Power Electronics for Photovoltaic Energy System of an Oceanographic Buoy

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***Abstract*- This paper reports on design of power electronics for photovoltaic (PV) energy system of an offshore remote sensing apparatus. Challenges in design of a PV energy system for a marine application are investigated and the design limitations compared to inland PV system are discussed. The designed system includes PV cells as the main source of energy, electric storage (battery), maximum power point tracking (MPPT) and protection circuitries. An MPPT algorithm based on measuring the slope of the PV power-voltage curves is presented which can be implemented with simple analog electronic circuits. The MPPT circuit uses Sepic converter as a core and it also includes a protection unit for maintaining the battery voltage in a safe range. The performance of the proposed MPPT algorithm in presence of measurement noises is verified using a circuit simulation software tool (PSCAD). Simulation results verify that the algorithm appropriately regulates the voltage of PV cells at MPP and it is robust against measurement noises for a signal-to-noise ratio above -2db.**

***Keywords*- Stand-alone PV Systems, Tracking, Remote Sensing, Oceanographic Buoy, Sepic-Converter.**

I. INTRODUCTION

Oceanographic buoys are floating instruments that measure marine/metrological data and transmit them (via a wireless unit) to onshore stations for further analysis. Photovoltaic (PV) solar energy is the only reliable source of energy for wireless circuitry of a buoy [1, 2]. Design of PV energy systems for buoys compared to onshore systems is challenging due to a harsh marine environment. The limitations/requirements of the stand-alone PV energy system of a buoy compared with conventional inland PV systems are: 1) a buoy is often located far away of a shore and its cost of maintenance is huge, thus its PV energy system must be autonomous and robust, with additional electrical protections; 2) sea waves continuously fluctuate the structure of a buoy, therefore the topology of the PV power circuit of a buoy must be simple with minimum components to improve reliability; 3) the available surface area on a buoy to install PV panels is limited and panels are fixed which need efficient circuitry with a maximum power point tracking (MPPT) strategy. This paper deals with power electronics and system design aspects of a PV energy system for powering of "*Mowj-Negar*", the oceanographic buoy of Isfahan University of Technology (Fig.1). Several analog and digital MPPT techniques have been proposed for inland stand-alone PV energy systems [3-5] which have been reviewed to select a suitable topology for a buoy. Then, the topology has been improved herein to address the specific requirements of the buoy. The designed PV energy system includes: 1) a power electronic circuit using Sepic dc/dc switching converter as a core; 2) a simple analog controller circuit for MPPT; and 3) the required protections for electrical units of the buoy. The proposed controller can be implemented with discrete analog electronic components which improves reliability of the circuit due to its simple structure as compared with DSP-based digital controllers. To verify the performance of the designed system, the electronic circuits and its controller were simulated using the electrical model of buoy's instruments and solar panels. The simulation investigates the MPPT capability of the designed circuit and robustness of the circuit with respect to measurement noises.

Fig. 1 Mowj-*Negar*, the oceanographic buoy of Isfahan University of Technology

II. THE BUOY PV ENERGY SYSTEM

Fig. 2 shows the schematic diagram of the PV energy system of buoy. The input stage includes PV cells to capture energy of the sunlight irradiation. Next stage is a dc/dc converter which measures PV cells output voltages/currents and set the PV cells at their maximum power point. Instruments of a buoy periodically on/off during a day, however, we model the average power consumption of all instrumentations with a fixed load which is supplied with the buoy energy system.

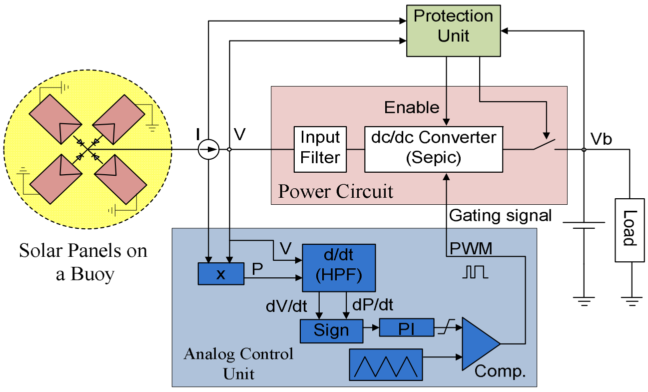

Fig. 2 The buoy PV energy system.

The dc/dc converter charges the battery during a sunny day and supplies power to the load. The battery must be protected against over charge. Thus, a protection unit is used to continuously monitor the battery voltage and disconnect it from converter at an over voltage condition.

The analog control unit in Fig. 2 consists of a high pass filter, a PI controller, a saw tooth signal generator, and a comparator. The detail function of this unit will be elaborated in the following sections.

III. ENERGY SYSTEM DESIGN FOR BUOY

The heart of MPPT circuit is a switch-mode dc/dc converter. Dc/dc convertors are widely used to convert an unregulated dc input into a controlled dc output at a desired voltage level. However, in a PV energy system, MPPT uses the converter to regulating the input voltage at the PV maximum power point. Input voltage regulation can be achieved via appropriate change in the duty cycle of converter.

A. Converter Selection and Design

A buck converter is a simple and efficient step-down dc/dc converter which is widely used in different applications. To implement the MPPT algorithm in the PV energy system of a buoy, we do need to measure terminal current and voltage of the PV cells. This necessitates using an additional low pass filters to mitigate the current pulsating and using high-side driver for the buck converter switch. Sepic converter is an alternative dc/dc converter for the PV energy system which has the buck-boost feature (Fig. 3). A Sepic converter has the merits of non-inverting polarity and easy-to drive switch. Furthermore, the input inductor of a Sepic converter will smoothen the measured current, hence, extra filter is not required. Integral characteristics of Sepic converter make it suitable for a low-power PV energy system and it may also be preferred for battery charging systems because of the blocking diode at the output. This diode prevents discharge of battery in PV cells during a night. Other advantage of Sepic over a simple buck converter is the capacitive isolation which protects the cells and battery against a switch failure.

Figure 3shows the schematic circuit of a Sepic converter connected to a PV array to provide a stepped-up-down voltage to the load. The input capacitor models the parasitic

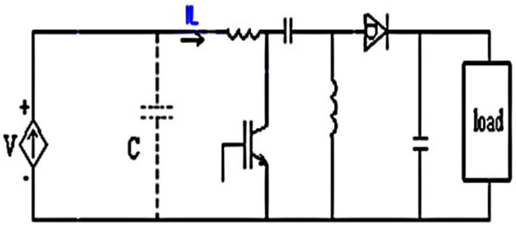

Fig.3 PV array connected to a Sepic circuit.

capacitance of the array and any intentional capacitive filter at the input of the converter. The goal is to force I_L to track I_{Lmax}, the corresponding current to the MPP, independent of variations in the cells temperature and sunlight intensity.

B. The MPPT Control Strategy

The power-voltage characteristic of a PV cells yields:

$$\frac{dp}{dt}\times\frac{dv}{dt}>0 \Rightarrow V<V^*$$
$$\frac{dp}{dt}\times\frac{dv}{dt}<0 \Rightarrow V>V^* \tag{1}$$

where V^* is the optimum voltage point and V is the PV terminal voltage. The duty cycle of converter (d) should be controlled such that eventually V approaches V^*. A method to control d is:

$$d=k\int\frac{dp}{dt}\frac{dv}{dt}dt \tag{2}$$

where k is a constant gain. Based on (2) the voltage and duty cycle increase (decreases), respectively. The output voltage of the converter is fixed and equals the battery voltage and the input/output voltage relation is given by:

$$V_{in}=V_o\frac{1-d}{d} \tag{3}$$

Since the output voltage $V_o$is constant at battery voltage level, any increase (decrease) in d leads to decrease (increase) in the input voltage. Thus, based on (1), we obtain the following control law for MPPT:

$$\frac{dp}{dt}\times\frac{dv}{dt}>0 \Rightarrow V<V^* \Rightarrow d \text{ should decrease}$$
$$\frac{dp}{dt}\times\frac{dv}{dt}<0 \Rightarrow V>V^* \Rightarrow d \text{ should increase} \tag{4}$$

Eq. (4) shows that a negative k in (2) will lead to appropriate change in d such that V approachesV^*.

The control law can also be expressed in term of current by multiplying (4) with dp/di as:

$$d=k\int\frac{dp}{dt}\frac{di}{dt}dt \tag{5}$$

Based on (5), MMP can be achieved via control of current, instead of voltage in (2), by changing d. However, in (5) k must be positive, since the current and voltage are inversely related in a PV array.

Implementations of control laws (2) or (5) have some practical limitations due to using derivatives of electrical quantities. To mitigate this problem, we suggest an alternative approach which uses sign of derivatives as discussed in the following section.

C. Alternative Method

Based on (1) and discussion in [6], the signs of derivatives in (2) can be used instead of the derivatives. Thus, the control law can be modified as:

$$d = k\int sign\left({dp}/{dt}\right)\times sign\left({dv}/{dt}\right)dt \qquad (6)$$

Using the sign function limits the high amplitude of a derivative quantity due to a noise, which is a significant improvement to (2). The sign function can be readily realized using a simple logic gate, a saturated op-amp comparator, or it can be implemented with inexpensive synchronous demodulator integrated circuits (ICs).

The sign functions in the integrand of (6) are advantageous from a noise standpoint, though the integrand never asymptotically approaches zero. Another improvement to this method is to bind the integrand, such that law (2) is preserved if the derivatives are within a pre-specified small range.

D. Battery Protection

PV array size is designed to charge the battery and powered the output load during a day. When the battery is fully charged, it should be protected against overcharging to avoid damages to the battery. Several practical protection circuitries have been presented to control charging/discharging of a battery [7]. To design a protection circuit for buoy, we model the battery with a 1F super capacitor. Then, a simple circuit for protection of battery is shown in Fig. 4, using a Zener diode in series with an optocoupler. In this circuit, as soon as the voltage of battery reaches to a pre-specified upper level, the optocoupler will be activated and it can provide a control signal, for example to turn off the converter or disconnecting the battery from the cells. An improved charge controller circuit can be designed to use an output command based on a hysteresis loop which is adjusted corresponding to upper and lower limits of the battery voltage levels.

E. Differentiator Circuit

The basic differentiator circuit with single R and C (Fig. 5) is not widely used in practice because of sensitivity to a sensor measurement noise. Thus, we used the improved circuit of Fig. 6, which acts as a differentiator at low frequencies and limits the amplifying gain at high frequencies. Such a circuit provides a better noise rejection performance.

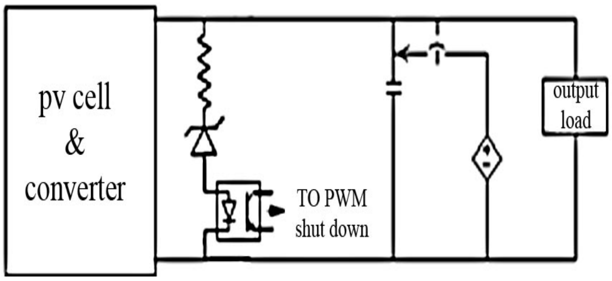

Fig. 4 Schematic of a battery protection circuitry

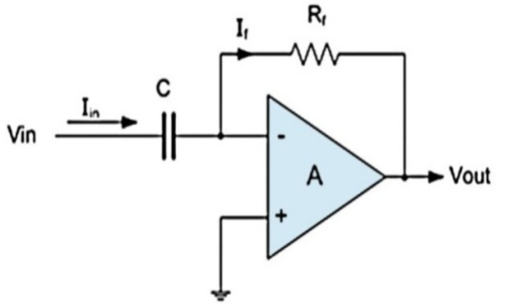

Fig.5 Basic single resistor and single capacitor differentiator circuit.

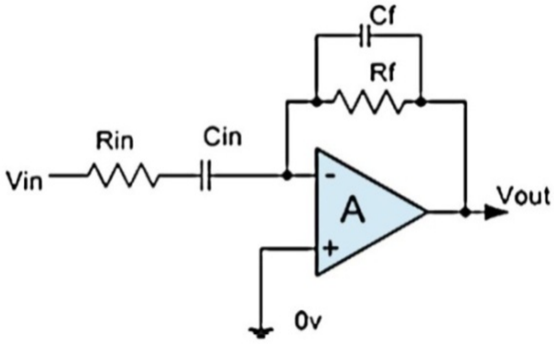

Fig.6 Improved differentiator amplifier circuit.

IV. DESIGN VERIFICATION

To verify the validity and performance of the suggest algorithm for MPPT in buoy PV energy system, the PV cell model, dc/dc converter, control loop based on (6), and the battery protection unit were simulated using PSCAD/EMTDC software tool as shown in Figs. 8 to 10. An analog multiplier was used for implementing the integrand of (6). To show robustness of the circuit against noise, a noise generator was used for adding noise with uniform distribution to the measured signals. The protection unit measured the output voltage and when the voltage exceeds its upper limit, the unit disconnects the PV cells path that charges the battery.

Fig. 7(a) shows the test signal (current) corresponding to a variation in sunlight radiation in the model of solar panels. Fig. 7(b) shows the capability of the control circuit to track the optimum operating point when the current increases as shown in Fig. 7(a). To evaluate the robustness of controller, a noise signal was added to the measured signals. The simulation results show that a sensor with signal-to-noise ratio (SNR) above -2 dB has no significant effect on the performance of the controller. However, SNR less than -2dB impacts on controller at low power operating points as shown in Fig.7(c).

Based on the results shown on Fig. 7, we conclude that the designed circuitry properly addresses the required MPPT specifications for a buoy with adequate robustness against noises.

V. CONCLUSION

Conceptual design of building blocks of a PV energy system for a buoy has been presented. It has been discussed that for offshore remote sensing applications, simplicity and robustness of the circuits are the key features of a successful design. Based on this fact, a simple algorithm for maximum power point tracking is presented and its performance is verified based on simulation. Simulation results show that the proposed algorithm can successfully track the maximum power point in presence of measurement noises.

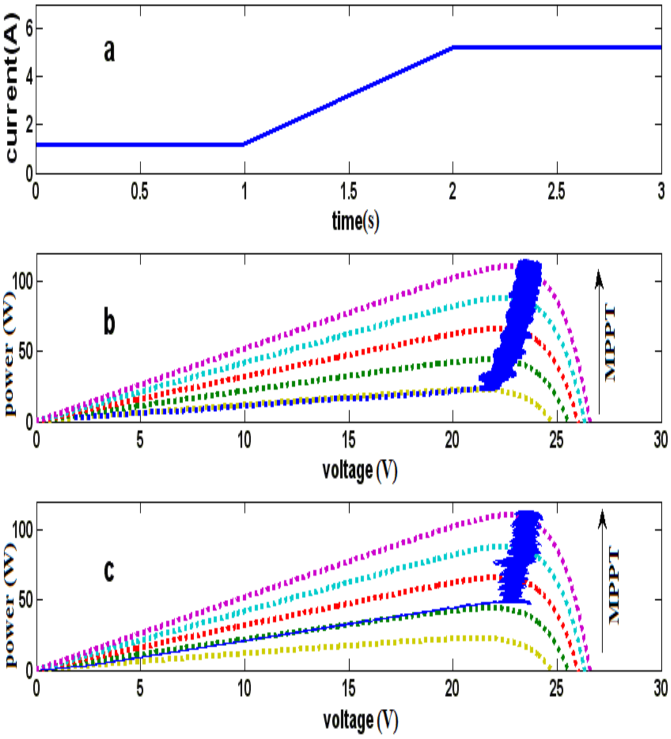

Fig. 7 Buoy's PV energy system simulation results: (a) variation of PV cell's current corresponding to sun light radiations; (b) MPPT performance with SNR>-2dB (c) Effects of noise with SNR<-2dB on MPPT capability.

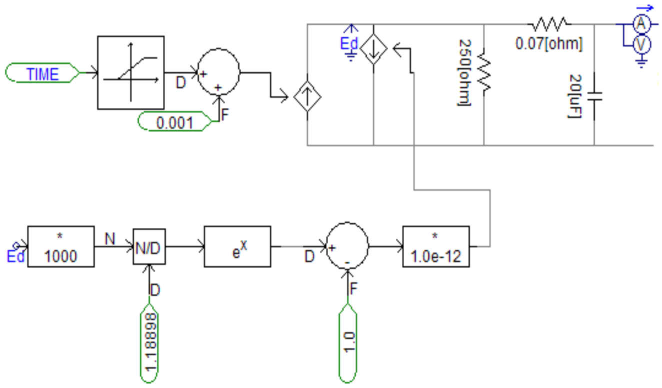

Fig. 8 Model of a PV cell with variable input radiation.

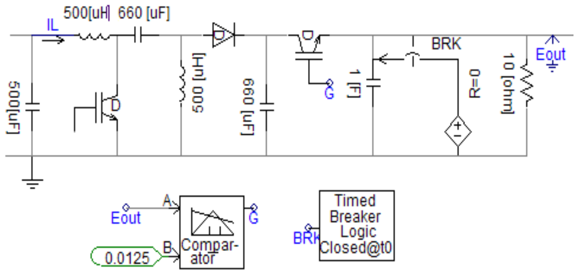

Fig.9 Schematic of electronics including Sepic converter, battery and load model, and the battery protection unit.

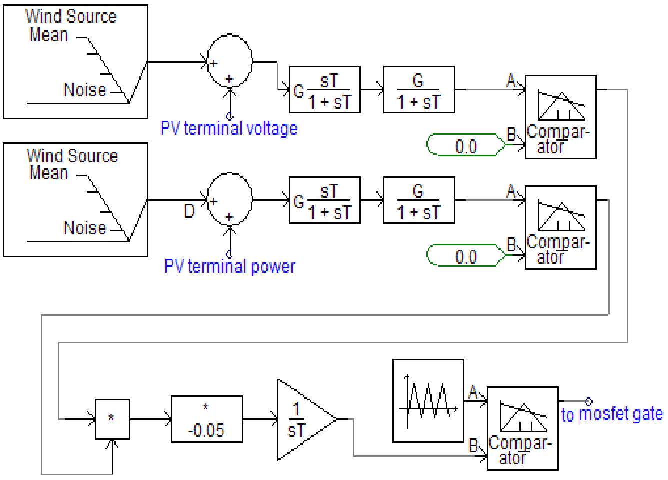

Fig.10 Analog control loop to produce appropriate duty cycle for Sepic converter.

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