

DESIGN AND IMPLEMENTATION OF PROGRAMMABLE PV EMULATOR

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Abstract—Integration of PV panel with existing utilities requires development of equipment's, technologies and tools. The intermittent availability of appropriate site conditions makes it a challenge to create and perform tests with regard to these equipment's using physically installed SPV array. In such conditions a PV simulator can be used. PV simulators are capable of generating output characteristics similar to that of a PV panel or array. The cost and time expended on experimentation can be greatly reduced. In this work, a DC-DC buck converter is used to get the desired output, while operating in two control modes. This dual control method allows for efficient regulation in both zones and produces smooth trajectories in line with a mathematical model or lookup table to mimic any PV characteristics under varied temperatures and irradiation.

Keywords—PV, SPV, Buck converter, Irradiation.

I. INTRODUCTION

The demand for energy in different forms is constantly increasing, particularly renewable energies, namely: hydraulic, wind, solar, geothermal and bio-energy energy. Today, solar energy has taken a large part of the market due to the continued development of PV system technology and lower prices. Owing to availability and accessibility of Solar energy, it is one of the most important and sustainable sources of clean energy. Solar energy also has the benefit of being completely free of cost and still available in abundance despite of intermittent irradiation. The downsides to the PV system being, the high initial investment and low efficiency may be ignored, as the advantages far outweigh them. Therefore, the research and development related to the PV system is of great importance. The area of interest from a power electronics perspective includes improving the efficiency of the solar PV cell by extracting more energy from the panels, developing appropriate control strategies for the system. MPPT techniques are used for drawing maximum power from the panel under varying conditions. It requires the tracking of the maximum power point in the power-voltage characteristics of the PV cell.

The research entailing these techniques must consider the varying atmospheric conditions such as irradiance, temperature and shading. The problem in the research of such systems is the large area and investment required to install an appropriate PV array. A typical PV array producing up to 1kW of peak power may need 5-8 m² of area. Also, it is not possible to control or mimic the atmospheric conditions or emulate grid perturbations. Only when the PV panel is operating at its maximum power point does it provide the most power (MPP). As a result, several studies have been conducted in order to monitor this point. As the conversion of solar energy to electricity depends on the level of solar irradiation and the atmospheric temperature, these MPPT algorithms, tools and equipment's must be tested under different conditions so as to validate their accuracy and efficiency. There are several methods that can be used for the purpose of testing, one of which is to physically install the desired capacity of solar panels and collect the data in real-time. However, this method comes with various limitations such as intermittent availability of solar irradiation, inconsistent weather conditions, inability to perform these tests at time, difficulty in collecting data from site and transferring it to the workplace. This work proposes a low-cost PV emulator to test the real-time operation of PV array related ancillaries.

A PV emulator is a programmable power supply that can produce output identical to a PV array. It is capable of simulating the non-linear characteristics of a PV panel. It may be programmed to emulate any PV panel at any atmospheric condition. It consists of a buck converter and a reference generator which allows a variety of I-V and P-V curves for different values of solar radiation to be simulated under laboratory conditions regardless of actual solar radiation levels. This PV emulator is a simple and easy to build in a conventional laboratory environment. A PV panel has a non-linear I-V characteristics. On observing the I-V characteristics of a PV panel, its operating range can be divided into two regions, namely CCR and CVR. Both these regions require dedicated operating modes to ensure accurate and fast reproduction of the characteristics. These modes revolve around the MPP, so quick and precise shifting from and to each mode is essential. This project proposes a hysteresis controller to ensure effective operation in both these regions by seamlessly switching to the desired

operating mode. This dual control mode strategy ensures effective control in both regions and provides smooth trajectories as per mathematical model or lookup table to mimic any PV characteristics under various temperatures and irradiation [1],[2]. The proposed emulator can be useful for testing of various tools and technologies used for integrating SPV panels with existing utilities.

II. EXISTING TECHNOLOGIES

The practical implementation of a PV emulator may consist of a power conditioning circuit, a reference generator, a controller, a method for switching between modes and a load. A few existing techniques are discussed below:

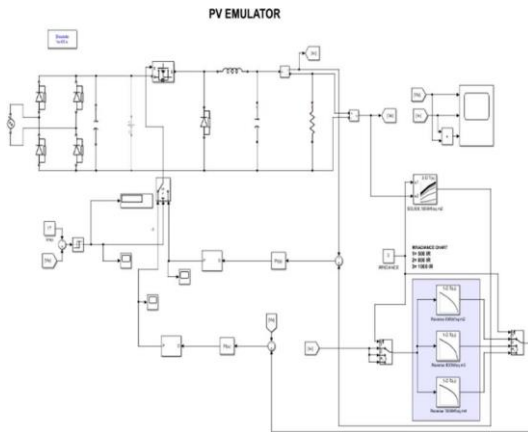


Fig. 1 Simulation circuit

A. PV Modelling Methods

Modelling of PV panels is an appropriate way to generate desired characteristics and behavior according to the input given. The modelling of a PV panel can be done by taking weather data such as irradiance and temperature as inputs, while producing a corresponding voltage and current as output. The modelling may be done in three different ways mentioned here:

- Electrical Circuit Model- Within which the equation of the current-voltage characteristic is determined using the Kirchhoff current law and a diode-based equivalent circuit.
- PV interpolation model or Curve fitting approach- This method allows reproducing the current-voltage characteristic of the module using a mathematical function by linear interpolation between particular points of the I-V curves of the PV modules.
- Look-Up table method - This a purely experimental approach and requires a lot of memory in the microcontroller to store the large amount of data necessary for different conditions.

B. Mathematical Equivalent Models of PV Module

The electrical or analytical modelling of a PV panel may be done in several different ways depending on the electrical system components used to represent the module. Some

models are 1D, 1D1R, 1D2R, 2D2R, 1D2R1C, 2D4R, 3D2R, 3D5R, xD2R, 2D1R1Rv. Here D represents diode and R represents resistor and C represents capacitor, with the number representing the number of components used in the circuit. 1D model is single diode model, 1D1R uses a diode and a resistor to represent the PV module. Out of these models 1D model is only used to understand the basic characteristics of a PV module. The 1D1R takes into consideration the dissipative effects and the sum of several contact resistance and the resistance of the materials of the module and causes a reduction in the power converted by the device. The 1D2R model is more robust considering temperature influence. It emulates the behaviour of construction defects which cause leakage currents within the PV cell. The 1D2R model is commonly used [2],[3],[4]. It is also known as single diode R_{sh} model. The fig.2 given below is an example of 1D2R model.

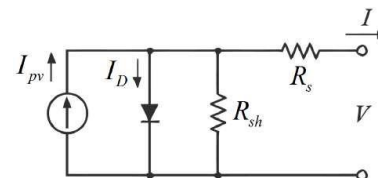


Fig 2 1D2R Model of PV panel

C. Power Conditioning Circuit

A DC-DC Buck converter-based solution for power supply in a PV emulator is very often used. The characteristics of the PV panel is simulated by adjusting the value of current by generating the reference current value using measured voltage. The duty cycle of the PWM signal given to the gate of the MOSFET may be varied to obtain the desired output. Most PV emulators have only current control mode (CCM) i.e., the current reference is generated using measured voltage from the PV panel and used to vary the current. However, this will only produce accurate results in the constant current region because in the constant voltage region the variation in voltage is too small to be detected and this may produce incorrect characteristics.

D. Reference Generator

PV emulators are programmed for simulating characteristics at STC (Standard testing condition), which is an irradiance of $1000\text{W}/\text{m}^2$ and temperature 25°C . Simulating panels at STC allows for an appropriate means of comparing different panels. However, there are downsides to this technique. The STC is not very easily observed in real life, making the Look-Up table values thus obtained of very little meaning to the simulating real life conditions accurately. The atmospheric conditions are also constantly varying which is still a problem as the emulator is programmed to work at only one set of atmospheric condition.

E. Switching Technique

Generally used switching techniques include PI, hysteresis, sliding mode control, ON/OFF control etc. A PI controller is a combination of proportional and integral control action. By combining two control actions, shortcomings of both are mutually eliminated. By introducing PI controllers to a system, the steady state error can be drastically reduced without interfering with the stability of the system. Sliding mode control is increasingly used with uncertain systems that have non-linear dynamics. SMC is a robust and quick-

converging control scheme [9]. However, it suffers from chattering effects produced in the control responses. Hysteresis control also known as bang-bang control produces a significant change in the controller's output every time the error between control references and control variables crosses either the positive or negative hysteresis band's boundary. The controller quickly reacts to any deviation from control references, which are the reason of the high gain behaviour of these controllers. On-Off Control assigns the Controller Output (CO) to one of two positions such that the final control element (FCE) is either fully open or fully closed. Unlike intermediate value or PID control, there is no in between. Most industrial processes require greater latitude when it comes to adjusting the CO's position. On-Off Control can result in excessive variability as the controller has so few options for maintaining Set Point. A process equipped with On-Off Control will constantly overshoot its Set Point and cycle as a result. The work demanded of the FCE regularly accelerates the time to failure and increases maintenance costs.

III. METHODOLOGY

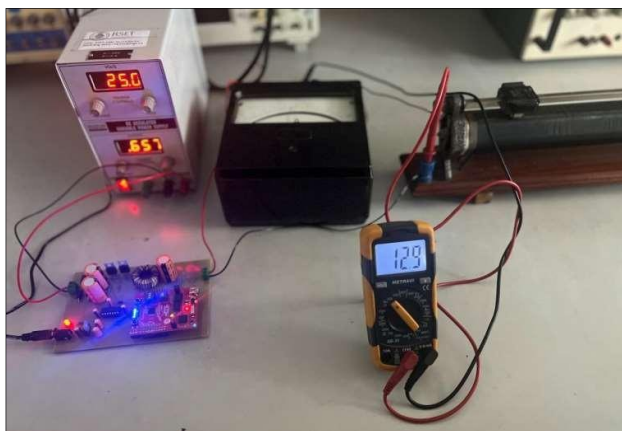


Fig 3 Testing Circuit

In this project we have selected the Look-Up table technique for modelling the I-V characteristics of the panel. This method being purely experimental means that the values will be closer to what can be achieved in real life conditions. It does require more memory within the microcontroller for storing large amounts of data for varying conditions.

The power supply circuit used is a DC-DC buck converter is constructed to emulate the characteristics of the PV module. However, here both CCM and VCM is implemented. This provides more accurate operation of the emulator with characteristics bearing greater resemblance to an actual PV module by generation of appropriate reference values in both CCR and CVR. This is made possible by using two look-up tables one for CCM and another for VCM. One look-up table generates the reference current value corresponding to the measured voltage value (CCM), while the other look-up table generates reference voltage value corresponding to measured current value (VCM).

For obtaining the look-up table values 1D2R equivalent model of PV module was implemented. This model being the most widely used for the reasons that with varying conditions it produces more accurate results. A PV model represented by a user defined function was developed in MATLAB for both the look-up tables comprised of the

equivalent equations of 1D2R model. The emulator is expected to operate under varying irradiance conditions, which is implemented by using multiple sets of look-up tables for different irradiance values (500W/m², 800W/m², 1000W/m²). The temperature is kept constant at 25° C. The 1D2R model is shown in fig 2.

Switching between both control modes- CCM and VCM is desired to be done depending on the operating point. Hysteresis control was implemented for this purpose [1]. It produces the output signal corresponding to the error between reference and measured value. In this case the reference value is the voltage at maximum power point (Vmpp). When the error is negative the emulator needs to operate in the current control mode and in the voltage control mode when the error is positive. Hysteresis control was observed to have a faster response to changes in input and hence it was chosen [7],[8].

A. PV Model Design

PV model design equations for obtaining current as output for voltage as input-

- $T_{cell} = 273 + T$ (1)
- $vt = (A * k * T_{cell} * N_s) / q$ (2)
- $I_{SC_T} = I_{SC} + ((I_{SC} * (\frac{K_i}{100})) * (T - 25))$(3)
- $V_{OC_T} = V_{OC} + ((V_{OC} * (K_v/100)) * (T - 25))$... (4)
- $I_s = I_{SC_T} / (e^{\frac{70C_T}{vt}} - 1)$ (5)
- $I_{ph} = I_{SC_T} * (\frac{G}{1000})$ (6)
- $I = I_{ph} - (I_s * (e^{\frac{(7+(i*R_s))}{vt}} - 1)) - \frac{(V+(i*R_s))}{R_{sh}}$ (7)

PV model design equations for obtaining voltage as output for current as input-

- $T_{cell} = 273 + T$ (8)
- $vt = (A * k * T_{cell} * N_s) / q$ (9)
- $I_{SC_T} = I_{SC} + ((I_{SC} * (\frac{K_i}{100})) * (T - 25))$... (10)
- $V_{OC_T} = V_{OC} + ((V_{OC} * (K_v/100)) * (T - 25))$ (11)
- $I_s = I_{SC_T} / (e^{\frac{70C_T}{vt}} - 1)$ (12)
- $I_{ph} = I_{SC_T} * (\frac{G}{1000})$ (13)
- $V = vt * \log(1 + \frac{(i-I_{ph})}{I_s}) - i * R_s$ (14)

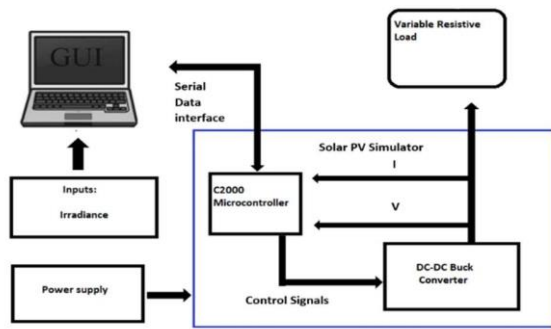


Fig. 4. Hardware Block Diagram

Here I_{pv} is the reference current, I_{ph} is the photocurrent of the model, I_d is the diode current, I_{sh} is the current across shunt resistance, i_{ccs} is the short circuit current, G is the irradiation and G_s is the irradiance at STC, similarly T is the temperature and T_s is the temperature at STC. I_{sat} Saturation current, A is the diode ideality factor, Q is the charge of electron and K is Boltzmann's constant. V_{ocs} is the open circuit voltage at standard condition, V_{oc} is the open circuit voltage, R_s cell intrinsic series resistance and R_{sh} is the cell intrinsic shunt or parallel resistance. For both equations value of electron charge, q is taken as 1.6×10^{-19} and Boltzmann's constant, $k = 1.38 \times 10^{-2}$, also equations (1) and (8) are for calculating temperature in Kelvin and equations (2) and (9) are the thermal voltage equations. Equations (3) and (10) are for calculating short-circuit current considering temperature, while (4) and (11) are for open-circuit voltage considering temperature. (5) and (12) are equations for calculating reverse saturation current. (6) and (13) are for calculating photocurrent. Equations (7) and (14) are output current and voltage equations of the model respectively. The input parameters given to the model is shown in Table 1 [10].

Table 1 PV Model Input Parameters

Parameter Name	Value
Short-Circuit Current (I_{sc})	1.25A
Open-Circuit Voltage (V_{oc})	21.7V
Ideality Factor (A)	1
Series resistance (R_s)	1.3
Shunt Resistance (R_{sh})	362
Number of cells in series (N_s)	36
Temperature coefficient of current (K_i)	0.102
Temperature coefficient of voltage (K_v)	-0.36099

B. Buck Converter Design

Buck Converter design equations-

- $\Delta I_L = (Y * I_{OUT_{max}})$(15)
- $L = (V_{OUT} * (V_{IN} - V_{OUT})) / (\Delta I_L * f_s * V_{IN})$(16)
- $C_{OUT} = (\Delta I_L) / (8 * f_s * \Delta V_{OUT})$(17)

Here ΔI_L is output ripple current, Y is ripple factor (generally varies from 0.2 to 0.4), $I_{OUT_{max}}$ is maximum output current, L is inductor value, V_{OUT} and V_{IN} are the output and input voltage, f_s is the switching frequency and

C_{OUT} is the capacitor in the buck converter circuit. Equation (15) is used to calculate output current ripple, while equation (16) and (17) are used for calculating the inductor and capacitor value, respectively.

IV. RESULTS

The simulation of the PV simulator was carried out in MATLAB/Simulink. The circuit diagram and results are discussed below-

A. Simulation Circuit

The input to the buck converter is required to be DC and as the simulator is supposed to operate on domestic AC supply a rectifier circuit is added to convert AC to DC. Rectifying AC to DC produces harmonics, to filter this out a capacitor of appropriate value is given. The resulting DC output is provided to the buck converter. The output of the buck converter is taken across a resistive load. Both voltage and current are measured at the output of the converter.

This converter is designed to operate in two modes CCM (current control mode) and VCM (voltage control mode). Lookup tables are used for the purpose of reference generation. In CCM the measured voltage is given as input to a 2D- lookup table which returns the corresponding current reference value. The difference between this reference and measured value is given as input to a PI controller which produces a signal that can eliminate error. This signal is given to a PWM generator that changes the duty cycle of the firing pulse given to the gate terminal of the MOSFET. Similarly, in VCM the measured current is given as input to the lookup table which returns the reference voltage value.

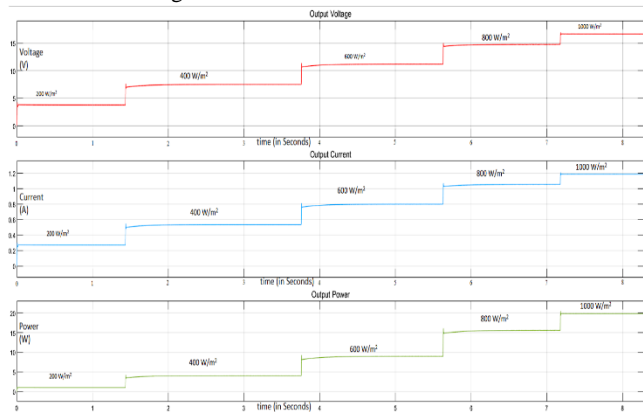


Fig. 5. Simulation result

The switching between both modes is done using a hysteresis controller depending on the sign of the difference between measured voltage and the V_{mpp} (maximum power point voltage). When the value measured is less than V_{mpp} the circuit operates in CCM. During this operation the difference between V_{mpp} and measured voltage is negative. When measured value is more than V_{mpp} the circuit operates in VCM. During this operation the difference between V_{mpp} and measured voltage is positive. A relay and switch block were used in Simulink to implement this control strategy. The simulation circuit created in

MATLAB/Simulink is shown in fig.1. The output of the simulation circuit is given in fig.6

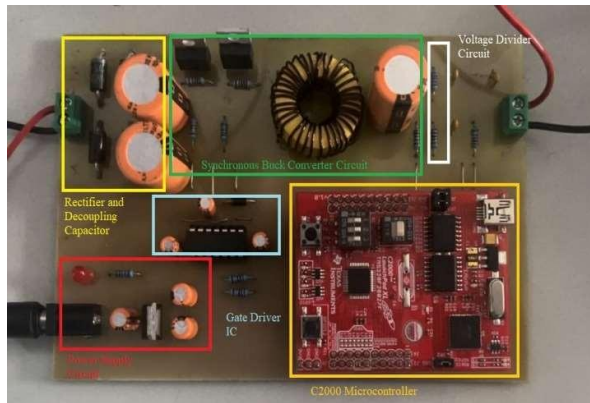


Fig. 6 PCB Layout

B. Hardware Schematics and Setup

The hardware circuit consists of a rectifier circuit with 4 ultra-fast diodes UF5048, buck converter with IRF540N MOSFET and ACS712 current sensor, gate driver circuit of IR2110 [2] and a voltage regulator circuit to power the C2000 microcontroller.

The input is given to the PV emulator section and the rectifier circuit converts it into DC and is passed on to the buck converter where it is stepped down to appropriate level and passed on to the voltage divider section and current sensor to implement the current control mode and voltage control mode as and when required. The voltage regulator circuit consists of AP1117 and L7805 voltage regulators to step down the voltages to appropriate levels to power ON the microcontroller which gives appropriate control signals. The gate driver adjusts the duty ratio of the MOSFET as per the microcontroller signals to control the output voltage and current. The gate driver drives the 2 MOSFETs for switching ON and OFF to avoid short circuit in the circuit. A basic block diagram of the hardware setup is as given in fig.4. A C2000 family microcontroller, LAUNCHXL-F28027F, was used as a controller for processing and computing the duty cycle for MOSFET, thereby controlling the output [5]. The output of the converter is taken across a rheostat, which acts as the resistive load [6].

C. Simulation and Hardware Results

The simulation results are as given below in Table 2

Table 2 Simulation Output

Irradiance	Voltage	Current	Resistance
1000	16.5	1.1	14
800	13.5	0.96	14
500	8.5	0.60	14

The hardware results are shown in Table 3. The simulation and hardware experiments were carried out for three values of irradiances 500W/m², 800W/m², 1000W/m². The setup

used for carrying out the experiment is shown in fig.3. The load was kept constant at 14Ω, and the corresponding current and voltage values were obtained as shown in table 2 and table 3. These values were found to be well within acceptable limits of each other.

Table 3 Hardware Output

Irradiance	Voltage	Current	Resistance
1000	13	0.98	14
800	9.5	0.72	14
500	4.3	0.3	14

VI. CONCLUSION

A DC-DC Buck converter-based PV simulator was implemented in this paper. This device is capable of reproducing the characteristics of a PV panel accurately, as it has dedicated operating modes for different regions of the characteristics. The converter was observed to be able to regulate its output in accordance with the LUT values given. The double control modes allow for precisely controlling the output of the converter in both constant current and constant voltage regions. A programmable 20W PV simulator was designed and built. The converter is programmable, so the LUT data can be changed at any instant, allowing for different configuration of PV panel or array to be simulated.

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