CHAPTER 5

DESIGN AND DEVELOPMENT OF A MODEL-BASED HARDWARE SIMULATOR FOR PHOTOVOLTAIC ARRAY FOR TESTING OF PV POWER CONVERTERS

5.1 INTRODUCTION

Photovoltaic (PV) hardware simulators or rather PV emulators are power converters accomplished with controls such that it reproduces the current-voltage i-v characteristics of PV modules under all required ambient conditions. Thus, the emulators are primarily intended to act as a PV power source in experiments to verify the reliability of Power electronic interfaces. This chapter proposes a novel PV emulator detailing its model parameter extraction, mathematical modeling, hardware design & development to represent an 115W solar panel Shell Solar-S115 for demonstration. This chapter concludes with the steady state and transient state test results of the Shell solar-S115’s hardware emulator.

5.2 NEED FOR PV EMULATORS

PV emulator systems are electrically analogous to PV arrays but their outputs can be set to a particular i-v relationship resulting due to a unique ambient condition. They are very much necessary for the assessment of PV energy conversion system modules such as DC-DC converters, DC-AC converters, maximum power point tracking algorithms, grid synchronization circuits etc. For consistent performance of these PV power converters the experiments need to be repeated for every load/grid condition at diverse operating conditions like different irradiance-G and temperature-Tc. This becomes difficult with a solar PV panel, as it is not practical to
repeatedly set the steady-state and transient insolation at all values and as required. To perform intense testing of the PV power converter’s functionality, its closed loop control, its performance when subjected to grid disturbances, a real-time hardware infrastructure is essential. Thus the simulator is primarily intended as a power source to the converter in experiments to verify the reliability and repeatability of operation of the converter in steady-state as well as in transient conditions of all possible insolation/grid conditions. Such a hardware simulator has to produce dc outputs effectively as will be given by a PV panel at any operating condition. This enable the rapid prototype development of the PV converters, new MPPT algorithms, and new control algorithms etc. because of the simple and cheap field-trial process, less time-consuming experiments and the independency on the weather conditions.

5.3 STATE OF THE ART IN PV EMULATORS AND IDENTIFIED INADEQUACIES

Wide varieties of hardware PV simulators have been reported in the literature. In a research paper Nagayoshi Hiroshi et al. (2002) (2003) used the output of a single photo sensor and is magnified using linear amplifiers to emulate the PV array. No temperature variation has been considered. The series resistance, the ideality factor and reverse saturation current of cells in an array may be different from that of a single photo sensor that can cause errors in the model. The major drawback of this method is its lower efficiency due to linear amplification. This will be a serious concern for high power simulators.

The simulator proposed by Jaakko Ollila (1995), uses a switching power converter with an analog control and matching only the open circuit and short circuit points of the simulator with those of the actual PV panel. Also changes in load conditions only have been considered and the changes in
insolation have not been accounted. Using switching power converter, a digital control strategy is adapted by Jaakko Ollila (1995), Eftichios Koutroulis et al. (2006) and Yuan Li et al. (2009), in which a Look Up Table (LUT) is used to store the V-I relationship of a PV array for some discrete insolation conditions. The LUT is referred to for the control of the power converter so that the converter output is the same as the values in the table. No provision for accounting the change in insolation is reported by Eftichios Koutroulis et al. (2006), and Yuan Li et al. (2009) have utilized only three sets of insolation conditions are used which are manually selected. The variable insolation conditions are not realized. Different types of PV cell models are reported by the following authors Tsai et al. (2010), Pon Venkatesh et al. (2011), Mummadi Veerachary et al. (2006), Kashif Ishaque et al. (2011), Carrero et al. (2010) and Ying-Pin chang et al. (2010), and model based emulators are reported by Martin-Segura (2007) & Di Piazza (2007), in which the first did not consider the changes in the ambient conditions while in the second these were considered, but it is applicable for a particular site. The irradiance is given a site data. Thus it is dependent on the site data, and that constrains the universal use of the simulator.

The present research work is intended to presents a model based hardware PV simulator, which emulates i-v characteristics of any commercially available PV panel at any temperature and irradiance conditions. The model parameters are extracted using only the published cell characteristics of the manufacturer. None of the values required for the cell equation has been assumed as has been done often in the literature Atlas & Sharaf (2007), Ramasamy & Thangavel (2012), Mazouz & Midoun (2011), Faisal Mohamed & Heikkl Koivo, (2010), thus the model replicates the commercial PV panel very closely. The emulator uses the model for obtaining the V-I relationships, thus no Look up tables are used requiring large memories. This enables to obtain the characteristics at any insolation conditions, compared to
the simulators presented by Jaakko Ollila (1995), Eftichios Koutroulis (2006) and Yuan Li (2009), where, emulation at certain discrete insolation is only reported. First the mathematical modeling of a commercial PV array is explained followed by the design specification of the converter used in the simulator. The hardware setup is developed and the experimental results are presented. The simulator can be used for testing of power converters in PV applications where it can replace the actual panel at any desired insolation level as well as for testing of various Maximum Power Point Tracking (MPPT) algorithms.

5.4 MATHEMATICAL MODEL OF PV PANEL WITH EXTRACTED PARAMETERS

In a solar cell, when photons of the incident radiation collide with the valence electrons of the silicon they will be absorbed, releasing electrons and holes into the crystal lattice. On open circuit a direct emf or voltage appears across its terminals. When an external electrical circuit is connected to its terminal a direct electric current flows. A solar cell is basically a current generator, whose output current and voltage depend on the irradiance \( G \) and the Cell temperature \( T_C \). Figure 5.1 shows the equivalent circuit of a single solar cell. The V-I characteristics of the cell are determined by the diode. The \( i-v \) characteristics of a commercial solar module S115 is presented in Figure 5.2.

![Figure 5.1 Equivalent circuit of solar PV cell](image-url)
The output voltage of a single solar cell as used by I.H. Atlas et al. (2007) in volts is expressed as,

\[ V_c = \frac{A k T_c}{e} \ln \left( \frac{I_{ph} + I_o - I_c}{I_o} \right) - R_s I_c \]  \hspace{1cm} (5.1)

where, \( A \) is diode ideality factor, \( I_{ph} \) is photo current (A), \( I_o \) is reverse saturation current (A), \( e \) is electron charge (Q), \( R_s \) is series resistance of the cell (\( \Omega \)), \( k \) is Boltzmann’s constant, \( T_c \) is cell operating temperature in Kelvin, \( V_c \) is cell output voltage (V), \( I_c \) is cell output current (A).

There are four manufacture dependent parameters present in equation (5.1), viz, \( I_{ph}, I_o, A \) and \( R_s \). The values of these parameters are unique for a module and depend on the type of semiconducting materials used, type and amount of doping and the processing technology used and also the physical size of the panel. For an accurate modeling these parameters are to be known, and generally they are not available and some typical values for these parameters are assumed in models. In the proposed research work the values of the manufacture-dependent parameters viz, \( I_{ph}, I_o, A \) and \( R_s \), pertaining to a particular PV panel are extracted from the \( i-v \) characteristics.
published in the data sheet of that particular PV panel. A curve fitting based extraction technique is adapted for the extraction of the model parameters.

5.4.1 Model parameter extraction by curve fitting

The first unknown parameter $I_{ph}$ in equation (5.1) is seen to be equal to $I_{sc}$ under short circuit of panel as drop in $R_S$ is too small to make the diode conduct any significant value. From the module’s short circuit current $I_{sc}$, and the number of parallel branches $N_p$ in the module, $I_{ph}$ for a cell is found as $I_{sc}/N_p$. The remaining three process dependent parameters for the model are estimated through careful curve fitting of the data sheet characteristics by selecting three points on the published characteristic curve at Standard Test Condition (STC) for the module of interest. As the solar arrays are to be operated at MPP, the model as well as the emulator has to be more accurate near MPP. So the first point is selected at MPP. The second and the third points are selected at the left of MPP and at the right of MPP. The three points for Shell Solar ‘S115’ chosen for verification of the model are $P_1(V_1=26.80\,V, I_1=4.29\,A)$, $P_2(V_2=25.74\,V, I_2=4.43\,A)$ and $P_3(V_3=27.93\,V, I_3=4.06\,A)$ on the published $i-v$ characteristics. Substitution of the co-ordinates of $P_1$, $P_2$ and $P_3$ suitably scaled down to a single cell value, in equation (5.1) gives three equations with three unknown parameters. Using a computer based numerical solution results the values for the three unknown parameters as $I_0=9.25\times10^{-6}\,A$, $A=1.8$ and $R_S=0.000192\,\Omega$. The computer based numerical procedure for parameter extraction is given in the Appendix 4.

5.4.2 PV panel model development

The value of $V_C$ can now be evaluated from equation (5.1) for any current $I_C$ at STC. Then correction in voltage $\Delta V_C$ due to change in irradiance and the consequential change in cell current $\Delta I_C$ and temperature are introduced to get cell voltage $V_C$ at any irradiance to complete the model.
At a given irradiance $G$, whenever the ambient temperature ($T_A$) varies, it causes the cell temperature ($T_C$) to vary. Also the change in $G$ causes change in cell current ($\Delta I_C$) and cell temperature ($\Delta T_C$). Finally these changes cause a change in cell voltage ($\Delta V_C$) which is evaluated in volts as:

$$\Delta V_C = -\alpha_{VOC} \Delta T_C - R_s \Delta I_C$$ \hspace{1cm} (5.2)$$

where, $\alpha_{VOC}$ is the temperature coefficient of voltage, available in the data sheet. $\Delta I_C$ in Amperes and $\Delta T_C$ in Kelvin caused at any $G$ are evaluated as:

$$\Delta I_C = \beta_{ISC} \left( \frac{G}{G_{stc}} \right) \Delta T_C + \left( \frac{G}{G_{stc}} - 1 \right) I_{SC, stc} \hspace{1cm} (5.3)$$

$$\Delta T_C = T_C - T_{stc} \hspace{1cm} (5.4)$$

where, $\beta_{ISC}$ is the temperature coefficient of current from data sheet, $T_C$ is the cell temperature at any irradiance and $T_{stc}$ is the Cell Temperature at STC.

The cells operate at a higher temperature than the ambient as reported by Roger Messenger & Jerry Venture (2003). The cell temperature $T_C$ in Kelvin at any irradiance $G$ is found as,

$$T_C = T_A + \left( \frac{T_{NOCT} - 20}{G_{NOCT}} \right) G \hspace{1cm} (5.5)$$

where, $T_A$ is the ambient temperature, $T_{NOCT}$ is the normal operating cell temperature and $G_{NOCT}$ is irradiance at NOCT. Both are available from the data sheet. Then the cell output voltage in volts and current in amperes for any required $G$ and $T_C$ are obtained as,

$$V_C = V_{C, stc} + \Delta V_C \hspace{1cm} (5.6)$$

$$I_C = I_{C, stc} + \Delta I_C \hspace{1cm} (5.7)$$
The cell model includes equations (5.1) to (5.7) and gives the cell voltage for a given cell current at any $T_A$ and $G$. Thus the cell model calculates the cell voltage, for a given cell current. The panel voltage and current are calculated using the number of series cells in a string and number of parallel strings in a module.

5.5 DESCRIPTION OF THE SIMULATOR SYSTEM

The block diagram of the hardware PV simulator is shown in Figure 5.3. The circuit consists of a DC-DC buck converter fed from a dc source and controlled by PIC16F877 microcontroller. The mathematical model of the PV array with parameters extracted from the actual panel is implemented in the microcontroller program.

![Figure 5.3 The proposed hardware PV simulator](image)

The user defined inputs for the system are the ambient temperature $T_A$ and Irradiance $G$. The required insolation values are entered into the model through a keypad and the same are displayed in LCD. The third input to the simulator is the load current, which serves as the PV module current for the mathematical model. With these three inputs the micro controller estimates the panel output voltage using the model. This is the reference voltage and the
actual output voltage from the converter is the feedback signal for the closed loop system. The voltage error is used to control the converter output voltage such that the simulator output will be same as the voltage estimated by the mathematical model for the given current and the entered insolation.

5.6 HARDWARE DESIGN

The buck converter shown in Figure 5.4 is used as the power stage for the proposed simulator. The output voltage and current of the converter should be equal to the array voltage and current, at any operating condition.

![Power circuit of PV simulator](image)

Figure 5.4 Power circuit of PV simulator

The hardware simulator is designed to represent the solar panel S115 for demonstration. The salient details of the S115 are \( V_{oc} = 32.8 \text{ V}, I_{sc} = 4.7\text{A}, V_{MPP} = 26.8\text{V}, P_{MPP} = 115\text{W} \). For the buck converter a 35V, 5A power supply is used as an input. The switching frequency \( f_{sc} \) of the DC-DC converter is decided based on the switching frequency \( f_{s} \) of the interfacing inverter sourced from the PV simulator. Corresponding to a typical value of 5 kHz, a reasonable switching frequency value for the inverter, a switching frequency of 20 kHz is selected for the DC-DC converter. As these frequencies are far away, minimum interaction is expected between the emulator and the interfacing converter as reported by Ned Mohan et al. (2008).

The buck converter is designed for continuous current operation with a steady-state peak to peak inductor current \( (\Delta i) \) and voltage ripple \( (\Delta v) \)
of 5% and 0.5% respectively. With the chosen $f_{sc}$ of 20 kHz, the values of the filter elements are designed based on equations

\[ V_u = V_{dc} D \quad (5.8) \]

\[ \Delta i = \frac{D V_{dc} (1 - D)}{f_{sc} L} \quad (5.9) \]

\[ \Delta v = \frac{V_{dc} D (1 - D)}{8 L C f_{sc}^2} \quad (5.10) \]

where, $D$ is the duty ratio, $V_{DC}$ is dc Input voltage $L$ is the filter inductor and $C$ is the filter capacitor.

The minimum values of $L$ and $C$ are found as 1.45 mH and 1.97 μF respectively. The inductor is fabricated and its internal resistance $r_l$ is measured as 0.14Ω. Instead of the calculated minimum $C$ of 1.97 μF, 330 μF is used so as to improve the transient response under step load conditions.

Figure 5.5 shows the closed loop control of the buck converter, which includes the PI controller acting as the compensator for the converter.

**Figure 5.5 Control of the converter**

The compensator is so designed that (i) the gain at low frequencies is high to minimize the steady-state error in the output of the converter and (ii) The crossover frequency as high as possible for fast response and the
phase margin is large enough to allow good stability. A value of 90° is chosen for phase margin as stability is more important in a grid connected system.

The converter transfer function \( G_p(s) \) and the compensator transfer functions \( G_c(s) \) are given as,

\[
G_p(s) = \frac{V_{dc}}{LC \left[ s^2 + s \left( \frac{1}{CR} + \frac{r_i}{L} \right) + \frac{1}{LC} \right]} \quad (5.11)
\]

\[
G_c(s) = \frac{k_p s + k_i}{s} \quad (5.12)
\]

The values of \( k_p \) and \( k_i \) are designed as 0.001 and 2 respectively, so as to achieve the above mentioned design features.

The bode plot of the open loop transfer function \( G_p(s)G_c(s) \) of the converter system given in Figure 5.6 shows the phase margin as 90.9° at a cross over frequency of 70.2 rad/sec.

![Bode Diagram](image-url)

**Figure 5.6 Bode plot of the PI controlled buck converter**
The experimental set up for the simulator is built to represent Shell solar module S115. The experimental set up consists of a DC-DC buck converter, which employs two power MOSFETs one as a switch and the other as the freewheeling diode, and a low pass filter with values as follows: \( L = 1.45\text{mH}, \ C = 330\ \mu\text{F}, \ r_l = 0.14\Omega \).

The mathematical equations which depict the PV panel are coded in PIC16F877 microcontroller, operated with a clock frequency of 20 MHz. Figure 5.7 shows the experimental set up of the hardware simulator. The LCD and keypad are interfaced with the microcontroller, so that the values are entered through keypad to one of the input ports. The third input i.e. the load current is sensed using a Hall effect sensor and given to the built in ADC of the microcontroller. The calculations to determine the reference voltage takes far less than 50\(\mu\text{s} \) by the controller, thus the input quantities, i.e. current and voltage are sampled at 50 \(\mu\text{s} \) interval. The comparator and the discrete PI controller are also programmed in the microcontroller.

![Figure 5.7. The hardware simulator](image)
5.7 PERFORMANCE OF THE SIMULATOR

The static V-I characteristics of the Simulator has been obtained to validate its performance under steady-state and transient conditions. The transient response of the hardware simulator has been obtained by (i) Switching between two different load levels (ii) Introducing a sudden change in the ambient temperature and (iii) Introducing a sudden change in the irradiance.

For obtaining steady-state characteristics, load test is conducted on the Simulator and the voltage and current values has been obtained experimentally and plotted for different sets of ambient conditions. In Figure 5.8 and 5.9 the steady-state V-I characteristics of the hardware PV simulator are presented and compared with the data sheet. The experimental data and the data sheet values are matched using a 9th degree polynomial curve fit, and the deviation between them is found to be 0.5 % to 1.5 % for different insolutions.

![V-I Characteristics of S115](image)

**Figure 5.8** $i$-$v$ Characteristics of the emulator at $T_C = 25^0C$, $G = 800$W/m$^2$
The dynamic response of the Simulator is obtained for change in the load resistance as well as change in the irradiance. The response of the PV simulator for a load change is experimentally obtained by switching a load resistance using a MOSFET switch. The load is switched from maximum power point load $R_{MPP} = 6.3 \ \Omega$ to open circuit $R_{OC}$ at $G = 1000\text{W/m}^2$, $T_C = 25^\circ\text{C}$. It is observed that the output voltage switches between its maximum power point voltage $V_{MPP}$ to open circuit voltage $V_{OC}$. This is given in Figure 5.10 (a) and Figure 5.10(b).

Figure 5.11 (a) and 5.11 (b) gives the dynamic change in output voltage when there is an increase and decrease in irradiance respectively with constant temperature. Figure 5.12 gives the dynamic change in output voltage for change in cell temperature with constant irradiance. In each case the load resistance was kept as $R_{MPP}$ corresponding to the initial insolation condition.

Figure 5.13 gives the dynamic change in output voltage when the insolation changes from STC i.e. $G = 1000 \text{ W/m}^2$ and $T_C = 25^\circ\text{C}$, to NOCT i.e. $G = 800 \text{ W/m}^2$ and $T_C = 44^\circ\text{C}$. Finally in Figure 5.14 the output voltage
of the simulator for a step change in G from 200 W/m\(^2\) to 1000 W/m\(^2\) and vice versa is presented. The response time of the emulator is found to be in the range of 50 – 150 µs for various step insolation changes.

Figure 5.10. Output voltage for step load change (a) from \(R_{OC}\) to \(R_{MPP}\) (b) from \(R_{MPP}\) to \(R_{OC}\) under \(G=1000\,\text{W/m}^2\), \(T_C = 25^\circ\text{C}\)

Figure 5.11. Output voltage for step change in G (a) from 800 W/m\(^2\) to 1000 W/m\(^2\) at \(T_C = 40^\circ\text{C}\) (b) from 800 W/m\(^2\) to 400 W/m\(^2\) at \(T_C = 60^\circ\text{C}\)
Figure 5.12 Output voltage for step change of $T_C$ from 20$^\circ$C to 60$^\circ$C with $G=1000$ W/m$^2$

Figure 5.13 Output voltage for step change of insolation from STC to NOCT
Figure 5.14 Output voltage for step change in G
(a) from 200 W/m² to 1000 W/m² at $T_C = 24^0C$
(b) from 1000 W/m² to 200 W/m² at $T_C = 25^0C$

5.8 CONCLUSION

A model based hardware PV simulator has been built and tested in the laboratory. The simulator uses a mathematical model that can be tailored to match any commercially available panel. The model based simulator gives V-I characteristics as that of any PV panel at any specified ambient conditions. The ambient conditions, as required by the operator can be input into the simulator system. As a test case the published data of 115W solar panel Shell S115 has been used to build the simulator. The prototype has been tested in the laboratory for steady-state and transient conditions of insolation and load. For step change of insolation the output voltage is seen to change within few tens of micro seconds. This is as expected, as there is no appreciable time constant involved in a PV cell. The results are compared with the cell characteristics available in the literature and compliance is confirmed. The simulator is very useful as an input power source for testing of converters designed to interface PV panels to a load, especially when load is a utility grid. This simulator is used in this research work for obtaining repeated test conditions for the PV converter systems, especially testing with the micro grid model coming up in the next chapter of the thesis.