Abstract-- An implementation of a digitally controlled stand-alone PV power supply consisting of PV array, battery and inverter is presented. Peak power tracking using Incremental conductance algorithm and four state battery charging with temperature compensation are described. Some simulation results are presented.

Index Terms-- Solar energy systems, modeling and simulation, photovoltaic battery charging, maximum power point tracking, digital control

I. INTRODUCTION

Stand-alone photovoltaic power supply system (SAPS) is established as a reliable and economical sources of electricity in rural remote areas, especially in developing countries where the population is dispersed, has low incomes and the grid power supply is not fully extended to these areas due to viability and financial constraints.

SAPS are defined as autonomous system that supply electricity without being connected to the electric grid. A scheme for SAPS is shown in Fig. 1.

The power supplied by PV generator (module) depends upon the insolation, cell temperature and module voltage. Battery forms an important element of a stand-alone PV system. The battery is necessary in such a system because of the fluctuating nature of the output delivered by the PV arrays. Both the battery voltage and the PV array voltage vary during operation due to the changing state of charge and atmospheric conditions.

In order to draw the maximum power from the module, a Maximum Power Point Tracker (MPPT) device must be inserted between the PV module and the battery.

A major problem of batteries in SAPS is their inability to live up to the expectations of the user due to poor functioning of battery chargers. This includes: Overcharging, incomplete charging and prolonged operation at a low state-of-charge (SOC) which results into increasing the running costs due to replacement of the batteries before their expected lifetime.

The electricity produced by solar cells is direct current and can be used that way or converted to alternating current using an inverter. Inverters which operates in SAPS provide ac power from a DC battery. Typical DC voltage levels are 12, 24 and 48V dc depending on the power levels which ranges from a few hundred watts to a few kilowatts. Many household appliances requires low-distortion sinusoidal waveforms, and hence the use of true sine wave inverters, though expensive, is recommended for SAPS.

The paper describes the application of power electronics in designing and implementing a digitally controlled stand-alone PV power supply. This includes modeling and simulation of solar array. Buck converter is used as an interface between solar array and a battery for MPPT and battery charging. Incremental conductance algorithm is used for MPPT. A four state charging algorithm with temperature compensation which is recommended by battery manufacturers is used with the 12V, 115Ah flooded-lead acid battery. The charging algorithm includes disconnection of the load connected to the battery when the battery voltage become less than the recommended threshold value. Texas Instruments Digital Signal Porcessing TMS320F240 is used.

II. SOLAR MODULE CHARACTERISTICS

The I-V solar module characteristics significantly influences the design of the converter and the control system. An equivalent circuit for a PV module is shown in Fig. 2. [1].

![Fig. 1. Stand-alone PV power system scheme](image-url)
The module equivalent circuit current \( I \) can be expressed as a function of the module voltage \( V \) by [1]:

\[
I = I_{sc} \left\{ 1 - K_1 \left[ \exp(\left( \frac{K_2 V^{m}}{V_{oc}} \right)) - 1 \right] \right\}
\]

where the coefficients \( K_1, K_2 \) and \( m \) are defined as:

\[
K_1 = 0.01175; \quad K_2 = \left( \frac{K_4}{V_{oc}^{m}} \right)
\]

\[
K_3 = \ln \left( \frac{I_{sc} (1 + K_4) - I_{mpp}}{K_4 I_{sc}} \right); \quad m = \frac{\ln \left( \frac{V_{mpp}}{V_{oc}} \right)}{\ln \left( \frac{I_{mpp}}{I_{sc}} \right)}
\]

where:
- \( I_{mpp} \) - current at maximum power point
- \( V_{mpp} \) - voltage at maximum power point
- \( I_{sc} \) - is short circuit current
- \( V_{oc} \) - is open circuit voltage of module

Equation (1) is only applicable at one particular insolation level, \( G \), and cell temperature, \( T_c \). When insolation and temperature changes, the change in above parameters can be calculated using:

\[
\Delta T_c = T_c - T_{STC}
\]

\[
\Delta I = \alpha_{scT} \left( \frac{G}{G_{STC}} \right) \Delta T_c + \left( \frac{G}{G_{STC}} - 1 \right) I_{SC,STC}
\]

\[
\Delta V = -\beta_{ocT} \Delta T_c - R_s \Delta I
\]

\[
V_{new} = V_{STC} + \Delta V; \quad I_{new} = I_{STC} + \Delta I
\]

Equation (1) was used in Matlab to model PWX750 module. The I-V and P-V characteristics for various irradiance at fixed temperature \( T=25^\circ C \) obtained from the model are shown in Fig. 3 and Fig. 4 respectively. Fig. 5 and Fig. 6 shows the I-V and P-V characteristics for various temperature and fixed irradiance of 1kW/m² respectively.

<table>
<thead>
<tr>
<th>Parameters for 80W Photowatt Panel PWX750 at STC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>Maximum Power rating, ( P_{mpp} )</td>
</tr>
<tr>
<td>Minimum Power rating, ( P_{min} )</td>
</tr>
<tr>
<td>Current at MPP, ( I_{mpp} )</td>
</tr>
<tr>
<td>Voltage at MPP, ( V_{mpp} )</td>
</tr>
<tr>
<td>Short circuit current, ( I_{sc} )</td>
</tr>
<tr>
<td>Open Circuit Voltage, ( V_{oc} )</td>
</tr>
<tr>
<td>Short circuit current temperature coefficient, ( \alpha_{scT} )</td>
</tr>
<tr>
<td>Open circuit voltage temperature coefficient, ( \beta_{ocT} )</td>
</tr>
<tr>
<td>NOCT (Normal Operating Cell Temperature)</td>
</tr>
<tr>
<td>Insolation, ( G=0.8W/m² ), ( T_a=20°C ), wind speed=1m/s</td>
</tr>
</tbody>
</table>

where \( T_{a,ref} \) is the reference ambient temperature used to specify NOCT (20°C for PWX750 module).
The I-V characteristics for some set of irradiance and temperature given by: 
\[ \{G, T\} = \{(1000, 25), (1000, 60), (800, 45), (500, 25)\} \] is shown in Fig. 7.

I-V characteristics from the simulation correlates well with the I-V curves provided by the module manufacturer, which means that the above model is correct and can be used for testing other functionality such as Maximum Power Point Tracking (MPPT) and battery charging algorithms.

Note that if a PV array is composed of \( N_{ms} \) modules in series and \( N_{mp} \) modules in parallel, the I-V characteristics of the array is derived by scaling the characteristics of one module with a factor \( N_{ms} \) in voltage and \( N_{mp} \) in current.

### III. MPPT Algorithm

Simulation results in section II shows that the power supplied by PV module depends upon the insolation, cell temperature and module voltage. MPPT device is required to extract maximum power from the PV module.

Several MPPT methods had been reported [2-5]. Comparative study made by [5] shows that incremental conductance (IncCond) algorithm tracks fast the MPP under rapid changing atmospheric conditions. IncCond algorithm can be best described by the flowchart of Fig. 8 at every MPP sampling.

A. Testing the IncCond algorithm

The algorithm was coded into an s-function in simulink and linked with the PV module model developed in section I. Fig. 9 shows the results from simulation for different irradiance and temperature \( \{G, T\} \).
In a SAPS system, it is important to charge batteries as fast as possible. This necessitates that as much energy as possible should be transferred to the batteries, without damaging the batteries during the charging process. Battery manufacturers recommend four state charge algorithm for lead-acid batteries. These states are: trickle charge, bulk charge, over-charge and float charge as shown in Fig. 10.

![Battery voltage and current over one charging cycle using a four state charge algorithm.](image)

**Fig. 10. Battery voltage and current over one charging cycle using a four state charge algorithm.**

In order to understand this charging algorithm, let us define the following parameters for a 12V battery.

**TABLE II**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity of the battery in Ah, C</td>
<td>Given*</td>
</tr>
<tr>
<td>Bulk charging current, $I_{BULK}$</td>
<td>0.02$I_{BULK}$</td>
</tr>
<tr>
<td>Bulk to overcharge transition voltage, $V_{B2O}$</td>
<td>0.95$V_{OC}$</td>
</tr>
<tr>
<td>Float to bulk transition voltage, $V_{F2B}$</td>
<td>0.9$V_{BF}$</td>
</tr>
<tr>
<td>Discharge threshold, $V_{CHGENB}$</td>
<td>Given</td>
</tr>
<tr>
<td>Load Disconnect voltage, $V_{LDV}$</td>
<td>Given*</td>
</tr>
<tr>
<td>Load reconnect voltage, $V_{LRV}$</td>
<td>Given*</td>
</tr>
<tr>
<td>$I_{OCT}$ - battery temperature coefficient</td>
<td>-3.9</td>
</tr>
</tbody>
</table>

"Given" in the value column in Table II means value recommended by battery manufacturers.

The battery charging involves the MPPT loop and battery regulation loop (voltage and current loop) as shown in Fig. 11. When each loop is activated depends on which charging state the process is in as explained below.

**Trickle charging state:** When the battery’s voltage is below a discharge threshold, $V_{CHGENB}$, the battery is either deeply discharged or has shorted cells. In this state, the charger begins in a low-current trickle-charge state where a small trickle current ($I_{TC}$) is applied. If there is shorted cells, the battery voltage will stay below $V_{CHGENB}$ preventing the charger from proceeding to the bulk charge mode. Otherwise, the charge will be slowly restored and the voltage will increase towards the nominal range until it reaches $V_{CHGENB}$. At that point the charger will advance to bulk charging state.

**Bulk charging state:** In this state the charger acts like a current source providing a constant charge rate at $I_{BULK}$. The MPPT loop is enabled while the battery voltage loop is disabled. The reference current in the battery current loop is $I_{BULK}$. The charger monitors the battery voltage and as it reaches a transition threshold of 0.95$V_{OC}$, the charger enters the over-charge state.

**Over-charge charging state:** This state is used to restore full capacity in a minimum amount of time at the same time avoiding over-charging. All the battery voltage loop and current loop are activated while an MPPT loop is deactivated. The $V_{Ref}$ now is equal to $V_{B2O}$. Initially, the overcharge current is the same as bulk-charge current, but as the over-charge voltage is approached, the charge current diminishes. $I_{Ref}$ is determined by the battery voltage loop. When the charge current becomes equal to $I_{OCT}$, the state changes to float charge state.

**Float charge state:** During this mode, the battery voltage is maintained at $V_{FLOAT}$ to maintain the battery capacity against self-discharge. The charger will deliver whatever current is needed to sustain the float voltage. State of battery voltage and current loops are as in over-charge mode but $V_{Ref}$ now is equal to $V_{FLOAT}$.

The battery will remain in the float state until the battery voltage drops to 90% of the float voltage due to discharging, at which point operation will revert to the bulk charge state.

**Disconnection of load:** The charger circuit disconnects all...
load from the battery when the battery voltage reaches \( V_{LDV} \) to protect the battery from over-discharge. The load will remain disconnected from the battery until the battery is recharged to \( V_{LRV} \).

Recommended threshold voltages for 12V flooded lead-acid battery in SAPS at 25°C are shown in Table III.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overcharge voltage, ( V_{BOC} )</td>
<td>15V</td>
</tr>
<tr>
<td>Floating voltage, ( V_{FLOAT} )</td>
<td>13.5V</td>
</tr>
<tr>
<td>Discharge threshold, ( V_{CHGENB} )</td>
<td>10.5V</td>
</tr>
<tr>
<td>Load Disconnect voltage, ( V_{LDV} )</td>
<td>11.4V</td>
</tr>
<tr>
<td>Load reconnect voltage, ( V_{LRV} )</td>
<td>12.6V</td>
</tr>
</tbody>
</table>

A. Battery temperature compensation

The voltage characteristics of a lead-acid cell have a negative temperature dependence of approximately -3.9 mV/°C/cell. The threshold voltage levels recommended for battery charging are normally referred to battery temperature of 25°C. This means for other battery temperatures, a charger must have some form of compensation to track the battery temperature.

Mathematically, temperature compensation can be expressed as:

\[
V_B(T) = \left[ V_{c,25} + \alpha_T (T - 25) \right] N_c
\]

where: \( V_B(T) \) is the new threshold voltage at \( T \) (°C), \( V_{c,25} \) is the cell threshold voltage at 25°C, \( \alpha_T \) is -3.9mV/°C/cell, \( N_c \) is number of cells in a battery.

According to [7], during higher temperatures, the PV systems with temperature compensation chargers shows a stabilization in water loss, while those without temperature compensation experiences water loss.

V. HARDWARE FOR EXPERIMENTS

The hardware configuration is shown in Fig. 11. It consists of: PWX750 80W PV module; a buck converter; 12V 115Ah flooded lead acid battery; inverter with transformer and LC filter; interface board for signal conditioning; TMS320F240 evaluation board and a PC.

Signals used for control are: PV current and voltage; Buck converter inductor current; battery voltage, current and temperature; inverter inductor current, load current and load voltage.

In the time of writing this paper, a prototype is in the final stage of completion. Experimental results including inverter control will be reported during the workshop.

Fig. 12. Block diagram for a digitally controlled PV SAPS.

REFERENCES