7]. The maximum operating point must always be followed to ensure that the PV generator has reached its maximum power output in real-time to maximize permanently the transferred energy.

3. DC / DC Converters
A photovoltaic generator (PV) works in optimum conditions; it must have an adaptable converter. This adaptation is achieved by searching automatically the maximum power point (MPP) of the PV generator [8]. The converter may be a DC / DC "Boost" or "Buck" according to applications. Figure 2 shows the boost converter structure with 'T' is the switching period 'of the duty cycle.

![Figure 2. Model of DC / DC boost.](image)

4. MPPT Controller
One of the most commonly used MPPT strategies is the perturb and observation method (P&O), the working principle is simple, we disturb the system power by acting on the control signal “PWM”, and observe the direction of the output power variation Figure 3. Indeed, the MPPT controller adjusts the voltage across the photovoltaic source by using a DC-DC boost converter Figure 2, and measures the output power. After that, it varies the voltage across the PV by changing the PWM duty cycle and takes a second power measurement. If the power increases, the maximum power is not yet reached so we must choose the new control signal by changing the PWM duty cycle in some direction. Therefore, we need to adjust the voltage in the positive direction until the power will not increase, that’s mean that the variation rate will be null [9]. Figure 4 present in details the MPPT algorithm implemented in this work.
Figure 3. Principle of the P&O algorithm

Figure 4. P&O algorithm.

5. Controlling the charge state
The state's control technique battery 'SOC' is the most convenient and most commonly used. It consists of measuring and calculating the arriving and leaving quantities of electricity during charging and discharging in terms of ampere-hours. This technique is called the coulomb metric measurement. The chosen model assumes that the battery charge status 'SOC' is the ratio of the amount of electricity received or returned by the battery and the capacity of the battery (Ah). The calculation of the battery charge status 'SOC' is done using the following recursive relation:

\[
SOC(t + 1) = \begin{cases} 
SOC(t) + \eta_b \times \frac{I_{b,t}}{C} \text{ (Battery charge)} \\
SOC(t) - \frac{I_{b,t}}{C} \text{ (discharge cycle)}
\end{cases}
\]  

(1)

With:
SOC (t+1) : State of charge at the moment (t+1)
SOC (t) : State of charge at the moment (t)
ηb : medium Faraday efficiency during the charging cycle. The typical value is 0.9.
Ib : Input current or battery output
C : Capacity of the battery

6. Photovoltaic inverter
Figure 5 shows a five levels cascaded H-bridge multilevel inverter. The inverter consists of two H-bridge cells connected in series which are fed by independent voltage sources. The outputs of the H-bridge cells are connected in series such that the synthesized voltage output is the sum of all of the individual cell outputs. The output voltage is given by equation:
\[ V = V_1 + V_2 \]  

Where the output voltage of the first cell is labeled \( V_1 \) and the output voltage of the second cell is denoted by \( V_2 \). There are five levels of output voltage i.e. \( V, V/2, 0, -V/2, -V \).

![Figure 5. Five level cascaded H-bridge multilevel inverter.](image)

7. Realization and experimental results
The block diagram of the complete solar system is shown in Figure 6, it consists of a PV generator, a battery, a DC-DC converter, an inverter, a MPPT control block and the battery state of charge estimator 'SOC'. A graphical interface is developed in Labview environment to manage the entire system.

![Figure 6. Block diagram of the complete system.](image)
Figure 7. MPPT hardware implementation.

Figure 7 shows the realized experimental system, the characteristics of the used PV module are as follows; maximum power is 30 W, open circuit voltage is 17.6 V, maximum current is 1.7 A. For the battery, nominal voltage is 12 V, capacity is 9 Ah, nominal current is 1 A, the electrolyte density is 1.23 kg/l, end of charge voltage is 14.8 V (20° C) and the end of discharge voltage is 10.5 V (20° C). The MPPT algorithm implementation is divided into two parts; the first one is the firmware which is loaded in the microcontroller, it is principal task establish communication between system and software application developed by LabVIEW which represents the second part of implementation “Graphical User Interface” shown in Figure 9. This software application extends the user possibilities to select other MPPT algorithm than the used one. The hardware system, in Figure 7, controls the photovoltaic power by detecting the panel voltage (V) and current (I) to determine the operating point corresponding to the maximum power.
Figure 8. Simulation of the implementation of MPPT algorithm in PowerSim.

Figure 8 shows the simulation diagram of the complete circuit in the Powersim simulator. The system consists of a PV panel, a DC-DC Boost converter, a resistive load, sensors for voltage and current measurement and the MPPT controller block.

The P&O algorithm shown in Figure 4 is implemented in the MPPT control block. The graph in Figure 8 shows the evolution of the power delivered by the solar panel with different irradiation values (500, 1000 and 1500 W/m²). The maximum power point is reached after a few seconds after starting the MPPT algorithm execution, which proves the performance of the system in terms of dynamics. Once the desired operating point is reached, the DC-DC BOOST converter control is kept constant. Maximum power point values are indicated in blue while the actual values are shown in red.

The acquisition device used in this system is based on an Arduino module that integrates Atmel microcontroller; it measures both current and voltage of the solar panel and generates the control signal of the DC/DC converter which is the PWM signal. For detecting and reading the current supply delivered by the photovoltaic module, a shunt resistor is placed in series with the analogue-digital converter input of the microcontroller card. The shunt resistor of the sensor provides a voltage proportional to the current flowing through it. To measure the PV generator voltage, the node between the two resistors in series must be connected to the analog input of the microcontroller.

Figure 9 reveals the Graphical User Interface (GUI) that we have designed; it allows to the user the full access to all system features. This interface is developed in the Labview environment, it provides several display and options control:

(a) Automatic or manual control
(b) Choosing the MPPT algorithm
(c) (d) & (i) current, digital voltage and power indicators
(e) (f) & (j) current, voltage and power graphical indicators
(k) Initialization of the serial communication
(l) & (g) Error indicator and shutdown button
(h) Indicators and additional orders

All these control options and indicators are the basic interface necessary to control the entire system, additional indicators and buttons control are added to provide extra access to the system. The main state of charge (SOC) controller objective is supervising the real time battery state in a standalone photovoltaic system. The main part of the developed system is a microcontroller which implement the SOC algorithm based on the coulomb metric counting method. To evaluate the proper functioning of
this technique, two tests are made; the first one determines the SOC profile of the battery in charge cycle as shown in Figure 10. The last test determines the battery profile in discharge cycle as shown in Figure 11.

In the charging phase, only the battery is connected, the charge current varies between 0 and 2 A depending on the sunlight. The charge state management program is implemented in the microcontroller and connected to the computer with a Labview application via a USB connection. Several values of the 'SOC' were identified in real time (Figure 10).

In the discharge phase, a resistive load is connected (10Ω, 25W) at the terminals of the battery that delivers a constant discharge current. Several points of the SOC measures in real time have been identified. Figure 11 shows the extracted values by our device.

From these practical results, it appears that the automatic control of the SOC battery charging status during the two processes charging and discharging is primordial to save battery life.

Figure 12 bellow shows the pattern of simulation by Power SIM of a signal-phase five level inverter type H-Bridge and a DC voltage source of 24V. In this topology, two power supplies with a value of 12V each are used. The output obtained has five levels with a maximum voltage of 24V.
Figure 12. Power circuit and PWM control of five level inverter in PSIM.

Waveform of compound voltage of signal-phase H-Bridge five levels inverter is illustrated in figure 13. The compound voltage shows a maximum value of 24V.

Figure 13. Output voltage of five levels inverter.

8. Conclusion
This paper presents an autonomous and efficient solar system with a solar controller MPPT. The heart of the developed device is a microcontroller that integrates the MPPT control algorithm and the charge state 'SOC' batteries algorithm based on the coulomb-metric method, as well as the control of the various electronic switches of the inverter.

The proposed approach is based on developing a graphical interface in the LabVIEW environment which gives the system a flexible and scalable structure for controlling, monitoring and supervising the entire system in real time. This application is used to implement multiple types of MPPT algorithm without any changes on the equipment part. Thus, the developed system can be a powerful tool in the industrial sector and in the field of research. The reliability of the proposed complete solar system is validated by the results of simulations in the PowerSim environment and experimental results achieved using a solar panel, an average lead-acid battery power and the proposed solar controller.

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