Design and Development of A Stand-Alone Solar Energy Harvesting System by MPPT and Quick Battery Charging

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***Abstract*— This paper presents a solar energy harvesting system applied especially for the flood warning system. The proposed topology is a stand-alone system that is required to harvest the maximum energy from the photovoltaic (PV) panel to charge batteries. Perturb and Observe method (P&O) is used to control converters using for Maximum Power Point Tracking (MPPT). Additionally, a Three-Stage Charging (TSC) method is used to quickly and safely charge the battery. The power management technique between the maximum power point tracking and the power charging processes is also proposed. The simulation results show that the P&O method can efficiently track the maximum power and the TSC method can properly control the charging process. Moreover, the MPPT method and optimal charging of the battery can work together with the proposed power management algorithm.**

Keywords— Photovoltaic (PV); Three-Stage Charging (TSC); Maximum Power Point Tracking (MPPT); Perturb and Observe method (P & O Method)

I. INTRODUCTION

At present, a renewable energy is one of the features that has been used in many applications, especially the use of a photovoltaic (PV) panel because it provides endless, clean and easy to use energy of the PV panel [1]. The use of a PV panel at maximum efficiency is to extract the Maximum Power Point (MPP) of the PV panel [2]. To extract the maximum value, it is necessary to calculate how to keep the system running at the MPP. This method is called the method of Maximum Power Point Tracking (MPPT) [3]-[7]. There are many factors that affect the MPPT control such as temperature, light intensity and load. The temperature and light intensity are caused by the change of environment. If the light intensity is changed, it will directly affect the current produced by the PV panel resulting in the deviated MPP. Also if the temperature is changed, it will directly affect the voltage of the PV panel and the MPP is changed. If the load connected to the PV panel is changed, the MPP will be changed as well.

Since the energy from a PV panels is available for limited time, depending on the duration of sunlight and weather, or environmental conditions in each period. The system may lack of reliability if it does not receive the maximum power from the PV panel. As the result, the power will not be constant and will not be active at all times. To improve the system reliability, a battery is added to store energy when there is sunlight and supply power back to the system when there is no sunlight as shown in [8] and [9]. However, having only one huge battery may cause the systems lack of reliability and low efficiency because the power to charge the battery must take longer time and many steps which may not consistent with the period of sunlight and weather. Therefore the battery charging control process is needed to quickly charge the battery and also to prevent the overcharging or the undercharging which results in the decrease of the battery lifetime or permanent damage of the battery as shown in [10] and [11]. Thus, if the MPPT control and the battery charging control processes are combined in same the system, they will make the system more reliable and efficient as stated in [12] and [13]. However, if the battery is fully charged, the remaining energy of the PV panel on the duration of sunlight become to the loss power. So the harvesting energy aim will be lost since it cannot store the solar energy effectively.

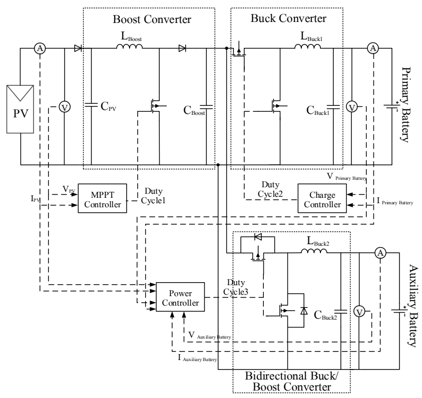

Fig. 1 Circuit architecture of the proposed solar energy harvesting system.

A solar energy harvesting system shown in Fig. 1 is designed for a flood warning system under the condition of having MPPT and quickly charging the batteries. The flood warning system is used in remote locations or without grid utility. Therefore, the power supply system needs to be reliable and sufficient to supply power to the flood warning machine at all-time, especially in an

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emergency situation. This paper focuses on solar energy harvesting for utilizing all available energy and to make the system more reliable. MPPT will be controlled at every moment along with the process of charging the battery. Finally, this paper has included an auxiliary battery to solve the problem of losing energy. The auxiliary battery will not be controlled in the charging process, so the remaining power, from PV panel, will be kept by the auxiliary battery. The system will be designed and simulated by using the "Simulink / MATLAB" software.

II. PROPOSED SOLAR ENERGY HARVESTING SYSTEM

A. *Circuit Architecture*

The circuit architecture of the solar energy harvesting system for tracking the maximum power of the PV panel and controlling the battery charging process is shown in Fig. 1. The system consists of the PV panel, the primary battery, the auxiliary battery and three main circuits. These circuits are explained as follows:

1) Boost converter: This circuit supports the difference of the voltage to track the maximum power point determined by the P&O method. To illustrate this goal, the voltage of the battery charging is 12 V, and the voltage of the MPP is 17 V. If the battery is directly connected with the PV panel, the voltage of the PV panel will be decreased to 12 V. This will change the MPP working points. The boost converter is selected and used to track the MPP because it is simple and high efficiency.

2) Buck Converter: The circuit controls battery charging by the TSC method. It controls the charging voltage and the charging current of the battery. The value of the voltage from the PV panel or the tracking system of the maximum power is higher than the voltage of the battery. The process of the buck converter will optimize charging voltage.

3) Bidirectional Buck/Boost Converter: This circuit allocates and harvests all power from the PV panel and controls the charging process of the primary battery. If the power of the PV panel is higher than the charging power of the primary battery, the bidirectional back/boost converter will be the buck converter to transfer the excess power to the auxiliary battery. However, if the power of the PV panel is lower than the charging of the primary battery, the bidirectional back/boost converter will be the boost converter to transfer the power from the auxiliary battery to the primary battery.

B. *MPPT Technique*

Maximum Power Point Tracking (MPPT) is the indirect technique to increase the efficiency of the PV panel. In Fig. 2, the PV panel is connected directly to the load which is represented by OB curve and the power is equal to P2, which matches to the value of the MPP. If the load is represented by OA curve, the power is equal to P1 which is less than the MPP (P2). Therefore, the converter used to find and track the maximum power (P2) of the PV panel.

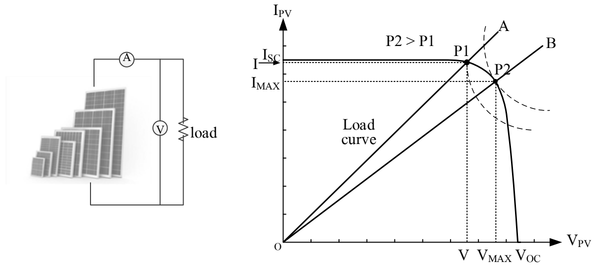

Fig. 2. The operation of the MPPT.

For the MPPT process, it will work continuously to make the system to operate at or around the MPP. There are many methods to track the MPP. The most common and basic method that can be applied to track the maximum power is the Perturb and Observe method (P&O method).

A principle of the P&O method works by adjusting the duty cycle of the converter, which indirectly perturb the power output of the PV. Then, the system compares the new power to the previous power to determine the next adjustment. Let's define the difference of the PV power output as

$$dP = P(k) - P(k-1) \tag{1}$$

- If the value $P(k) > P(k-1)$ is positive, the system will adjust the voltage (increase or decrease the voltage) by adjusting the duty cycle of the converter in the same direction.
- If the value $P(k) < P(k-1)$ is negative, the system will adjust the voltage (increase or decrease the voltage) by adjusting the duty cycle of the converter in the opposite direction.

The diagram of this method is shown in Fig. 3. The advantage of the P&O method is a simple method for MPP determination. The P&O method can also work well at steady state, when light intensity and temperature change slowly.

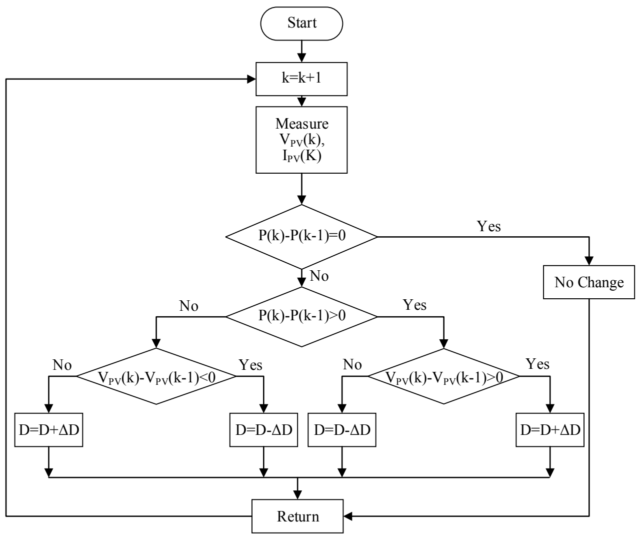

Fig. 3 Diagram of the P & O method.

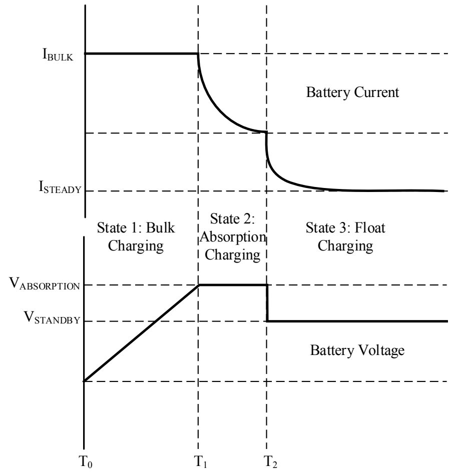

Fig. 4 Three stage charging the voltage and the current curve.

C. Charging Technique

The PV panel might not provide the constant voltage and current because the PV output depends on light intensity and temperature. Then the PV panel is not a suitable energy source for charging the battery. Therefore, if the battery will be used in the PV system, the performance of the battery will be decreased, the lifetime of the battery becomes shorter. In conditions of varying light intensity the battery may experience a low State of Charge (SOC). Typically, the battery charging process will be controlled by a converter to adjust the duty cycle for the value of the voltage and the current in charging process, for quick charging and protecting the battery [13].

To achieve a quick, complete, and safe charging process of the lead-acid battery, the method was implemented in the most practical way of the Three Stage Charging (TSC), which is divided into three stages. Fig. 4 shows a graph of the TSC.

1) Bulk charging: This state of charging, the current is kept constant, which will reduce time to charge the battery. It will charge in this state until the battery voltage reaches the absorption voltage. In this state, the battery will be recharged 70-80% of the battery capacity. It is the fastest state of charging.

2) Absorption charging: The charging voltage is kept constant. At the absorption voltage, it will be about 1.2 times of the nominal voltage of the battery. The current charge is reduced close to zero. In this state, the battery will be charged additionally 20-30% of the capacity.

3) Float charging: The voltage level will be reduced to a constant value, which is called standby-voltage. It is approximately 1.13 to 1.15 times of the nominal voltage of the battery. In this state, the battery is charged by a small current to maintain the voltage of battery. It is important to maintain the voltage of the battery in a full state of charge.

III. Operating Principles

Three controlled charging modes for a primary battery ($P_{\text{Primary Battery}}$) and an auxiliary battery ($P_{\text{Auxiliary Battery}}$) are shown in TABLE I.

TABLE I. Each mode of Management power system

Mode	Management power system
Mode I	$P_{PV} - P_{loss} > P_{\text{Primary Battery}}$
Mode II	$P_{PV} - P_{loss} = P_{\text{Primary Battery}}$
Mode III	$P_{PV} - P_{loss} < P_{\text{Primary Battery}}$

Each mode of the power control is provided to control different ways as follows.

A. Mode I

In the first mode, it is divided into two cases. In the first case, the auxiliary battery can harvest power remaining after deducting the power losses in the system of charging power to the primary battery controlled. In the second case, if the auxiliary battery is fully charged, the auxiliary battery will not harvest power remaining after deducting the power losses in the system of charging power to the primary battery controlled.

For example, we assume the PV output power equal to 180 W and the controlled primary battery ($P_{\text{Primary Battery}}$) charging process is equal to 67 W. The system loss of power is 10 W, so 180-67-10 = 103 W of power are left to charge the auxiliary battery ($P_{\text{Auxiliary Battery}}$) by uncontrolled charging process as shown Fig. 5.

B. Mode II

In this mode, the net output power is available to sufficiently charge only the primary battery. The converter for the auxiliary battery is turned off, as shown in Fig. 6.

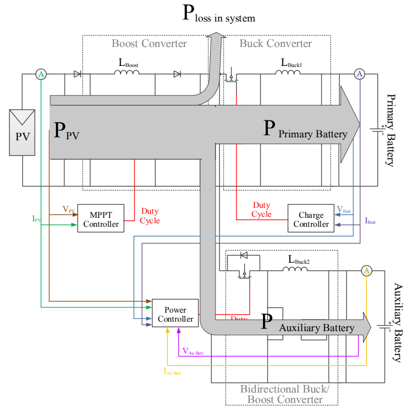

Fig. 5 Direction of the power transmission mode I.

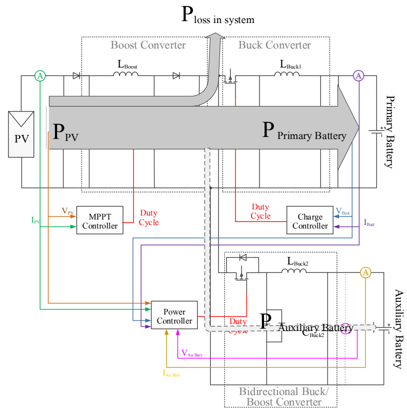

Fig. 6 Direction of the power transmission mode II.

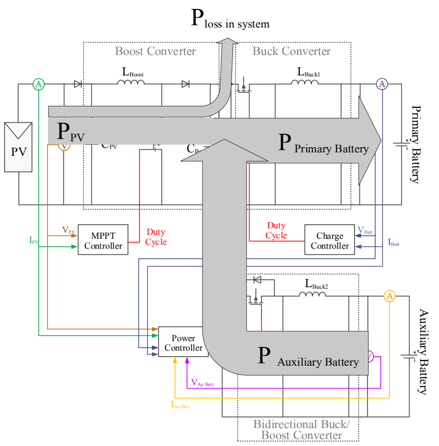

Fig. 7 Direction of the power transmission mode III.

C. *Mode III*

In the third mode, it will be divided into two cases. In the first case, the auxiliary battery supplies power to the primary battery charging adequate for control procedures after deducting the energy losses in the system. In the second case, the auxiliary battery is unable to supply power to the primary battery charging procedure.

For example, if the PV output power equals to 30 W and the primary battery ($P_{\text{Primary Battery}}$) wants 67 W to control step of charging and the system loss of power is 10 W, the auxiliary battery ($P_{\text{Auxiliary Battery}}$) must supply 67-30-10 = 27 W to charge the primary battery as shown in Fig. 7.

IV. Simulation Results

To confirm the concept of the solar energy harvesting system and test the validity of the system, we change light intensity in order to see whether the system is able to track the maximum power and to see that the system is able to control energy in the process of battery charging. We simulated using the "Simulink / MATLAB" software. KV235-60M solar module is chosen for a MATLAB simulation model. TABLE II shows its electrical specification from data sheet. The simulation results are shown in Fig. 8-Fig. 12.

Fig. 8 shows that the controlled TSC can realize the voltage and the current stabilized charging of the charging system.

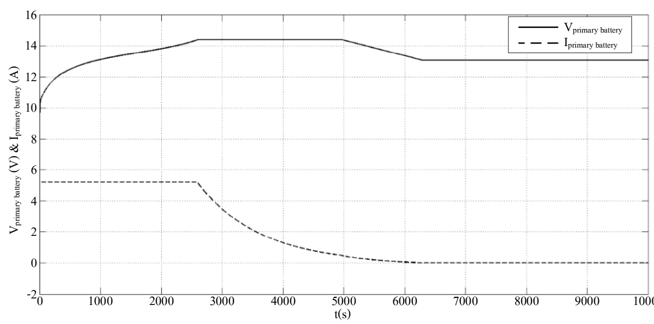

Fig. 8 The voltage and the current of the battery charging process by the TSC method

TABLE II. The Electrical Data of the KV235-60M Solar Module Relates to Standard Test Conditions [STC]: 1,000 W/m², AM 1.5, 25 °C. Taken from the Datasheet

Parameters	Values	
Maximum Power (P_{mp})	235	W
Maximum Power Voltage (V_{mp})	29.6	V
Maximum Power Current (I_{mp})	7.94	A
Open circuit voltage (V_{oc})	36.8	V
Short Circuit Current (I_{sc})	8.45	A
Number of Cells (PCS)	60	PCS

Fig. 9 shows the changing of light intensity from 500 W/m^2 to 250 W/m^2 at 0.5 second, and from 250 W/m^2 to 500 W/m^2 at 1 second and from 500 W/m^2 to 700 W/m^2 at 1.5 second. Fig. 10 and Fig. 11 show graph of the power, the voltage and the current of the PV panels to track the maximum power. Fig. 12 shows the solar power, the primary battery power and the auxiliary battery power for management of power to the system.

According to the simulation results shown in Fig. 10, the system is able to track the maximum power of the PV panel when the light intensity changes from 500 W/m^2 to 250 W/m^2 at 0.5 second, and from 250 W/m^2 to 500 W/m^2 at 1 second and from 500 W/m^2 to 700 W/m^2 at 1.5 second. In a rapidly changing of the light intensity, the result in a tracking system for maximum power of the PV panel is slow and erroneous at first, but the system can track the maximum power of the PV panel. Fig. 11 shows the voltage of the PV panel, which has changed slightly when the light intensity change. It also shows that the current of the PV panel is changed according to the light intensity. If the light intensity is very high, the current value is also high.

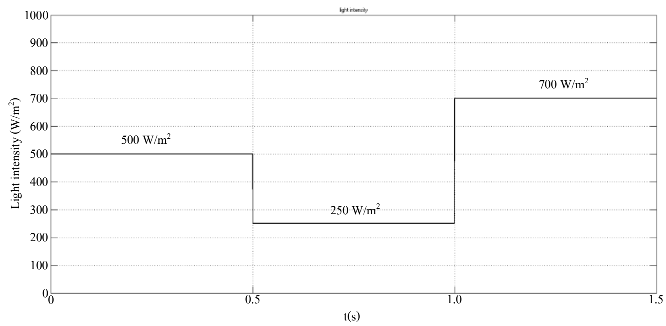

Fig. 9 Light intensity condition.

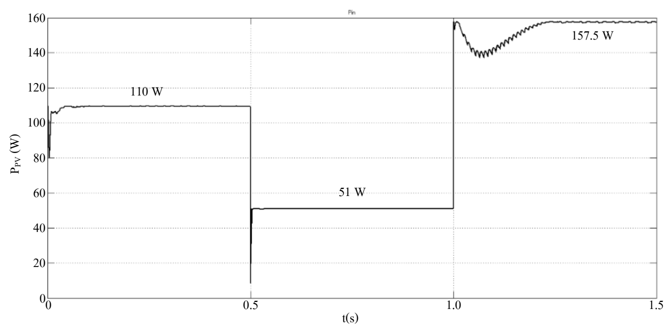

Fig. 10 The power of the PV panel in changed light intensity condition (500 W/m^2 - 250 W/m^2 - 700 W/m^2).

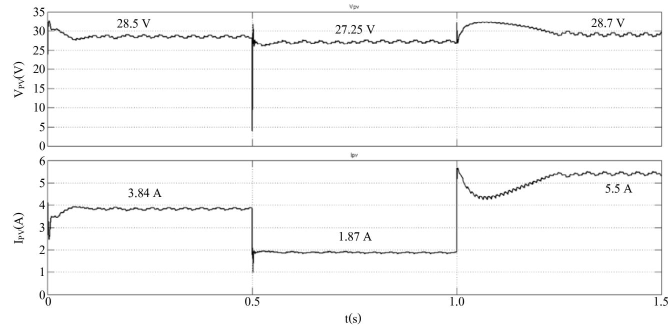

Fig. 11 The voltage and the current of the PV panel in changed light intensity condition (500 W/m^2 - 250 W/m^2 - 700 W/m^2).

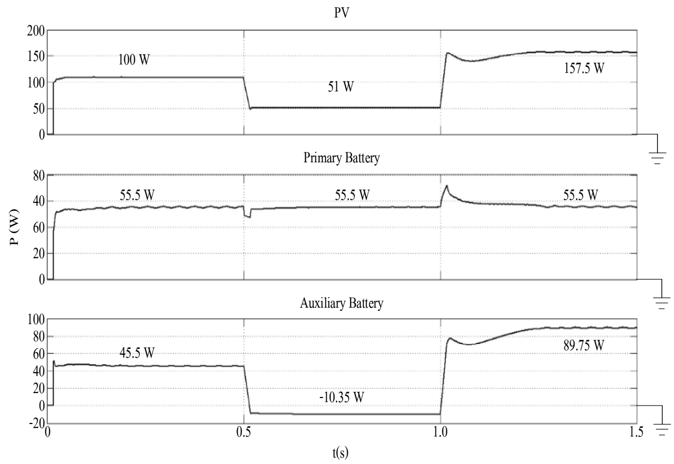

Fig. 12 Output power of the PV panel, the primary battery and the auxiliary battery in changed light intensity condition (500 W/m^2 - 250 W/m^2 - 700 W/m^2).

In addition, Fig. 12 shows the system allocation of the power in each mode. During the time between 0 to 0.5 second, the system works in mode I, where the PV power output is 110 W and the required battery power is 55 W. The remaining power equals 50 W, which is charged to the auxiliary battery. During the time between 0.5 to 1 second, the system works in mode III, which the power of the PV panel equals 50 W less than the power of the primary battery required 55 W. The auxiliary battery supplies power equal 10 W to the primary battery charging and during the time between 1 to 1.5 second, the system works in mode I again.

V. CONCLUSION

This paper presents the modified TSC system for solar energy harvesting applications. The purpose of the proposed system is to combine the PV panel MPPT to develop the most efficient process for the lead-acid battery and the power management technique. We have proven that the designed system can utilize solar energy and control the charging of battery at maximum efficiency, so that the lead-acid battery can be quickly and safely charged.

Finally, the simulation results show that the proposed system is feasible and it will be implemented in the battery charging system for the flood warning system in future works.

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