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Power Electronics Engineering

Elixir Power. Elec. Engg. 40 (2011) 5189-5192

ISSN: 2229-712X

Design considerations in stand alone solar photovoltaic system

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ARTICLE INFO

Article history:
Received: 30 August 2011;
Received in revised form:
17 October 2011;
Accepted: 27 October 2011;

Keywords
SPV,
Battery Charging Control,
Sliding Mode Controller,
MATLAB

ABSTRACT

This paper presents sizing and control methodologies for a lead-acid flow battery-based energy storage system fed by Solar Photovoltaic system. The results show that the power flow control strategy does have a significant impact on proper sizing of the rated power and energy of the system. This paper focuses on the development of a control strategy for optimal use of the battery storage system through sliding mode controller. The effectiveness of this control strategy has validated through experimentation.

Introduction

Solar Photovoltaic (SPV) system directly converts sunlight into electricity. It is very reliable and clean source of energy. It has a wide range of applications and it includes different components depending on the applications. One of the most commonly used SPV system is a standalone SPV system [1]. The typical standalone SPV system consists of an input section, storage section and output section as shown in Fig.1.

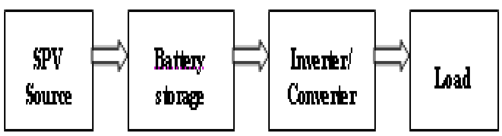

Fig.1 Structure of Standalone System

Depending on the load requirement SPV system should be properly sized. Different size of SPV modules produce different amount of power. To find out the sizing of the SPV module the total peak-watt produced needs.

The total peak watt required to produce by the SPV modules can be achieved by combination of modules. In this work, the proper combination which will produce the require peak-watt for a chosen application as well operates near to Maximum Power Point (MPP) is suggested.

For this work battery storage system is considered. All simulations have been carried out using MATLAB-SIMULINK. The following sections describe the design and modeling of each part of the standalone battery charging system.

Solar Photovoltaic Array Modelling

In this section, the modeling of SPV system is described. The well known one diode model of SPV module and the improved modeling equations presented in [2]-[3] is used to simulate SPV array.

The current-voltage and power-voltage characteristics for different insolations are shown in Fig.2 and for different temperatures are shown in Fig.3.

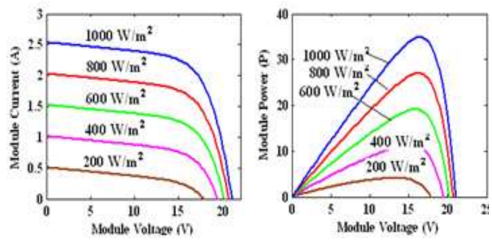

Fig.2 Simulated V-I and V-P Characteristics of SPV module for Various Insolation at Constant Temperature T=250C

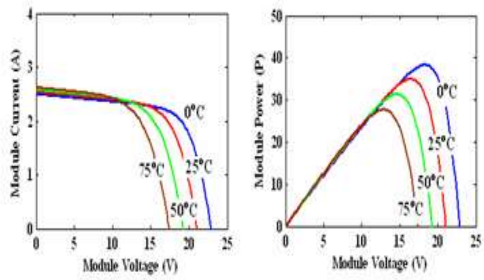

Fig. 3 Simulated V-I and V-P Characteristics of SPV module for Various Temperature at Constant Insolation G = 1000W/m²

Sizing of spv array for charging application

The SPV array configurations [4] are classified as follows:

- Series array configuration.
- Parallel array configuration.
- Series-Parallel (SP) array configuration.
- Bridge Link (BL) array configuration.
- Total-cross-tied (TCT) array configuration.
- BL and TCT array configurations are used in high power applications.

SPV modules are connected in series to get the requisite voltage and then connected in parallel to get required current levels. Depends upon the load requirements configuration will be chosen. Battery will drive the load. Depends upon the load requirements the array configuration will be chosen. Consider the single phase induction motor is the load.

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The Single phase induction motor driven by the battery via inverter. The load will be driven by the battery current 7.8A. Here Current requirement is high. So SP array configuration will satisfy load requirements. For the single phase induction motor to maintain the battery discharging current will be equal to charging current so that charging current of the battery is equal to or more than the load requirement current. For this rating, 2*4 SP array configuration provides required power. For a 2*4 array, there are 4 parallel strings with each string having 2 solar cells connected in series.

Open Circuit voltage ~42.48 V

Short Circuit Current ~10.2A

But for any combination, more number of parallel connected modules reduces the stress on Maximum Power Point Tracker (MPPT). The advantage of the parallel connection for battery charging application is described with the help of Fig 4. It is observed that the Maximum Power Point (MPP) of individual modules lie almost in the same vertical line along with that of the parallel array. Hence by connecting the modules in parallel, even without MPPT, almost the system is operating at MPP

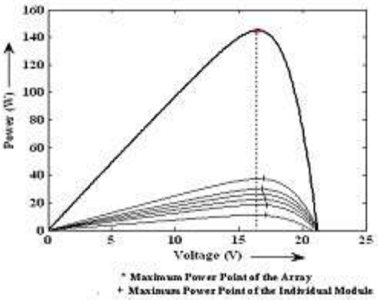

Fig. 4 V-P Characteristic for Parallel SPV Configuration

This is not true in the case of series connection. This can be understandable by Fig.5 where some of the modules in series connected receive different insolation. The operating point of the individual module as well as the array is away from MPP.

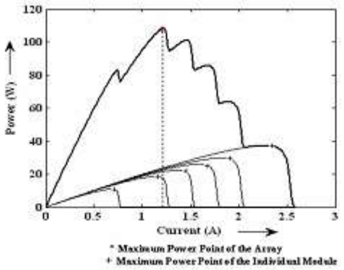

Fig. 5 V-P Characteristic for Series SPV Configuration

Converter Selection

DC-DC Converter which is used as an interface in between solar panel and the load. DC-DC converter can step up (Boost), step down (Buck) or both increase and decrease voltage (Buck-Boost).Commonly Boost converter is used in SPV system for its higher efficiency. But Boost converter is only applicable for cases where the battery voltage is higher than the SPV module voltage [5]-[6]. Buck converter is not using here because of their low efficiency .So Buck-Boost has chosen for this work. In this paper Buck-Boost converter is chosen for resistance matching to achieve MPP tracking. The design equations of the converter are given from (1) to (3). Buck-boost converter gain ratio is given by

$$M = \frac{-D}{1-D} \quad (1)$$

In buck-boost converter the inductor and capacitor values are obtained with the use of (2) and (3).

$$L = \frac{V_{PV}D}{f_s \Delta t} \quad (2)$$

$$C = \frac{V_B D}{f_s \Delta V} \quad (3)$$

The SIMULINK model of Buck-Boost converter is shown in Fig. 6.

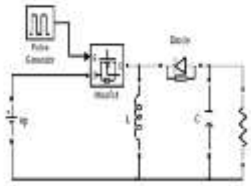

Fig. 6 Buck-Boost Converter-Simulation Model

The design parameters used in simulation are L=200µH, C=350µF and f_s=10 kHz. The design parameters are chosen based on the PV module specifications and battery. The detailed battery modeling has been discussed in [5].

Specifications:

The PV module specifications are: I_{sc}=2.55A, V_{oc}=21.25, P_{max}=37.08W, V_{max}=16.54 and I_{max}=2.25A.

The specifications used for the battery are given below.

Battery type: Exide (SMF)

Nominal Voltage: 12 V

Standby use: 13.6 V~ 13.8V

Cycle use: 14.6V~14.8V

Maximum initial current: 20A

Nominal capacity: 100Ah

Fig. 7 shows the output voltage and power of the Buck-Boost converter

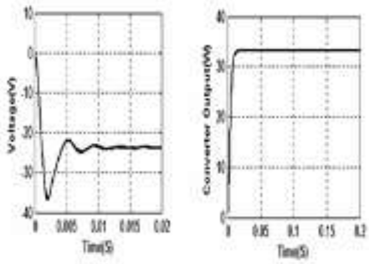

Fig. 7 Simulated Characteristics of the Buck-Boost Converter

Controller System

Battery life time gets reduced due to two major reasons: Low PV energy availability for longer period and improper charging control. For proper charging, charge controller will be used. The battery charging controller in standalone PV system is to fully charge the battery without permitting overcharge while preventing reverse current flow at night and to prevent deep discharge under various load conditions. Mainly two controller circuits are required to perform these two requirements [5]-[6].

Load Switch Controller

When SPV power is not sufficient to satisfy the load at that time the battery is also act as a source to satisfy the load requirement. To control the deep discharge of the battery with the use of load switch controller. The load switch controller function is as follows when the battery voltage is reduced less than the lower limit of the battery the load is disconnected from the system with the use of the switch controller. The switch controller voltage and current waveform are shown in Fig. 8.

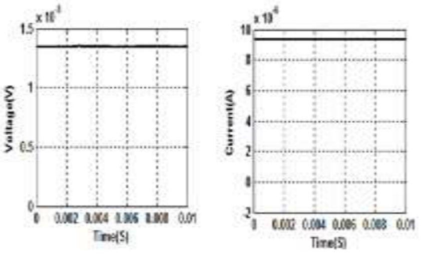

Fig. 8 Load Switch controller output

Charging Controller

When available SPV power is greater than the load power the excessive power will charge the battery. The limiter behind the charging controller will set the charging current command(I_{b*}) to be a maximum charging current level as the battery voltage (V_b) has not reached its maximum charged voltage command (V_{b*}). If the power condition is sufficient, the system will operate in the constant current charge stage. As the battery voltage approximately reaches the voltage command (V_{b*}), the limiter will enter the linear region, and the charging current command (I_{b*}) will reduce. This stage is called the constant-voltage charge stage. Finally, as the battery voltage reaches the voltage command (V_{b*}) and the limiter output (I_{b*}) is reduced to be approximately zero, the battery is in the floating-charge stage, i.e., the fully SOC.

The charging controller has been implemented using sliding mode controller. Sliding mode control is a form of variable structure control (VSC). It is a nonlinear control method that alters the dynamics of a nonlinear system by application of a high-frequency switching control. The sliding mode control approach is recognized as one of the efficient tools to design robust controllers for complex high-order nonlinear dynamic plant operating under uncertainty condition.Motion with state trajectories in some Surface of the state space with finite time needed for the state to reach this sliding surface [7]-[10]. The major advantage of sliding mode is low sensitivity to plant parameter variations and disturbances which eliminates the necessity of exact modeling. Sliding mode control enables the decoupling of the overall system motion into independent partial components of lower dimension and, as a result, reduces the complexity of feedback design. Sliding mode control implies that control actions are discontinuous state functions which may easily be implemented by conventional power converters with "on-off" as the only admissible operation mode. The phenomenon "Sliding Mode" may appear in dynamic systems governed by ordinary differential equations with discontinuous state functions in the right-hand sides. In Sliding mode control method control state variables are forced in such a way to allow the system to stay on a selected surface called sliding surface.

Two state variables x_1, x_2 are chosen as i_L and V_c respectively, i_L is the current through the inductor, V_c is the voltage across the capacitor also considered ideally as the output voltage V_o.

The state equations for a buck-boost converter during ON state can be written as

$$\frac{di_L}{dt} = \frac{V_{in}}{L} \qquad (4)$$

$$\frac{dV_0}{dt} = -\frac{V_0}{RC} \qquad (5)$$

When the switch is OFF

$$\frac{di_L}{dt} = -\frac{V_0}{L} \qquad (6)$$

$$\frac{dV_0}{dt} = \frac{i_L}{C} - \frac{V_0}{RC} \qquad (7)$$

The dynamic model of the Buck-Boost converter is

$$\dot{x}_1 = E/L - \left(\frac{1-u}{L}\right)V_c \qquad (8)$$

$$\dot{x}_2 = \left(\frac{1-u}{c}\right)i_L - \frac{V_C}{RC} \qquad (9)$$

Where x_1 and x_2 are the state space vectors. (x_1- inductor current, x_2- Capacitor output). The switching function for the current control is defined as $S = i_L - i_{Lref.}$

$$\dot{x}_2 = \frac{dV_c}{dt}, x_2 = V_C \qquad (10)$$

$$\dot{x}_1 = \frac{di_L}{dt}, x_1 = i_L \qquad (11)$$

Switching-status signal u: u =1 when the switch S is closed. u=0 when the switch S is open. The dynamic equations are as follows

$$\frac{di_L}{dt} = \frac{V_{in}}{L} - \frac{(1-u)V_C}{L} \qquad (12)$$

$$\frac{dV_0}{dt} = \frac{(1-u)}{C}i_L - \frac{V_0}{RC} \qquad (13)$$

Using above state equations the SIMULINK based control model is developed for converter using sliding mode control principle. The voltage command V_p* is generated by the battery charging control loop. When the available SPV power is greater than the load power and the excessive power will charge the battery. When the available peak power of the SPV module is larger than the battery charging and load requirement.

Fig. 9 shows the charging and discharging currents (~ 8.37 A) of the battery with both power and battery charge controllers. From Fig. 9 it is understood that floating state of the battery is achieved.

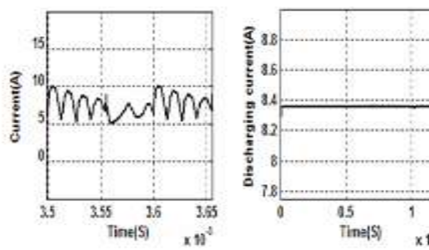

Fig. 9 Charging and discharging currents of the battery

Hardware Implementation

The hardware schematic of the proposed system is shown in Fig.10.

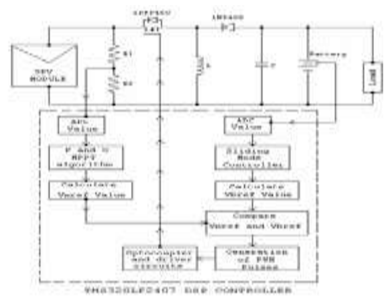

Fig. 10 Hardware Schematic of the Proposed Controller

The voltage level of the Digital Signal Processors (DSP) is (0-3.3) V only. So it is necessary to step down the SPV panel voltage to provide analog input to the controller. For this purpose a voltage divider is used here. The output from this circuit is given to the analog to digital converter (ADC) in the DSP controller. The buck-boost converter circuit consists of inductor, semiconductor switch, diode, capacitor and battery. L=200µH and C=330µF are used here. The inductors are wound in a Ferrite double-E core. MOSFET IRFP450 is used as the semiconductor switch. Heat sinks are attached to the MOSFETs. The diode 1N5408 is used in the circuit. MOSFET is switched at high frequency (20 kHz).The output voltage of the buck-boost converter varies with respect to turn on and turn off time period of the MOSFET. This circuit consists of the DSP controller and opto-coupler-transistor circuit. In DSP controller sliding mode controller will be implemented .With the use of Sliding mode controller V_{ref} value will be determined. This value compare with the V_{ref} value. V_{mref} Value determined with the use of P&O algorithm [11]-[12]. Compare these two values and find out the V_p Value. To provide supply to the collectors of both opto-coupler and transistor power supply circuit is used which consists of step down transformer, bridge rectifier, regulator. The transformer steps down the ac supply voltage to 15V.The bridge rectifier converts 15V ac to dc and 1000µF capacitor is used as filter to remove the ripple. The regulator 7812 ensures 12V dc supply to both opto coupler and the transistor. The control pulses generated from the DSP controller are given to opto-coupler MCT2E.The opto-coupler is used to isolate the boost converter circuit from the DSP controller. The output of the opto coupler is given to transistor BD139 which drives the buck-boost converter. The hardware set up is shown in Fig.11. The oscillogram outputs of the system are shown in Fig.12 and Fig.13 for 2X3 SPV system with two different insolations.

Fig.11 Hardware setup of the system with battery

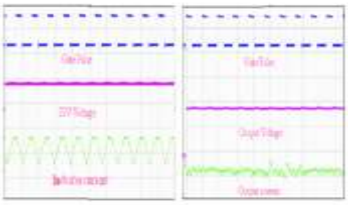

Fig.12 Input and output Waveforms of the converter for 0.3 duty ratio

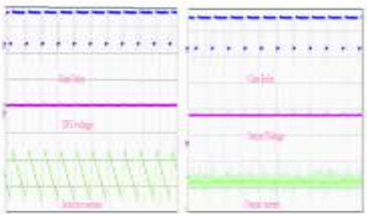

Fig.13 Input and output Waveforms of the converter for 0.6 duty ratio

Conclusion

In this paper, the proper sizing of SPV array for a standalone SPV system has been discussed and the merits of proper sizing has also been presented. Moreover SPV system with proper power flow controller and battery charging controller has been presented. The proposed system has been simulated in MATLAB-SIMULINK environment and verified experimentally to prove the effectiveness of the proposed controller scheme.

Acknowledgement

The authors wish to thank the management of SSN college of Engineering, Chennai for providing all the facilities to carry out this work through internal funded project.

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