

Czech Technical University in Prague

Faculty of Electrical Engineering

Department of Power engineering and management



Master Thesis

CURRENT CONTROLLED
BUCK CONVERTER BASED PV ARRAY EMULATOR

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ZADÁNÍ DIPLOMOVÉ PRÁCE

I. OSOBNÍ A STUDIJNÍ ÚDAJE

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Studijní program: **Elektrotechnika, energetika a management**
Studijní obor: **Elektroenergetika**

II. ÚDAJE K DIPLOMOVÉ PRÁCI

Název diplomové práce:

Current Controlled Buck Converter Based PV Array Emulator

Název diplomové práce anglicky:

Current Controlled Buck Converter Based PV Array Emulator

Pokyny pro vypracování:

- 1) Describe and simulate the characteristics of PV modules.
- 2) Simulate and analyze buck converter for designing a Photovoltaic emulator
- 3) Evaluate buck converter based PV emulator at different load configuration.
- 4) Design buck converter components to act as the building block for PV emulator.

Seznam doporučené literatury:

- [1] KRISHNAN, R. Electric motor drives: modeling, analysis, and control. Upper Saddle River, N.J.: Prentice Hall, c2001
- [2] CHIASSON, John Nelson. Modeling and high performance control of electric machines. Hoboken: Wiley, 2005.
- [3] MOHAN, Ned. Advanced electric drives: analysis, control, and modeling using MATLAB / Simulink. Hoboken: Wiley, 2014.

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III. PŘEVZETÍ ZADÁNÍ

Diplomant bere na vědomí, že je povinen vypracovat diplomovou práci samostatně, bez cizí pomoci, s výjimkou poskytnutých konzultací. Seznam použité literatury, jiných pramenů a jmen konzultantů je třeba uvést v diplomové práci.

Datum převzetí zadání

Podpis studenta

DECLARATION

I hereby certify that I the sole author of this report and that neither any part of this report nor the whole of the report has been submitted for a master degree or other degree to any other University or Institution. I certify that, to the best of my knowledge, my report does not infringe upon anyone's copyright nor violate any proprietary rights and that any ideas, techniques, quotations, or any other material from the work of other people included in my report, published or otherwise, are fully acknowledged in accordance with the standard referencing practices. I declare that this is a true copy of our report, including any final revisions.

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Place:

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ACKNOWLEDGMENT

“Not only will atomic power be released, but someday we will harness the rise and fall of the tides and imprison the rays of the sun”

--- Thomas A Edison (1921)

It has been great honor and privilege to undergo my Master study in Power Engineering and Management in Czech Technical University (CVUT), **Prague**. I am very much thankful to my head of the department **Doc. Ing. Zdeněk Müller, Ph.D (Department of power engineering)** for providing support to meet my thesis requirements. I would like to take opportunity to express our humble gratitude to our guide **Ing. Jan Bauer** under whom I executed this thesis. His constant guidance and willingness to share his vast knowledge made me understand this thesis and its manifestations in great depths and helped me to complete the assigned tasks. He provided all kind of freedom, so that I learn many things by myself, but finally we achieved results for our thesis.

At last I wish to thank all others who directly or indirectly helped us in preparing this thesis and my study like **Dr. Ing. Jan Kyncl, Prof. Ing. Jiri Lettl, and specially Ms. Ivana Býmová.**

ABSTRACT

It is difficult to obtain the output characteristics of a PV module, due to the fact of the changing environmental conditions. Thus, a PV emulator, which is a power electronic converter that reproduces the desired output characteristics irrespective of the environmental conditions, is preferred. This gives the flexibility to analyze the PV module in various and constant atmospheric conditions. A performance of Buck based PV emulator is simulated and implemented with different types of load (linear/non-linear) and is compared with a physical PV module. This type of emulators can be used to check working efficiency and output elements like voltage, current, losses etc. at the places where there is no sufficient solar light available or some time due to weather, we cannot check these elements, but with this kind of device we can do those experiments.

According to my past studies, which was mainly based on electronics, I was much used to with electronics. So that I decided to do something regarding electronics in thesis, but in CVUT I studied mostly power engineering, so that I finalize this topic which can be work around both electronics and solar energy. This model can be design in many other types also, by using boost, cuk, buck-boost converter. There will be a chance to make small hardware of the simulation and we can compare results with simulations. But in this thesis, I only did work with buck converters and simulations using MTLAB.

Keywords:

PV array, MPPT, Solar Power, Simulator and Emulator, Power, Efficiency,

Buck, Boost and Cuk converters, Simulation, microcontroller.

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1. INTRODUCTION

1.1 PROJECT DEFINITION

A PV emulator, which usually is a power electronic converter, can reproduce the desired output characteristics irrespective of the environmental conditions. It gives opportunity to test and analyze different PV systems in intended and controlled environment.

1.2 OBJECTIVE

The objective of this study is to:

- To study the basics of Photovoltaic cell and it's modeling.
- To design circuit for current controlled PV array emulator
- To test and evaluate the performance of PV emulator with linear and non-linear load.
- Finally, to compare the behavior of PV emulator with real PV array.

1.3 OVERVIEW

Nowadays, due to the expansion of the rural and urban areas, the load demand is increasing day by day. Due to the increase in load demand, the use of electricity is also increasing and to produce the electricity, the cost is also increased. And by production of electricity, the natural resources are used by huge amount. So, production of electricity by non-conventional sources. Several factors like depletion of the conventional sources, increase in the cost of electricity, increased concern about the environment, government policies and incentives for renewable energy generation, etc. have drawn more attention of the researchers towards the renewable or non-conventional energy sources.

One of the most efficient methods among the non-conventional resources is the solar photovoltaic. Due to number of advantages of this like direct solar to electric energy conversion, no moving parts, modularization, no constraints in terms of site location etc. The use of solar PV system has increased in few past years.

However, PV systems do have some disadvantage as these include low efficiency, higher initial cost, interaction with the other systems connected in parallel, etc. Also, the effect of the partial shading may lead to decrease in the output power of the PV array; increase in harmonics, poor THD etc. hence, the use of solar PV system is under research work.

Our project objective can be achieved with the help of an experimental set up that is capable of reproducing the characteristics similar to that of a PV array. Such experimental set-up is called an emulator.

Some of the reasons, which suggest the need for an emulator to reproduce the characteristics of PV array, are as under:

- 1) The cost of actual PV array is very high.
- 2) The commissioning of actual PV array requires a large area.
- 3) It is difficult to emulate a PV array by simply having either a Current Source (CS) or a Voltage Source (VS).
- 4) It gives the liberty to carry out the experimentation even at the night times when sun is not available or under cloudy conditions and low insolation conditions (irrespective of environmental conditions).
- 5) It is difficult to reproduce and maintain the similar characteristics with the PV array as the insolation and other environment conditions do not remain same.

1.4 THESIS OUTLINE

This thesis describes the photovoltaic emulator which emulates the characteristics of a real PV panel using a current controlled buck converter. PV emulator testing is done with different types of load such as linear and nonlinear load.

1.5 SCOPE/ APPLICATION

- To perform various tests and analysis of the PV module, irrespective of the atmospheric conditions.
- Analysis of the PV panel used in satellites in the outer space.
- To test the PV module without using the actual physical panel/array.....

2 LITRATURE SURVEY

2.1 DISCUSSION

To gain a greater level of knowledge about the subject of PV cell and PV emulator a major literature review took place. Reading papers, journal sand websites provided a greater insight into the purpose of the project and answered many questions which arose on first glance of this project work. The journals and papers which were chosen to review were obtained from the IEEE Xplore, websites and from my supervisor. The literature review given below gave a clear theoretical framework about the subject in which this study was based.

2.2 RESERCH PAPER - 1

Title: Simulation of a PV Emulator

Authors: D. Dolan, J. Durago, J. Crowfoot and Taufik

Publication: North American Power Symposium, 2010, pp. 1-6.

Summary:

This paper outlines the simulation of a PV emulator. It explains the history of PV emulator and the topologies used. The design of a buck converter is explained with its basic equations. The response of PV emulator with a single load, and stepped increase/decrease in load resistance is presented with the simulation results.

2.3 RESERCH PAPER – 2

Title: Current Controlled Buck Converter Based PV emulator

Authors: A. Rana and H. Patel

Publication: Journal of Industrial and Intelligent Information vol. 1, no. 2, June 2013.

Summary:

This paper outlines the simulation of a current controlled buck converter-based PV emulator. PV emulator is a dc-dc converter which duplicates the behavior of a PV panel. The output characteristic of a PV emulator is independent of the weather conditions. The PV emulator is tested with linear resistive load and non-linear load and the results are compared with a real PV source. Finally, it is concluded that the results of emulator adhere closely to that of a real PV array.

2.4 RESERCH PAPER – 3

Title: Evaluating MPPT converter topologies using a MATLAB PV model

Authors: G. Walker

Publication: Journal of Electrical and Electronics Engineering, vol. 21, no. 1, 2001.

Summary:

This paper gives an accurate PV module electrical model based on Shockley diode equations. The evaluation of a model is done in MATLAB and is demonstrated for a typical 60W solar panel. This model is used to investigate the variation of maximum power point with temperature and insolation levels. A comparison of buck versus boost MPPT topologies is made which is compared with a constant voltage load. Finally, it is concluded that Boost converter have a slight advantage over buck converter as it can always track the maximum power point

2.5 PROBLEM STATEMENT

The inherent problems associated with conventional sources are as given below.

- Exhaustible
- Pollutes the environment
- High maintenance
- High cost

Solar power is widely used renewable source of energy. The output characteristics of PV panel depends on variety of factors like temperature, weather, irradiation received etc. So, it is very difficult to study the behavior of solar panel as characteristics keeps on varying. Also, it becomes difficult to carry out testing on a real PV panel as constant characteristics are required.

The above problem is solved using a Photovoltaic emulator that duplicates the characteristics of a PV panel irrespective of the weather conditions. So, the behavior of a PV panel can be studied and testing can be easily done using PV emulator whose output is independent of any of the above factors.

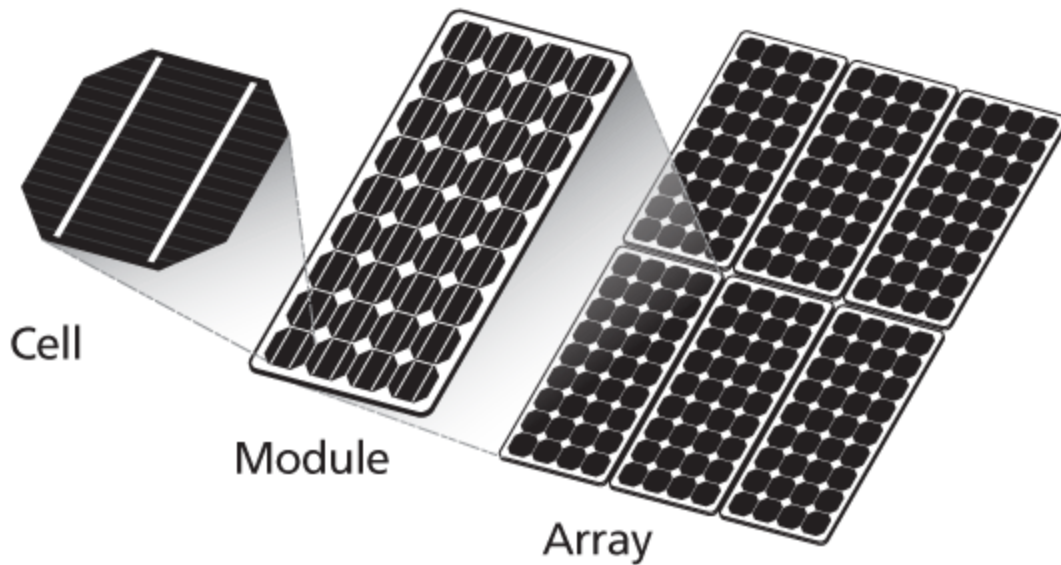


Figure 2. 1 Solar Cell, Module, Array

Figure 1 shows the difference between a solar cell, module and array. It shows that a module is made up of a number of cells and an array is made up of a number of modules.

2.6 SOLAR POWER

Solar power is an alternative energy source which is widely available to this country. This renewable energy is being explored in greater depths and in recent years its development has grown rapidly due to the large amount of funding it has received. This energy source is receiving large amounts of funding due to its renewable appeal, it's in exhaustible capacity and its non-polluting attractive nature. Solar powers evolution in the past ten-fifteen years has been gratefully accepted, but further work will ensure the performance of PV cells will transform from the sub parts at us which they currently hold.

2.7 PHOTOVOLTAIC SOLAR CELL

PV Module Anatomy

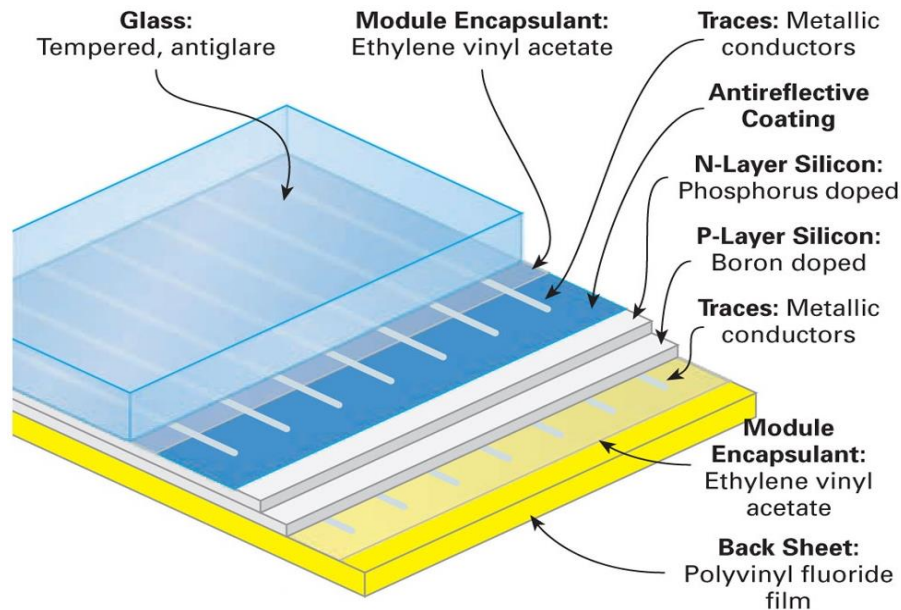


Figure 2. 2 PV Module Anatomy

Photovoltaic effect is a phenomenon in which solar energy is converted directly into electrical energy through the use of a solar cell. A PV cell is made of silicon, which is purified, melted and then crystallized.

A p-n junction is formed by joining the two types (p & n) together, and an electrical field is created. The excess electrons flow from the 'n-type' material to the 'p type' material. The electrons and holes leave behind exposed charges on dopant atom sites, fixed in the crystal structure. The region around the junction is depleted of charge carriers and is therefore known as the "depletion region". It is called the depletion region as the area is left bereft of charge carriers.

When P and N-type semiconductor materials are joined together they become a PN junction diode. Current does not flow through it. It is because without an electric field, the cell wouldn't work; the field forms when the N-type and P-type silicon come into contact. Suddenly, the free

electrons on the N side see all the openings on the P side, and there's a mad rush to fill them. But all the free electrons will not fill all the free holes. If they did, then the whole arrangement wouldn't be very useful. However, right at the junction, they do mix and form something of a barrier, making it harder and harder for electrons on the N side to cross over to the P side. Eventually, equilibrium is reached, and we have an electric field separating the two sides.

This electric field acts as a diode, allowing (and even pushing) electrons to flow from the P side to the N side, but not the other way around. It's like a hill, electrons can easily go down the hill (to the N side), but can't climb it (to the P side). Figure 2 shows the anatomy of PV cell. Sunlight, sometimes described as particles called 'photons', hits the PV cell and move into the cell. Photons strike electrons and dislodge them, these then become loose and start to move to the top of the cell. The greater the number of photons that are admitted by the cell results in a greater flow of electrons towards the top of the cell.

These then flows in to the external electrical circuit through the grid of metal placed on top of the cell. The electric fields in the solar cell put these free electrons in directional current, from which the metal contacts on top of the cell can generate electricity.

2.8 DIFFERENCE BETWEEN EMULATOR AND SIMULATOR

Emulation is the process of mimicking the outwardly observable behavior to match an existing target. The internal state of the emulation mechanism does not have to accurately reflect the internal state of the target which it is emulating.

Simulation, on the other hand, involves modeling the underlying state of the target. The end result of a good simulation is that the simulation model will emulate the target which it is simulating.



Figure 2. 3 PV simulator

A simulator is software, which is interfaced with an actual PV array. The PV array is exposed to sunlight or by any artificial way such as electric bulbs and lamps. The analysis is carried out by the simulator. The testing can be carried out in any atmospheric condition. Moreover, we can also carry out tests at night. When testing of a PV cell/array in a simulator, we can create a steady environment of certain amount of irradiation and temperature by using tungsten filament bulbs or by sodium vapor lamps. Also, we can test the array at night and in any kind of weather.

But it has certain limitations such as it requires an actual PV array. If the PV array manufacturer and the testing lab are at distant location, then the transportation becomes uneconomical. Also, due to the excessive use of the sodium vapor lamps, the energy units consumed will be at large number and hence more expensive. Moreover, if the PV array of satellite is to be tested, then we cannot create the exact atmospheric condition of the space, which includes the high temperature and irradiance.

On the other end, there are certain advantages on which an emulator is preferred rather than a simulator. In a PV emulator, an actual PV array is not required. Moreover, we can create any kind of atmospheric condition just by the software. Also, if the manufacturer and the testing lab is situated at a distant location, then just providing some input values such as open circuit voltage and short circuit current, we can emulate almost exact working of that array.

2.9 MODELING THE SOLAR CELL

Thus, the simplest equivalent circuit of a solar cell is a current source in parallel with a diode. The output of the current source is directly proportional to the light falling on the cell (photocurrent I_{ph}). During darkness, the solar cell is not an active device; it works as a diode, i.e. a p-n junction. It produces neither a current nor a voltage. However, if it is connected to an external supply (large voltage) it generates a current I_D , called diode (D) current or dark current. The diode determines the I-V characteristics of the cell.

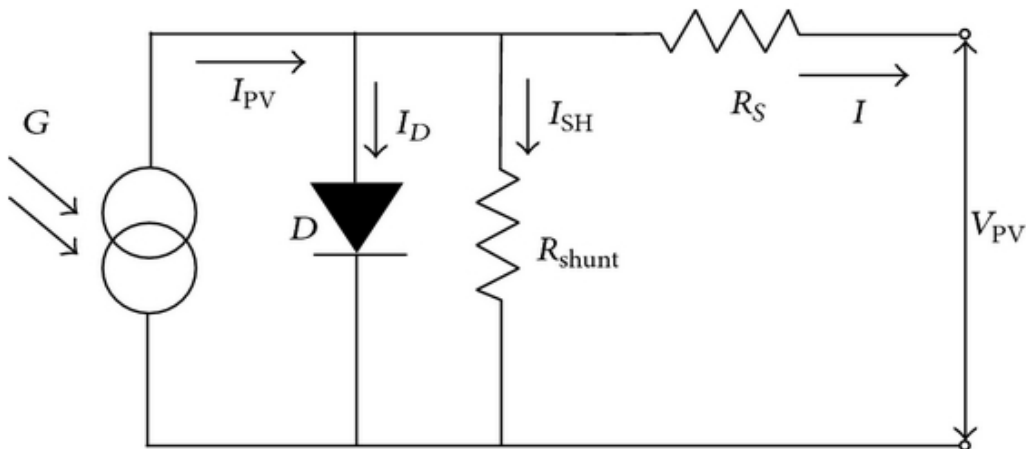


Figure 2. 4 circuit of PV cell

Fig. 4 shows an equivalent circuit to model a PV cell. A single diode model is considered along with the series resistance R_s to take into account the internal electrical losses. Shunt resistance R_p is generally very large and hence, ignored. The equation expressing the relation between output current (I_{pv}) and its terminal voltage (V_{pv}) under given solar radiation (G) and temperature (T) is

$$I_{pv} = I_L - I_0 \left(e^{\frac{q(V_{pv})+(IR_s)}{nkT}} - 1 \right) \dots\dots\dots \text{Equation 1}$$

where,

I_0 is the diode saturation current [A];

n is the diode quality factor;

q is the electronic charge (1.6×10^{-19} C);

k is the Boltzmann constant (1.6×10^{-23} J/K);

T is cell temperature [$^{\circ}$ C];

I_L is the photo current generated by PV cell

The non-linear transcendental equation is difficult to solve and hence, some numerical technique needs to be used to solve it. The approach suggested by Walker et.al [4], is used for solving (1). The characteristic for a particular module can be obtained using (1)-(8). However, some data for that module are required, which can be obtained from the datasheet of the PV module or a priority from experiments done on the module. Hence, to solve (1) the previously known values of open circuit voltage (V_{oc}) and short circuit current (I_{sc}) at two different temperatures T_1 and T_2 are used. The subscript ‘1’ and ‘nom’ refers to the standard conditions ($G_{nom} = 1000\text{W}/\text{m}^2$, $T_1 = 25^{\circ}\text{C}$).

2.10 CHARACTERISTICS OF PV

Description:

A typical I-V characteristic of the solar cell for a certain ambient irradiation G and a certain fixed cell temperature T , is shown in Fig 2. For a resistive load, the load characteristic is a straight line with slope $I/V=1/R$. It should be pointed out that the power delivered to the load depends on the value of the resistance only.

However, if the load R is small, the cell operates in the region M-N of the curve Fig 2.5, where the cell behaves as a constant current source, almost equal to the short circuit current. On the

other hand, if the load R is large, the cell operates on the regions P-S of the curve, the cell behaves more as a constant voltage source, almost equal to the open-circuit voltage.

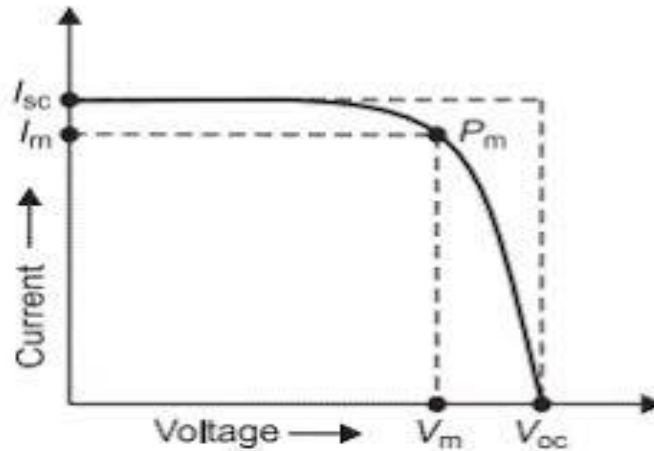


Figure 2. 5 Solar Cell Characteristics

A real solar cell can be characterized by the following fundamental parameters, which are also sketched in Fig.5

- Short circuit current: $I_{sh} = P_{sh}$. It is the greatest value of the current generated by a cell.

It is produced by the short circuit conditions: $V = 0$.

- Open circuit voltage corresponds to the voltage drop across the diode (p-n junction),

When it is transverse. by the photocurrent I_{ph} (namely $IL = I_{ph}$), namely when the generated currents are $I = 0$. It reflects the voltage of the cell in the night and it can be mathematically expressed as below:

$$V_{oc} = \frac{nkT}{q} \cdot \ln\left(\frac{I_L}{I_0}\right) = V_t \cdot \ln\left(\frac{I_L}{I_0}\right) \dots\dots\dots \text{Equation 2}$$

- Maximum power point is the operating point A(V_{max} , I_{max}) in Fig 2, at which the powerdissipated in the resistive load is maximum: $P_{max} = V_{max} I_{max}$.
- Maximum efficiency is the ratio between the maximum power and the incident light power.

$$\eta = \frac{P_{max}}{P_{in}} = \frac{I_{max}V_{max}}{AG_a} \dots\dots\dots \text{Equation 3}$$

Where G_a - the ambient irradiation and A - the cell area.

- Fill factor is the ratio of the maximum power that can be delivered to the load and he product of I_{sc} and V_{oc} :

$$FF = \frac{P_{max}}{V_{oc}I_{sc}} = \frac{I_{max}V_{max}}{V_{oc}I_{sc}} \dots\dots\dots \text{Equation 4}$$

The fill factor is a measure of the real I-V characteristic. Its valued is higher than 0.7 for good cells.

The fill factor diminishes as the cell temperature is increased.

Table 1 PV MODULE SPECIFICATION

Open circuit voltage	V_{oc}	21	V
Short circuit current	I_m	3.74	A
Voltage at MPP	V_m	17.1	V
Current at MPP	I_m	3.5	A
Maximum Power	P_m	59.9	W

For the simulation study, the Solar MSX60 60W PV module is considered.

The specifications of the PV module corresponding to 25°C temperature and 1000W/m2.

3 PV EMULATOR, BUCK, BOOST AND CUK CONVERTER

3.1 PV ARRAY EMULATOR

Several definitions of PV modules are available in literature. Some of them are as under:

“A PV array emulator is a power electronic converter that can reproduce the desired output characteristics irrespective of the environmental conditions.”

“A PV array emulator is equipment, which behaves exactly as that of a real PV module irrespective of the outside weather conditions.”

“A PV array emulator is simply a DC-DC converter that follows the approach or response of real PV module independent of factors like temperature and irradiance for testing of PV system equipment.”

3.2 NEED OF A PV EMULATOR

The electrical characteristics of a PV panel is dependent on variety of factors including the amount of irradiance on panel, temperature and the material used to make a PV panel. A PV emulator simulates the current and voltage characteristics of a photovoltaic panel under these varying conditions. Consistency of electrical characteristics may allow easier analysis and optimization of PV systems.

PV emulator is needed due to following reasons:

- 1) The cost of actual PV array is very high.
- 2) It is difficult to maintain and replicate similar characteristics with the PV array as the insolation and other environmental conditions keeps on varying.
- 3) PV emulator gives manifold degree of freedom to carry out experimentation even at night times or cloudy weather and low insolation conditions.
- 4) PV emulator can reproduce the different desired characteristics in no time with very less effort and cost by just making minor alterations in algorithm of the controller.
- 5) This report presents a current controlled and voltage controlled buck converter as a PV emulator which can exhibit the characteristics of the PV panels and further its performance is compared with that of the actual characteristics of PV panel.



Figure 3. 1 PV emulator hardware

3.3 SYSTEM CONFIGURATION OF PV EMULATOR

The system configuration for buck converter-based PV emulator can be designed using two topologies-

- 1) Current controlled Buck converter topology.
- 2) Voltage controlled Buck converter topology.

BUT OUR PROJECT IS BASED ONLY ON THE CURRENT CONTROLLED BUCK CONVERTER BASED PV EMMULATOR

3.4 OVERVIEW OF BUCK CONVERTER

The buck converter is a switched mode power supply, i.e. it provides digital control through PWM of a switch resulting in a linear response in output voltage. It uses two switches, a transistor and a diode, and an inductor to continually maintain a voltage on the output capacitor. Buck converters are DC-DC converters which are commonly used when the input voltage is too high and needs to be lowered to an appropriate level. A step-down converter produces a lower average output voltage than the DC input voltage V_d . It is widely used in regulated DC power supplies and DC motor speed control.

3.5 OPERATING PRICIPLE OF BUCK CONVERTER

The V_{oi} waveform in Figure 7 part (b) shown as a function of switch position. This waveform is what appears at the input to the low-pass filter in part (a) of Figure 7.

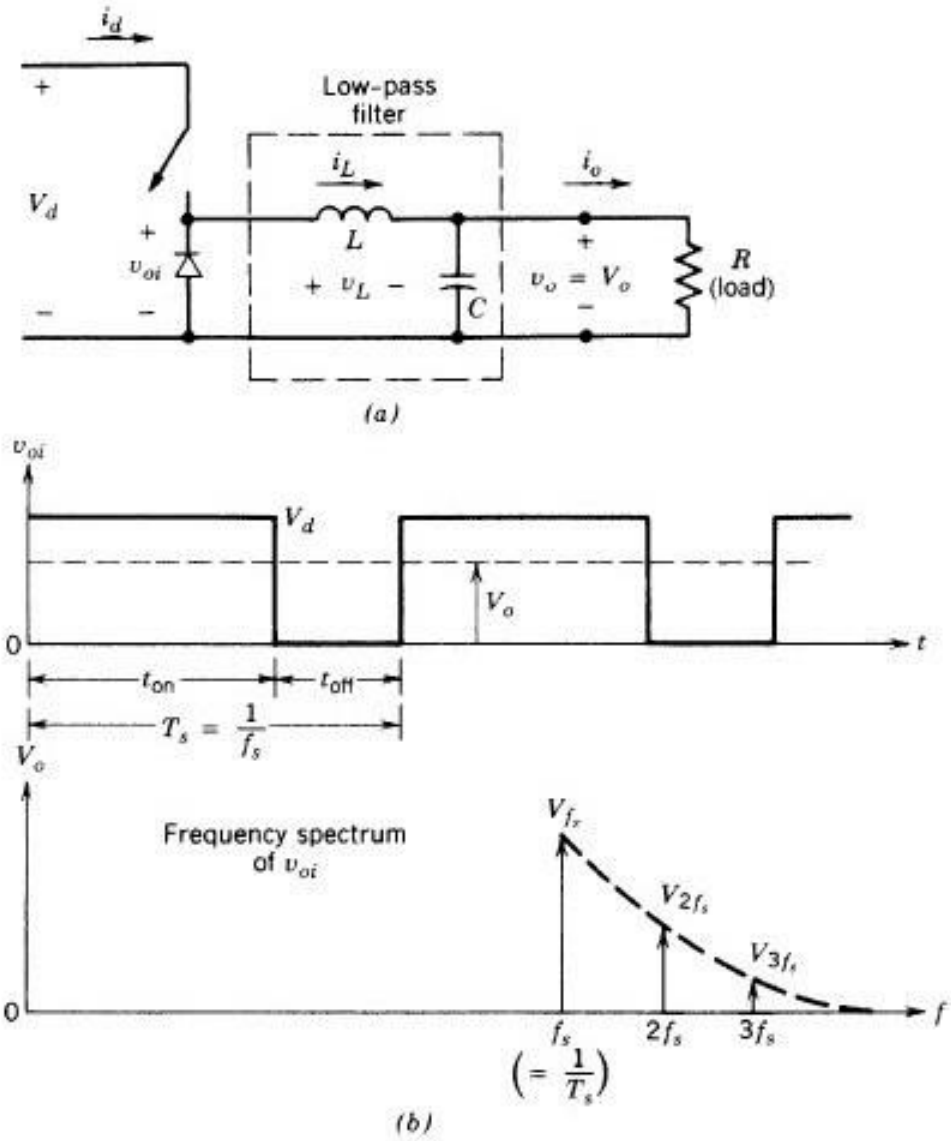


Figure 3. 2 Operation of buck converter

Figure 7: Bucking DC-DC converter showing simple circuit diagram (a), output voltage and frequency spectrum of output (b).

The average output voltage can be calculated in terms of switch ‘D’ using

$$V_o = D.V_d$$

Equation - 5

Where, V_o is the DC output voltage V_i is the DC input voltage, and D is the duty cycle of the converter. When the active time of the switch T_{on} increases, it increases the DC voltage at output.

The D is related to the 'on' time of the switch divided by the period of switching.

$$D = t_{on} / T_s \quad \text{Equation - 6}$$

T_s - the switching period, t_o - the duration the switch when it is ON per switching period. Any linear change in the duty cycle parameter causes a linear change in the output voltage V_o

3.6 OVERVIEW OF BOOST CONVERTER

The boost converters are used to convert the lower input voltage to higher output voltage. In a step up converter or a boost converter, when switch is closed, the load gets voltage supply from the capacitor which charges through the current passing through the inductor and when switch is open, the load gets supply from the input stage and the inductor.

Boost Converter is also called a DC to DC converter. These converters are designed using semiconductors switching devices.

Without using the Boost Converter: In semiconductor switching devices, the Linear regulated circuits (DC power regulated circuits) access voltage from the unregulated input supply (AC power supply) and due to this there is a power loss. The power loss is proportional to the voltage drop.

Using the Boost Converters: In switching devices, the converters convert the unregulated AC or DC input voltage to regulated DC output voltage.

Most of the Boost converters are used in SMPS devices. The SMPS with input supply access from the AC mains, the input voltage is rectified and filtered using a capacitor and rectifier.

3.7 OPERATING PRICIPLE OF BOOST CONVERTER

The main working principle of boost converter is that the inductor in the input circuit resists sudden variations in input current. When switch is OFF the inductor stores energy in the form of magnetic energy and discharges it when switch is closed. The capacitor in the output circuit is assumed large enough that the time constant of RC circuit in the output stage is high.

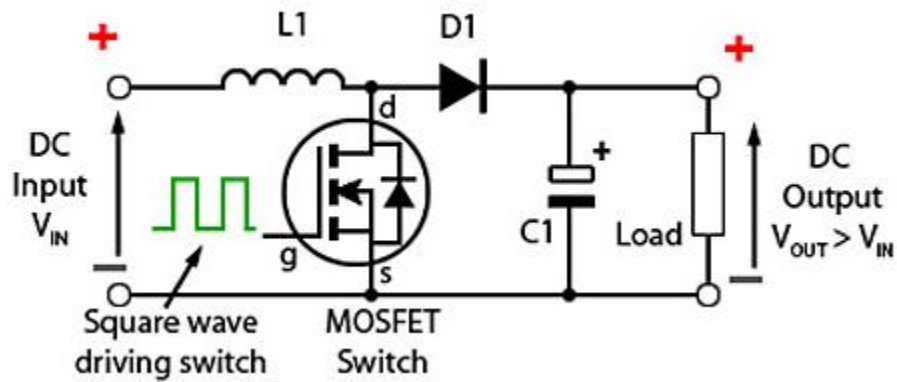


Figure 3. 3 Boost Converter

The boost converter can be operated in two modes

1) **Continuous conduction mode:**

In which the current through inductor never goes to zero i.e. inductor partially discharges before the start of the switching cycle.

Case-1: When switch is ON

When switch in ON the diode will be open circuited since the n side of diode is at higher voltage compared to p side which is shorted to ground through the switch. Hence the boost converter can be redrawn as follows

During this state the inductor charges and the inductor current increases. The current through the inductor is given as

$$I_L = (1/L) * \int V * dt \tag{Equation - 7}$$

Assume that prior to the opening of switch the inductor current is $I'_{L,off}$. Since the input voltage is constant

$$I_{L,off} = (1/L) * \int (V_{in}) * dt + I'_{L,off} \tag{Equation - 8}$$

Assume the switch is open for t_{on} seconds which is given by $D \cdot T_s$, where D is duty cycle and T_s is switching time period. The current through the inductor at the end of switch on state is given as

$$I_{L,on} = (1/L) * V_{in} * D * T_s + I'_{L,on} \quad \text{Equation - 9}$$

Hence $\Delta I_L = (1/L) * V_{in} * D * T_s$.

Case-2: When switch is OFF

When switch is OFF the diode will be short circuited and the boost converter circuit can be redrawn as follows

The inductor now discharges through the diode and RC combination. Assume that prior to the closing of switch the inductor current is $I''_{L,off}$. The current through the inductor is given as

$$I'''_{L,off} = -(1/L) * \int (V_{in} - V_{out}) * dt + I''_{L,off} \quad \text{Equation - 10}$$

Note the negative sign signifies that the inductor is discharging. Assume the switch is open for t_{off} seconds which is given by $(1-D) \cdot T_s$, where D is duty cycle and T_s is switching time period. The current through the inductor at the end of switch off state is given as

$$I''''_{L,off} = -(1/L) * (V_{in} - V_{out}) * (1-D) * T_s + I''_{L,off} \quad \text{Equation - 11}$$

In steady state condition as the current through the inductor does not change abruptly, the current at the end of switch on state and the current at the end of switch off state should be equal. Also, the currents at the start of switch off state should be equal to current at the end of switch on state. Hence

$$I''''_{L,off} = I_{L,on}, \text{ also } I''_{L,off} = I''_{L,off} \quad \text{Equation - 12}$$

Using the equations 9 and 11 we get

$$(1/L) * V_{in} * D * T_s = - (1/L) * (V_{in} - V_{out}) * (1-D) * T_s$$

$$V_{in} * D = - (V_{in} - V_{out}) * (1-D)$$

$$V_{in} * (D - 1 + D) = V_{out} * (1-D)$$

$$V_{out}/V_{in} = 1 / (1-D)$$

Since $D < 1$ $V_{out} > V_{in}$. Assuming no losses in the circuit and applying the law of conservation of energy

$$V_{out} * I_{out} = V_{in} * I_{in} \quad \text{Equation - 13}$$

This implies $I_{out}/I_{in} = (1-D)$, Thus $I_{out} < I_{in}$. As the duty cycle increases the output voltage increases and output current decreases. But due to parasitic elements in the lumped elements resistor, inductor, capacitor the step-up ratio V_{out}/V_{in} decreases at higher duty cycles and approaches zero at unit duty cycle.

2) Discontinuous conduction mode:

In which the current through inductor goes to zero i.e. inductor is completely discharged at the end of switching cycle.

The inductor in discontinuous mode drains all the current which it piled up in charging interval of same switching cycle. The current through the inductor is given as

$$I_L = (1/L) \int V_L * dt$$

$$= (1/L) * \text{area under the curve of voltage v/s time.}$$

$$V_{in} * D * T_s = -(V_{in} - V_o) * \delta * T_s \text{ (negative sign signifies that the inductor is discharging)}$$

$$V_{out}/V_{in} = (D + \delta) / \delta \quad \text{Equation - 14}$$

and the ratio of output to input current from law of conservation of energy is $I_{out}/I_{in} = \delta / (D + \delta)$.

3.8 OVERVIEW OF BUCK-BOOST CONVERTER

The buck boost converter is a DC to DC converter. The output voltage of the DC to DC converter is less than or greater than the input voltage. The output voltage of the magnitude depends on the duty cycle. These converters are also known as the step up and step down transformers and these names are coming from the analogous step up and step down transformer. The input voltages are step up/down to some level of more than or less than the input voltage. By using the low conversion energy, the input power is equal to the output power.

It is a type of DC to DC converter, and it has a magnitude of output voltage. It may be more or less than equal to the input voltage magnitude. The buck boost converter is equal to the fly back circuit and single inductor is used in the place of the transformer. There are two types of converters in the buck boost converter that are buck converter and the other one is boost converter. These converters can produce the range of output voltage than the input voltage. The following diagram shows the basic buck boost converter.

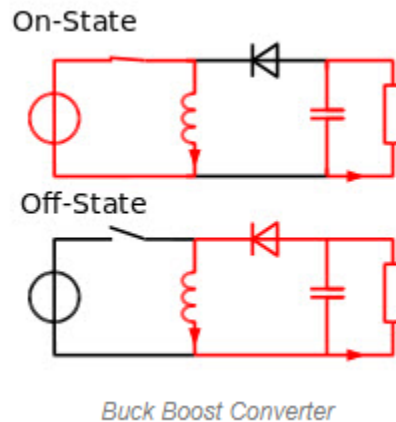


Figure 3. 4 Buck Boost converter

3.9 OPERATING PRICIPLE OF BUCK-BOOST CONVERTER

The working operation of the DC to DC converter is the inductor in the input resistance has the unexpected variation in the input current. If the switch is ON then the inductor feed the energy from the input and it stores the energy of magnetic energy. If the switch is closed it discharges the energy. The output circuit of the capacitor is assumed as high sufficient than the time constant of an RC circuit is high on the output stage. The huge time constant is compared with the switching period and make sure that the steady state is a constant output voltage $V_o(t) = V_o(\text{constant})$ and present at the load terminal.

3.10 OVERVIEW OF Cuk CONVERTER

Cuk converter is a type of DC/DC converter which has an output voltage magnitude that is either greater or less than the input voltage magnitude. It is a boost converter followed by a buck converter with a capacitor to couple the energy. Similar to the buck–boost converter Cuk converter is also inverting. It uses a capacitor as its main energy-storage component, unlike most other types of converters which use an inductor. The circuit of Cuk converter can be seen from Figure.

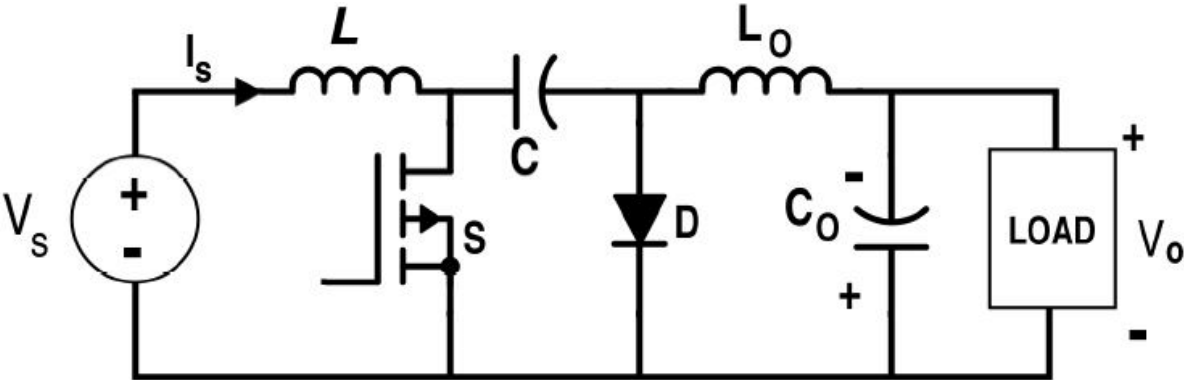


Figure 3. 5 Cuk converter

4 SYSTEM CONFIGURATION

4.1 CURRENT CONTROL BUCK CONVERTER BASED PV EMULATOR

Fig. 4.1 shows the system configuration for a PV emulator which comprises a buck type (step-down) dc-DC converter, sensors, conditioning circuits, controller a gate drive circuit. V_{in} represents a DC source of 100V.

Hysteresis (or bang-bang) control is used to provide controlled output current. The reference current for the hysteresis controller is derived using the PV model. The value of inductor L and filter capacitor C is 25mH and 2000 μ F, respectively.

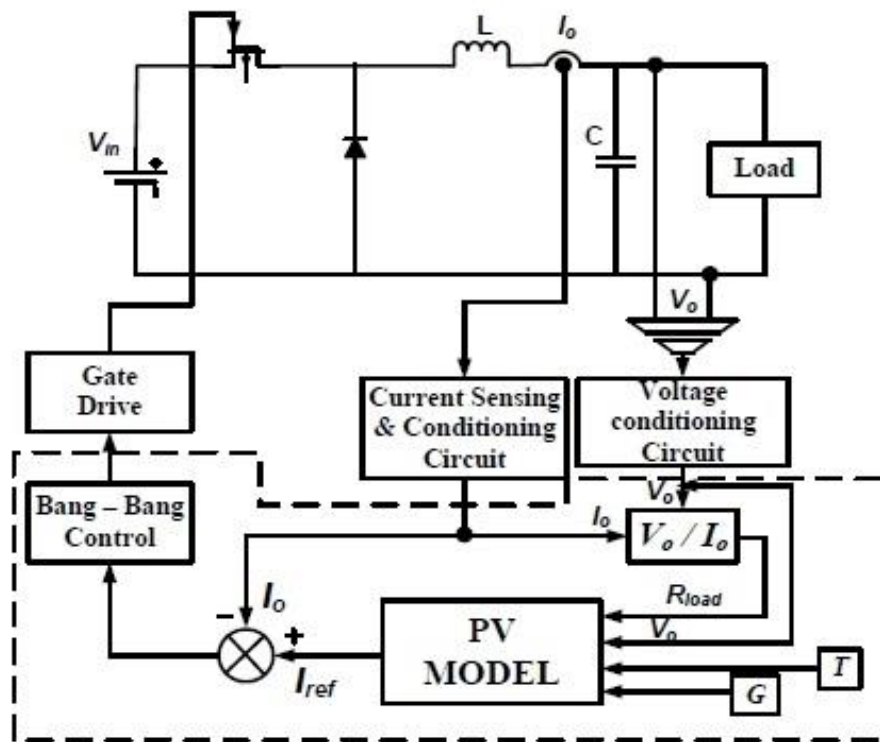


Figure 4. 1 System configuration of a PV emulator

Figure 8 depicts the system configuration for voltage controlled buck based converter. This topology differs from the above in the given manner. Unlike the current controlled buck converter topology where Bang-bang control is used to give a controlled current output I_o , Bang-bang control is used to provide controlled output voltage V_o .

The controller employs the PV model discussed in Section II. Using (1)-(8) and the parameters G, T, V_o and I_o , the controller computes the value of R_{pv} and R_{load} . R_{pv} is defined as the ratio of V_{pv} and I_{pv} .

Depending on the difference in the value of R_{pv} and R_{load} , the controller takes the corrective action to force the operating point where, difference in R_{load} and R_{pv} is zero or is negligible. The operating principle and the algorithm for controlling the dc-dc converter as the PV emulator, is discussed in the next section.

4.2 ALGORYTHERM FOR THE CONTROL OF CONVERTER

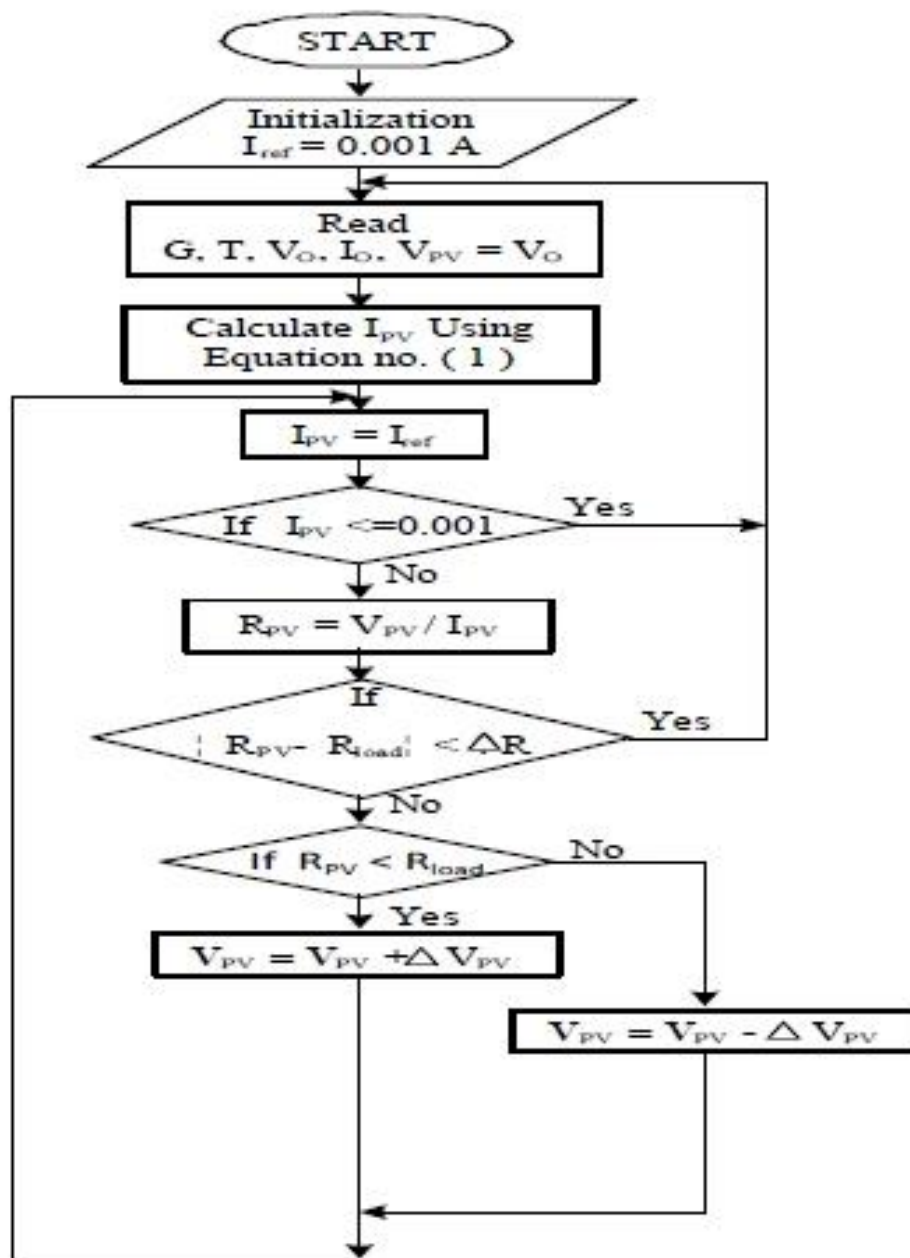


Figure 4. 2 System configuration of a PV emulator

Figure 9 shows the flowchart for the algorithm to control current controlled buck converter as PV emulator. It is initialized with passing of known values of some parameters ($T_1, T_2, V_{oc(T1)}, V_{oc(T2)}, I_{sc(T1)}, I_{sc(T2)}, n, k, q, G_{(nom)}$). Further the values of G and T are passed for which the performance of PV module is desired. To make the converter behave same as PV module the output voltage of the converter V_o should be same as V_{pv} generated by the PV module under given conditions I_{pv} is calculated using equation (1) and that value is used as reference current I_{ref} for controlling the output current of the converter.

R_{pv} (ratio of V_{pv} and I_{pv}) is compared with R_{load} obtained from V_o and I_o . Further the conditions are checked i.e if R_{pv} is less than R_{load} equation (1) is calculated using $V_{pv}=V_{pv}+\Delta V_{pv}$ and if R_{pv} is greater than R_{load} equation (1) is calculated using $V_{pv}=V_{pv}-\Delta V_{pv}$ and the new value of I_{pv} is stored as the reference value I_{ref} which is further fed to the Bang-Bang control. ΔR is the difference between R_{pv} and R_{load} which should be selected judiciously for the better performance of emulator.

4.3 OPERATING PRINCIPLE OF PV EMULATOR

Figure 9 depicts the operating principle of a system shown above. The operating principle remains same for both the topologies described above. It shows the V-I characteristics of a module to be emulated. It shows that as the load line R_{load} intersects the V-I characteristics of module at point c, the converter can act as an emulator if its steady-state output voltage and current are V_{pv3} and I_{pv3} respectively where $V_{pv3}/I_{pv3}=R_{pv3}=R_{load}$.

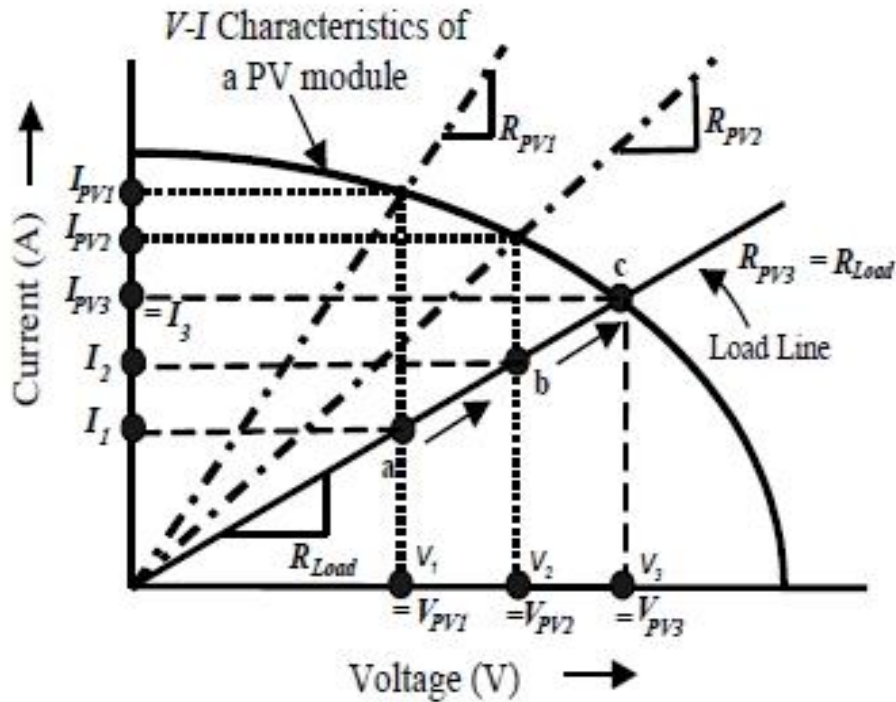


Figure 4. 3 Operating principle of PV emulator demonstrating the controlled shift of the operating point on the characteristics of a desired PV module

Let 'a' be the operating point. So, the converters output voltage is V_1 at current I_1 . The V-I characteristics of the module shows that an actual PV module can generate current I_{pv1} when operating at voltage $V_1 = V_{pv1}$.

The corresponding load resistance is R_{pv1} which is less than R_{load} . Thus, to force the converter to act as an emulator R_{pv} should be increased till it equals R_{load} . This can be achieved by increasing V_{pv} and decreasing I_{pv} .

As the same way, if the corresponding load resistance is more than R_{load} . Then, controller try to force the converter to act as an emulator R_{pv} should be decreased till it reaches R_{load} by decreasing V_{pv} and increasing I_{pv} .

5 SIMULATION RESULTS

5.1 THEORY

Performance of PV emulator is tested with two different topologies as explained in the earlier section for linear and non-linear load and the results are compared. A variable resistor is considered for a linear load, while DC-DC converter feeding a resistive load is considered as a non-linear load. The simulation results presented in this section are carried out in MATLAB/Simulink. For the simulation study, the Solarex MSX60 60W PV module is considered. The specifications of the PV module are given in the Table 1 below.

Table 2 MODULE SPECIFICATION

PARAMETER	VARIABLE	VALUE
Maximum Power	P_m	60 W
Voltage at P_m	V_m	17.1V
Current at P_m	I_m	3.5A
Short circuit current	I_{oc}	3.8A
Open circuit voltage	V_{oc}	21.1V
Insolation (at no shading)	G	1000 W/m ²
Temperature	T	25 °C

5.2 SIMULATION CIRCUITS AND RESULTS

Case – 1 Single Resistor linear load:

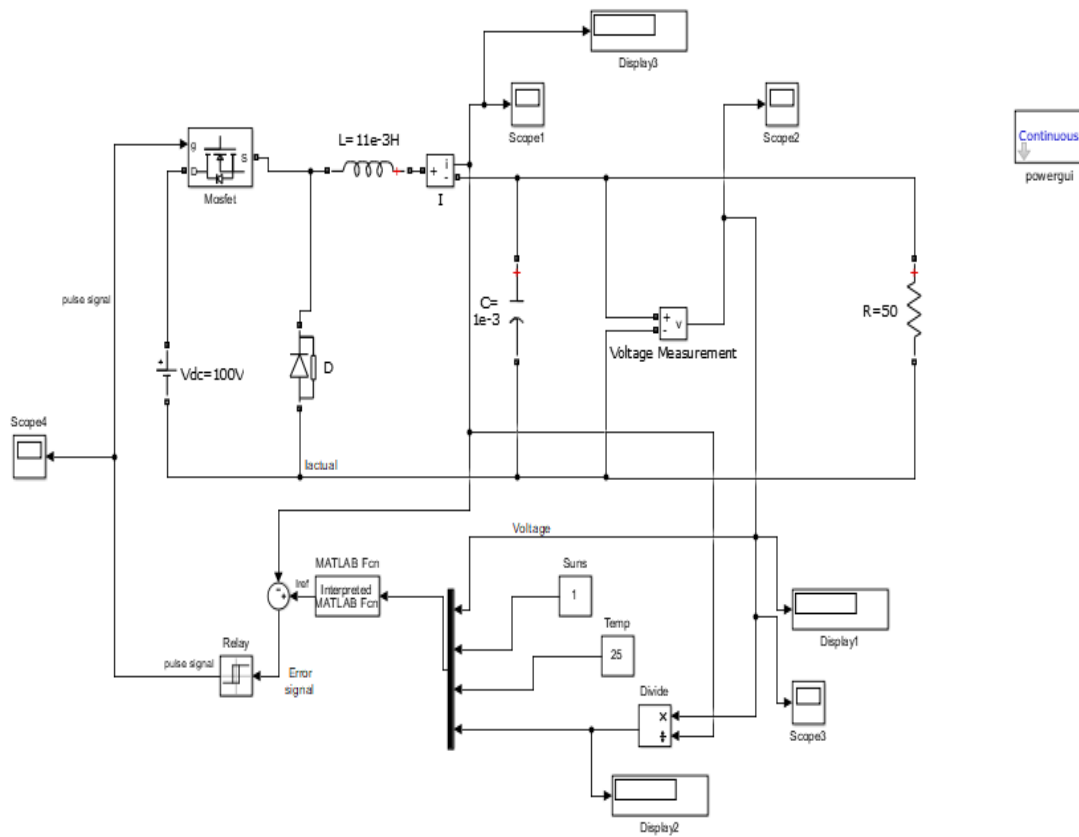
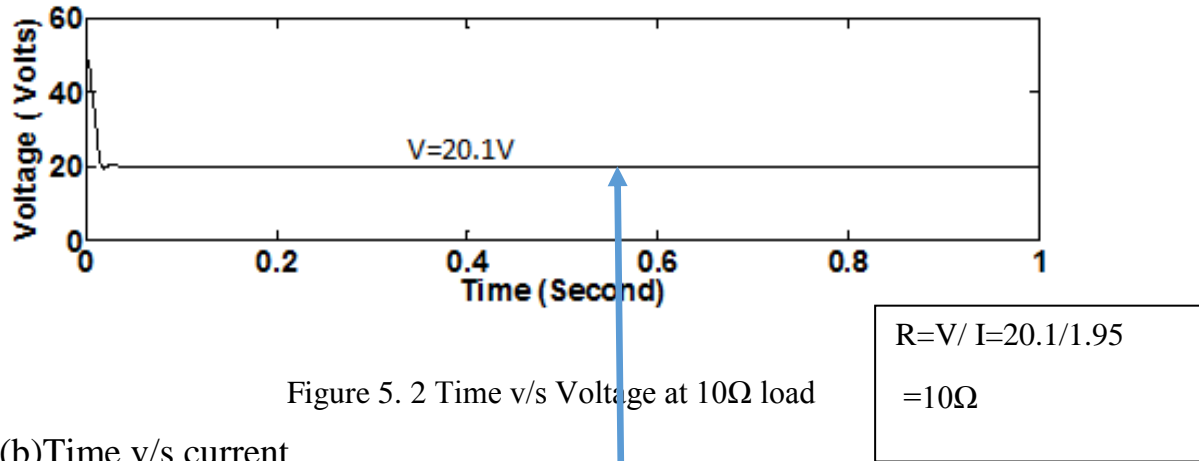


Figure 5. 1 Current controlled buck converter topology for single Resistor linear load

Waveform:

(a) Time v/s voltage



(b) Time v/s current

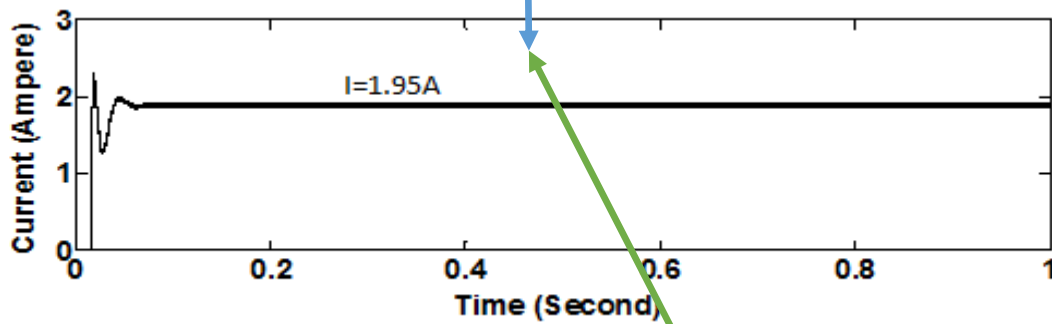


Figure 5.3 Time v/s Current at 10Ω load

(c) Real PV characteristics:

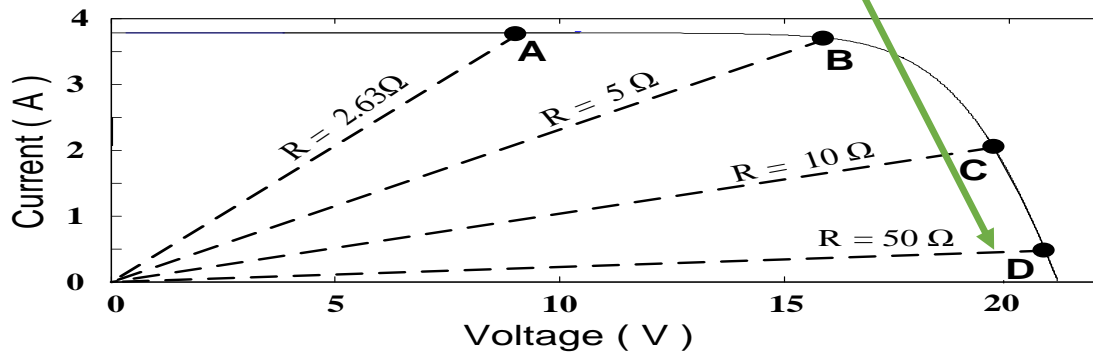


Figure 5.4 Actual PV characteristics

Case – 2 Multi Resistor linear load:

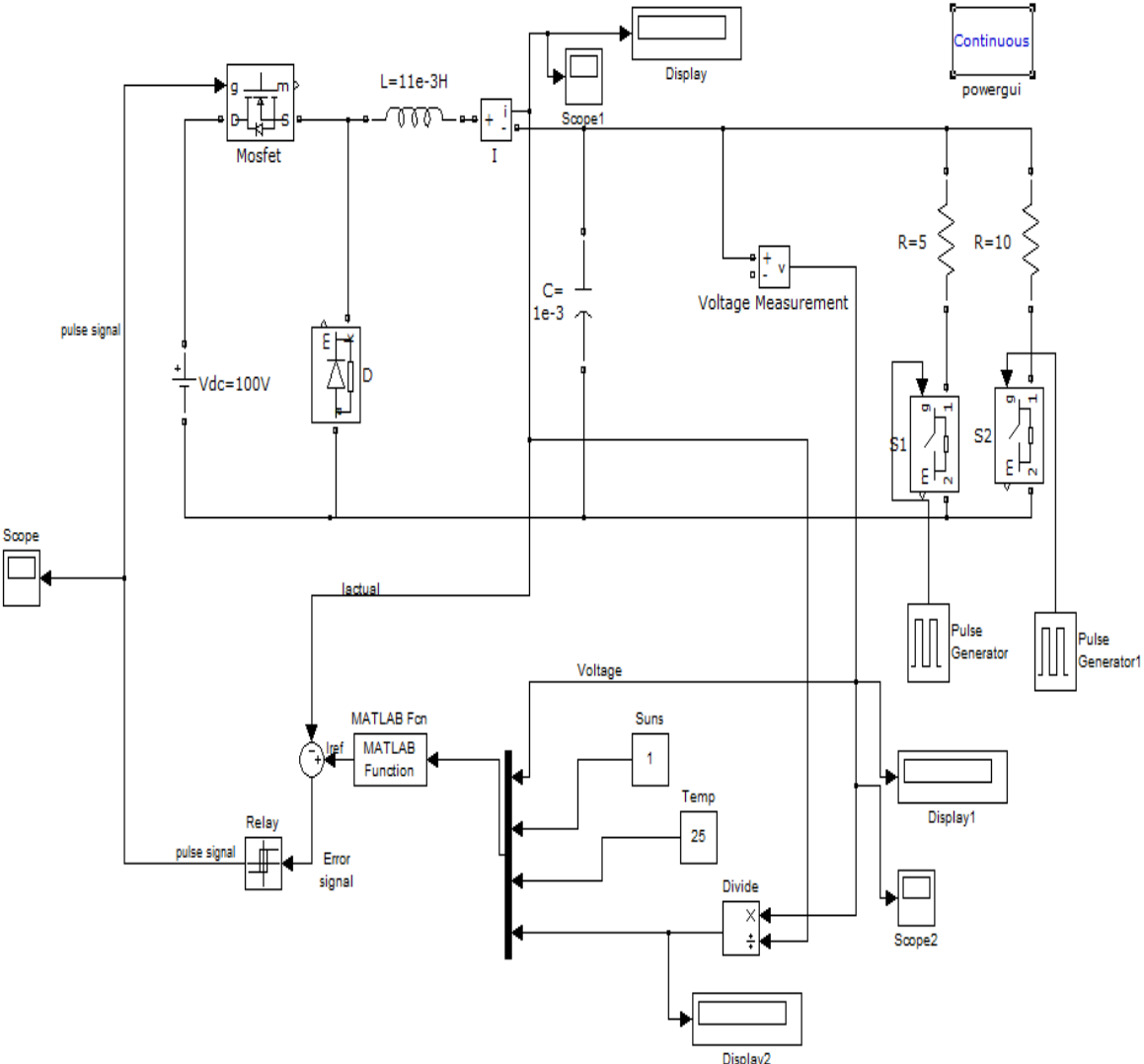
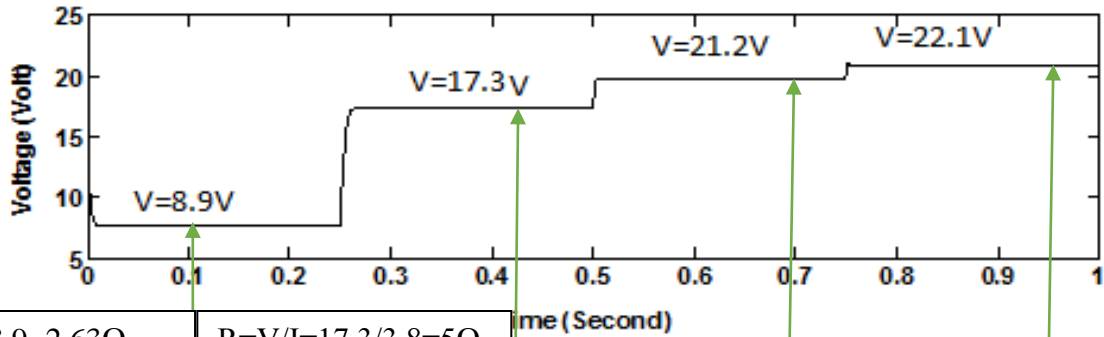


Figure 5. 5 Current controlled buck converter - for multi Resistor linear load

Waveform:

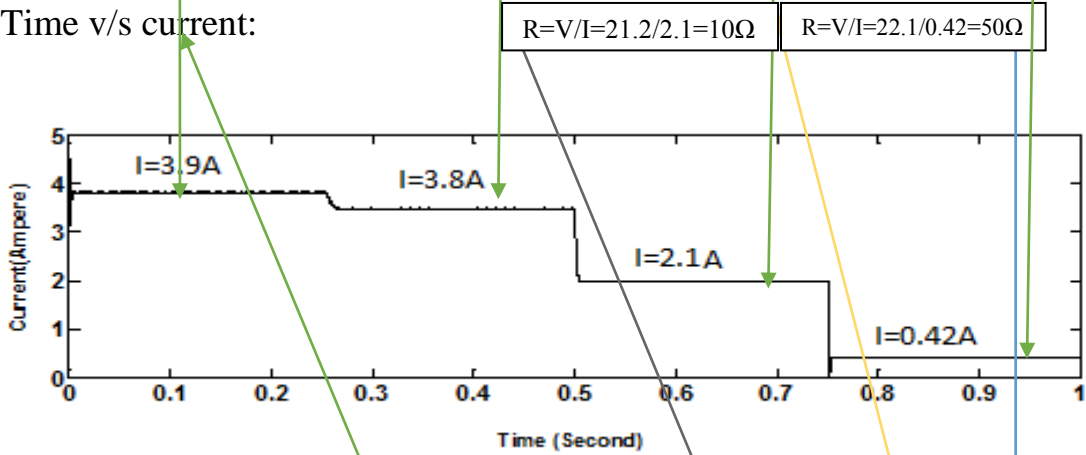
(a) Time v/s voltage:



$R=V/I=8.9/3.9=2.63\Omega$	$R=V/I=17.3/3.8=5\Omega$
----------------------------	--------------------------

Figure 5. 6 Time v/s Voltage at multi resistor load

(a) Time v/s current:



$R=V/I=21.2/2.1=10\Omega$	$R=V/I=22.1/0.42=50\Omega$
---------------------------	----------------------------

Figure 5. 7 Time v/s Current at multi resistor load

(c) Real PV characteristic:

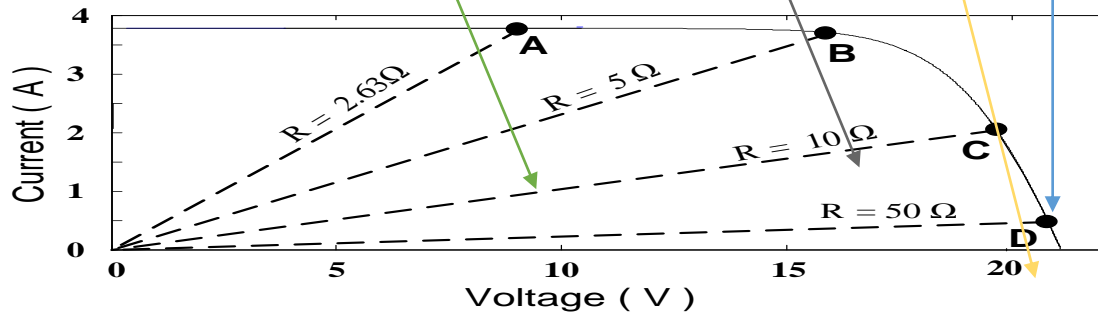


Figure 5. 8 Actual PV characteristics

Case – 3 Nonlinear loads:

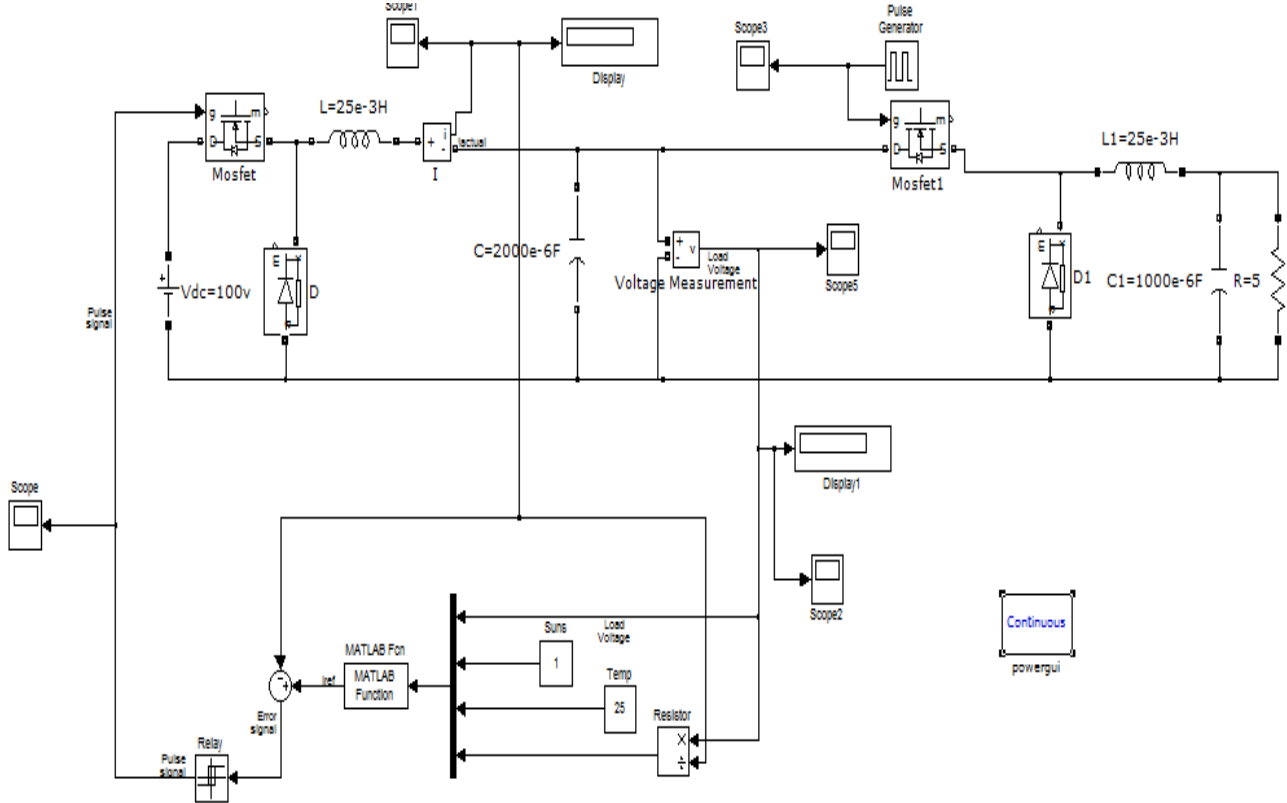


Figure 5. 9 Current controlled buck converter - for nonlinear load

WAVEFORM:

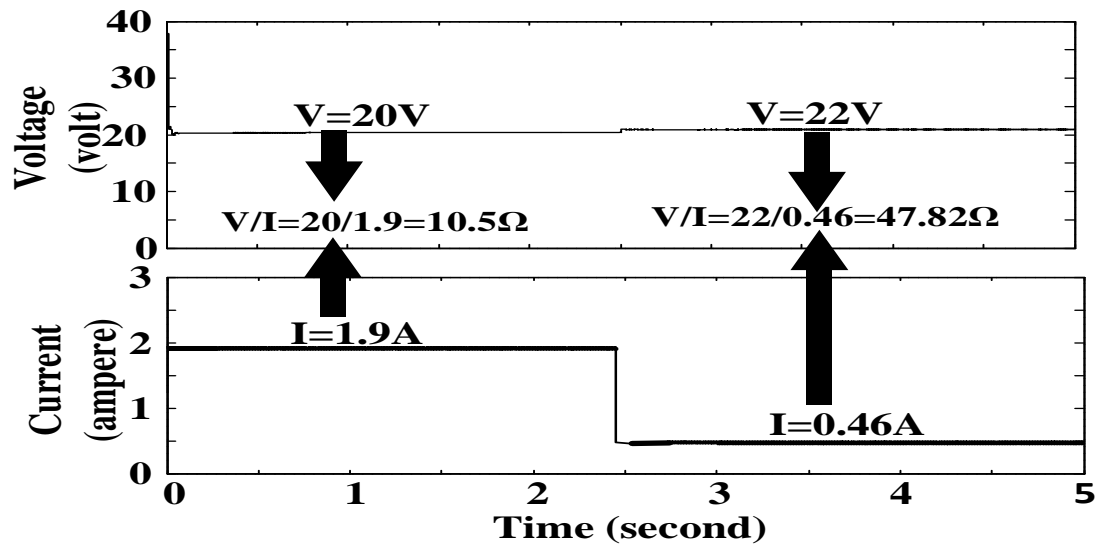


Figure 5. 10 Time V/S Voltage and Current for nonlinear load

5.3 M-file function for PV cell modelling

Function Ia = PVem(u)

Va=u(1);

Suns=u(2);

TaC=u(3);

Rload=u(4);

% current given voltage, illumination and temperature

% Ia = msx60(Va,G,T) = array voltage

% Ia,Va = array current,voltage

% G = num of Suns (1 Sun = 1000 W/m²)

% T = Temp in Deg C

k = 1.38e-23; % Boltzman's const

q = 1.60e-19; % charge on an electron

% enter the following constants here, and the model will be

% calculated based on these. for 1000W/m²

A = 1.2; % "diode quality" factor, =2 for crystalline, <2 for amorphous

Vg = 1.12; % band gap voltage, 1.12eV for xtal Si, ~1.75 for amorphous Si.

Ns = 36; % number of series connected cells (diodes)

T1 = 273 + 25;

Voc_T1 = 21.06 /Ns; % open cct voltage per cell at temperature T1

Isc_T1 = 3.80; % short cct current per cell at temp T1

T2 = 273 + 75;

Voc_T2 = 17.05 /Ns; % open cct voltage per cell at temperature T2

Isc_T2 = 3.92; % short cct current per cell at temp T2

TaK = 273 + TaC; % array working temp

TrK = 273 + 25; % reference temp

% when Va = 0, light generated current Iph_T1 = array short cct current

% constant "a" can be determined from Isc vs T

Iph_T1 = Isc_T1 * Suns;

a = (Isc_T2 - Isc_T1)/Isc_T1 * 1/(T2 - T1);

Iph = Iph_T1 * (1 + a*(TaK - T1));

Vt_T1 = k * T1 / q; % = A * kT/q

```

Ir_T1 = Isc_T1 / (exp(Voc_T1/(A*Vt_T1))-1);
Ir_T2 = Isc_T2 / (exp(Voc_T2/(A*Vt_T1))-1);
b = Vg * q/(A*k);
Ir = Ir_T1 * (TaK/T1).^(3/A) .* exp(-b.*(1./TaK - 1/T1));
X2v = Ir_T1/(A*Vt_T1) * exp(Voc_T1/(A*Vt_T1));
dVdI_Voc = - 1.15/Ns / 2; % dV/dI at Voc per cell –
% from manufacturers graph
Rs = - dVdI_Voc - 1/X2v; % series resistance per cell
% Ia = 0:0.01:Iph;
Vt_Ta = A * 1.38e-23 * TaK / 1.60e-19; % = A * kT/q

% Ia1 = Iph - Ir.*( exp((Vc+Ia.*Rs)./Vt_Ta) -1);
% solve for Ia: f(Ia) = Iph - Ia - Ir.*( exp((Vc+Ia.*Rs)./Vt_Ta) -1) = 0;
% Newton's method: Ia2 = Ia1 - f(Ia1)/f'(Ia1)

Vc = Va/Ns;
Ia = zeros(size(Vc));
% Iav = Ia;
for i=0:1:250;
for j=1:5;
Ia = Ia - ...
(Iph - Ia - Ir.*( exp((Vc+Ia.*Rs)./Vt_Ta) -1))...
./ (-1 - (Ir.*( exp((Vc+Ia.*Rs)./Vt_Ta) -1)).*Rs./Vt_Ta);
% Iav = [Iav;Ia]; % to observe convergence for debugging.
end

%Emulator
if Ia<=0.001
break;

```

```
else R=Va/Ia;
end
if R==Rload
    break;
elseif R<=Rload;
    Va=Va+0.001;
else
    Va=Va-0.001;
end
end
```

6 POSSIBLE HARDWARE MODEL

In this chapter we can see some information regarding hardware implementation of our simulations, unfortunately I did not end up with hardware model, but collected data with the help of my bachelor studies, which was mostly on power electronics, which can give us ideas how it can be done. This chapter presents the hardware configuration of PV array emulator based on Buck converter topology. We can design power circuit, gate driver circuit and microcontroller STM32F407 (32 bit), which form the main blocks of Buck converter-based PV emulator, and how we can do that is detailed in this chapter.

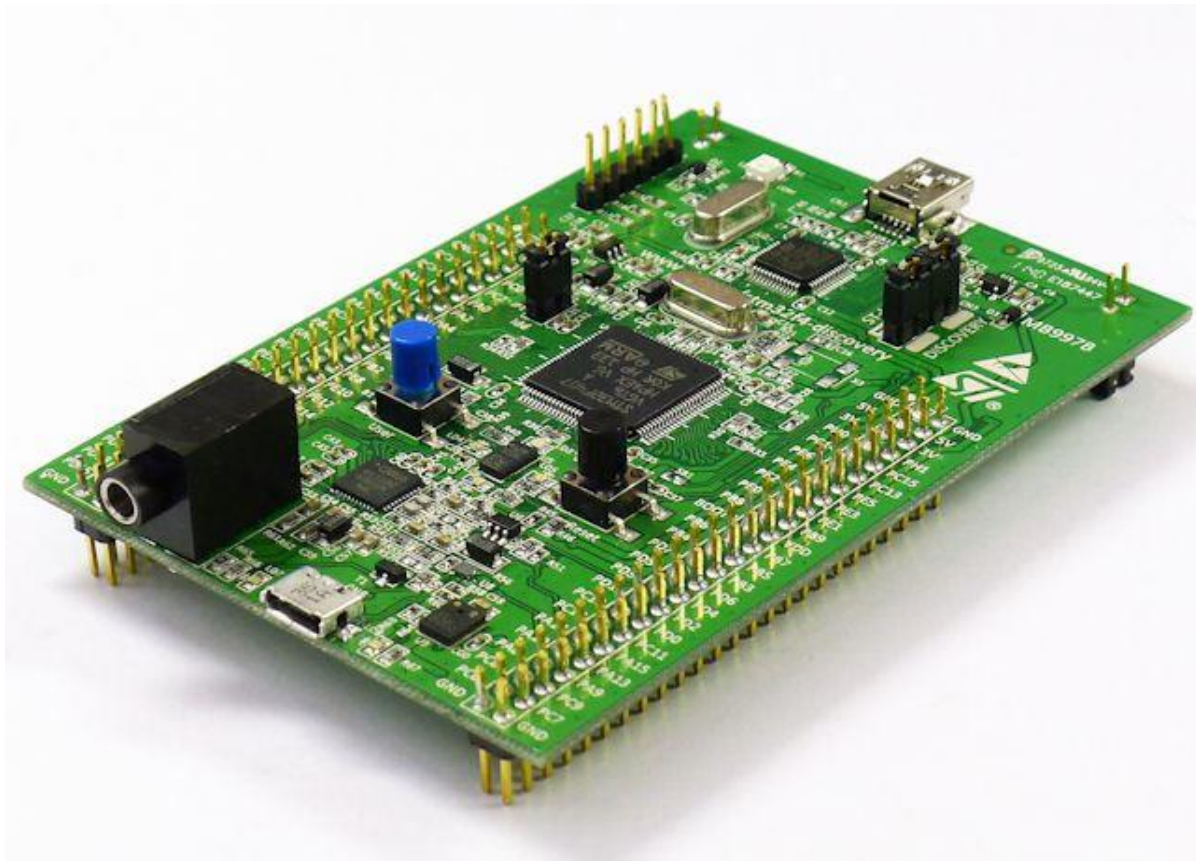


Figure 6. 1 STM32f407 Microcontroller

6.1 DATA FOR POWER CIRCUIT

230-70 V transformer can be used to convert the 230 V AC to 70 V AC. Using the 1-phase full bridge rectifier 70V AC can be converted into DC, which is filtered to obtain a constant DC of 100V using 1000uF capacitor. The filtered DC voltage is then applied as an input to Buck converter. The other alternative to decrease the size of the capacitor and to still obtain constant DC voltage with little ripple is to obtain the DC from 3-phase supply using 3-phase bridge rectifier. This is the list for specifications of the different components which can be used for Buck converter circuit.

- Inductors $L_1 = 11\text{mH}$
- Capacitors $C_5 = C_6 = 1000\mu\text{F}$
- IGBT can be used as a power switch
- UF5408 can be used as power diode
- Variable load of $0-50\Omega$ is obtained using a rheostat of $0-50\Omega$ 5 Amp.

The design of inductor L_1 is based on the following mathematical analysis:

➤ Step 1. During ON time voltage across inductor is given by-

$$V = L \frac{di}{dt} \quad \text{Equation 15}$$

$$V_{in} = V_{sw} - V_o = L \frac{\Delta I}{D/f} \quad \text{Equation 16}$$

Where V_{in} = applied DC voltage

V_{sw} = voltage across switch when it is on

D = duty cycle

f = switching frequency

I_o = output current

r = ripple ratio

➤ Step 2

$$\Delta I = r = \frac{(V_{in} - V_{sw} - V_o)}{L \cdot I_o} * \frac{D}{f} \quad \text{Equation 17}$$

$$D = \frac{V_o + V_d}{(V_{in} - V_{sw} + V_d)} \quad \text{Equation 18}$$

Where V_o = output voltage

V_d = diode voltage

➤ Step 3

$$r = \frac{(V_{in} - V_{sw} - V_o)}{(V_{in} - V_{sw} + V_d)} * \frac{V_o * V_d}{(L * f * I_o)} \quad \text{Equation 19}$$

$$L = \frac{(V_{in} - V_{sw} - V_o)}{(V_{in} - V_{sw} + V_d)} * \frac{V_o * V_d}{(r * f * I_o)} \quad \text{Equation 20}$$

➤ Step 4

$$r = \frac{I_l}{I_{out}} \quad \text{Equation 10}$$

6.2 GATE DRIVER CURCUIT (we can use TLP250)

We also need one circuit which can provide isolation between power circuit and the control circuit, for which, 12V DC required to control circuit will be obtained through another step-down transformer of 230/12V and a 1-phase bridge rectifier. Regulator IC can be used to regulate the DC voltage at a level of 12 V for driver TLP 250. The PWM pulses required to control the power switch of the Buck converter which will supplied from this driver IC TLP 250. MOSFET can be use, because it can help driver IC to not only provide the required driving capability but also isolation. We can also find information about output voltage and input current of the Buck converter, which are essential for controlling the converter as PV emulator and after that we can passed that to the controller STM32F407 to determine load resistance.

6.3 CONTROLLER CIRCUIT

For which we can use controller STM32F407, control circuit will work as brain in PV emulator. It will determine load resistance which can help us to sense output voltage and input current. By this we can obtain resistance of PV module, depending on the difference of load resistance and resistance of PV module, we can calculate the desired current I_{ref} . The reference current I_{ref} , is then compared with the input current and the input current can be controlled around I_{ref} using the principle of hysteresis.

The final script how control circuit works, which was describe in chapter 4, with algorithm.

CONCLUSION

PV emulator based on a current controlled buck converter with simulation has been presented. PV emulator was connected with linear and non-linear loads and its performance was evaluated and compared with a real PV source (with linear loads). The PV emulators mainly use to recreate V-I characteristics as real PV module. Simulation results show that the performance of emulator adheres closely to that of a real PV source. We can observe few ripples in voltage and current using this topology and it can be mitigated using proper filtration techniques. After using assumed data (chapter 6) we can make small working model of buck converter-based PV emulator, we can achieve result same as PV emulator, which is a moto of our thesis.

FUTURE SCOPE

The report has currently focused only on the current controlled for controlling buck based PV emulators. But the buck converter can also be designed for the voltage control. Similarly, these converters can be evaluated with other converters like Boost, Cuk etc. and can be compared with the results obtained with Buck based controlled schemes. It would be of interest to design a PV emulator for higher ratings. Another area which can be targeted is to emulate the PV array characteristics for non-uniform conditions like mismatch in the series connected modules, array receiving partial shading, different type of series connected modules in the array etc.

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