DISSERTATION ON

Effect of Loading on the Performance of Standalone Solar Photovoltaic Systems

Master of Technology:

Renewable Energy Technology

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Candidate's Declaration

I hereby declare that the thesis entitled **"Effect of Loading on the Performance of Standalone Solar Photovoltaic Systems"** being submitted by me is an authentic work carried out under the supervision of **Dr. J.P. Kesari, Associate Professor,** Mechanical Engineering Department, Delhi Technological University, Delhi.

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CERTIFICATE

It is certified that Sushant Chopra, Roll No. 2K13/RET/13, student of M.Tech. Renewable Energy Technology, Delhi Technological University, has submitted the dissertation titled "**Effect of Loading on the Performance of Standalone Solar Photovoltaic Systems**" under my guidance towards the partial fulfillment of the requirements for the award of the degree of Master of Technology.

He has studied the effect of resistance loading on the performance and efficiency of standalone photovoltaic systems using MATLAB. His work is found to be satisfactory during the course of the project. His enthusiasm, attitude, towards the project is appreciated.

I wish him success in all his endeavors.

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ACKNOWLEDGEMENT

Generally, individuals set aims, but more often than not, their conquest are by the efforts of not just one but many determined people. This complete project could be accomplished because of the contribution of a number of people. I take it as a privilege to appreciate and acknowledge the efforts of all those who have, directly or indirectly, helped me achieving my aim.

I take great pride in expressing my unfeigned appreciation and gratitude to my guide "Dr. J. P. Kesari", Founder of M.Tech Renewable Energy Technology, for his invaluable inspiration, guidance and continuous encouragement throughout this project work.

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SUSHANT CHOPRA

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Important Notation

1. PV Cell : Photovoltaic Cell

2. MPPT : Maximum Power Point Tracking

3. E : Energy of ejected or freed electrons

4. ν : Frequency

5. h : Plank’s Constant

6. ϕ : Threshold energy

7. Ios : Reverse saturation current of the cell

8. V & I : Output voltage and current

9. q : Charge of an electron i.e $1.6*10^{-19}$C

10. T : Cell temperature in Celsius

11. k : Boltzmann's constant, $1.38 * 10^{-23}$J/K

12. Iscr : Short circuit current at the temperature of 25 degree Celsius

13. Ki : Short circuit current temperature coefficient at Iscr

14. A : Ideality factor

15. Ilg : Light-generated current

16. Ior : Cell saturation current Tr

17. Ego : Band gap value for silicon

18. Tr : Reference temperature

19. Rs : Series resistance

20. Rsh : Shunt resistance

21. W : Watt

22. AC : Alternating Current

23. DC : Direct Current

24. P_i : Input Power

25. P_o : Output Power

26. V_i : Input Voltage

27. V_o : Output Voltage

28. J : Joule

29. L : Inductance

30. C : Capacitance

31. R : Resistance

32. JNNSM : Jawaharlal Nehru National Solar Mission

33. CERC : Central Electricity Regulatory Commission

33. GDP : Gross Domestic Product

34. CO_2 : Carbon Dioxide

35. KWh : Kilowatt hour

36. NVVN : NTPC Vidyut Vyapar Nigam

37. CCEA : Cabinet Committee of Cabinet Affairs

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ABSTRACT

The present master's thesis seeks to develop a better understanding of the conventional solar photovoltaic systems and simultaneously using that understanding to improve the performance and efficiency of the system. The present Photovoltaic systems consist of solar PV modules/arrays and a power electronic converter stage to step up or step down the DC voltage of the PV array. The power electronic converter is controlled by a Maximum Power Point Tracking controller which ensures that the system operates at the maximum power point and delivers maximum power at all times. The MPPT is a well researched and a well established technology and a rich literature exists of the various MPPT techniques. But there are limitations to MPPT which prevent the system to transfer the maximum power from the input to the output stage of the power electronic converter. The thesis focuses on the effect of output resistance of the converter stage (which in this case is a buck converter) on the power which has been tracked by the MPPT and is being transferred to the output of the converter. The output resistance is an integral part of the converter stage and the thesis aims to explore the effects on the response and the limits that the resistance puts on the power transfer from the input to the output stage covering the limitations of the MPPT technique. Accurate mathematical models are developed in order to explain the behavior of the buck converter connected to the PV system and using them to deduce the best practices in order to improve the efficiency and dynamics of the system. Finally the ideas developed are applied to the practical application of battery charging which is commonly used in modern standalone PV systems. The ideas developed in this thesis are generic in nature and can be extended to grid connected PV systems also (or in any renewable energy system for that matter) to control the power which is to be injected in the grid at any point in time.

Chapter1

INTRODUCTION

One of the chief concerns in the 21st century in the field of power is the everyday growing power demands but the shortage of ample resources to meet the growing power demand while using the conventional sources of energy. The demand for harnessing of alternative energy to be utilized besides the conventional systems has been mounting lately to keep up with the tremendously rising energy demand. Renewable sources like solar energy and wind energy are the main sources of energy which are being utilized in order to have sustainable growth. The unremitting use of fossil fuels has caused the fossil fuel deposits around the world to be reduced to a large extent and has also drastically affected the environment by polluting it and hence depleting the biosphere and resulting in a cumulative effect which is leading to global warming.

The abundant availability of solar energy and its accompanying technologies have made it possible to gather it and utilize it properly. Solar energy can be obtained from a standalone generating unit i.e. the generator supplies the electrical energy to a remote load or is stored in batteries or it can be connected to the local grid, depending on the accessibility of a nearby grid. Thus it can be effectively used to power the even the remotest rural areas of the country where there is a limited or no availability of the grid. The feature of portability is another advantage of using solar energy wherever whenever necessary.

In order to deal with the global energy crisis, one has to build up efficient systems and technologies to extract the power from the incoming solar radiation. The apparatus used in power conversion have become compact in their dimensions in the past few years. The progress in the field of power electronics and material sciences have significantly helped the scientists and engineers to come up with very compact but powerful systems to hold out the very high power demand. But these systems have a disadvantage of increased power density. The use of multi-input converter units that can efficiently handle the voltage fluctuations has been trending lately. But due to the low efficiency and high production cost of these systems, presently it is difficult to make them commercial as they can barely participate in the competitive markets as a main source of power generation.

1.1 Energy Scenario in India

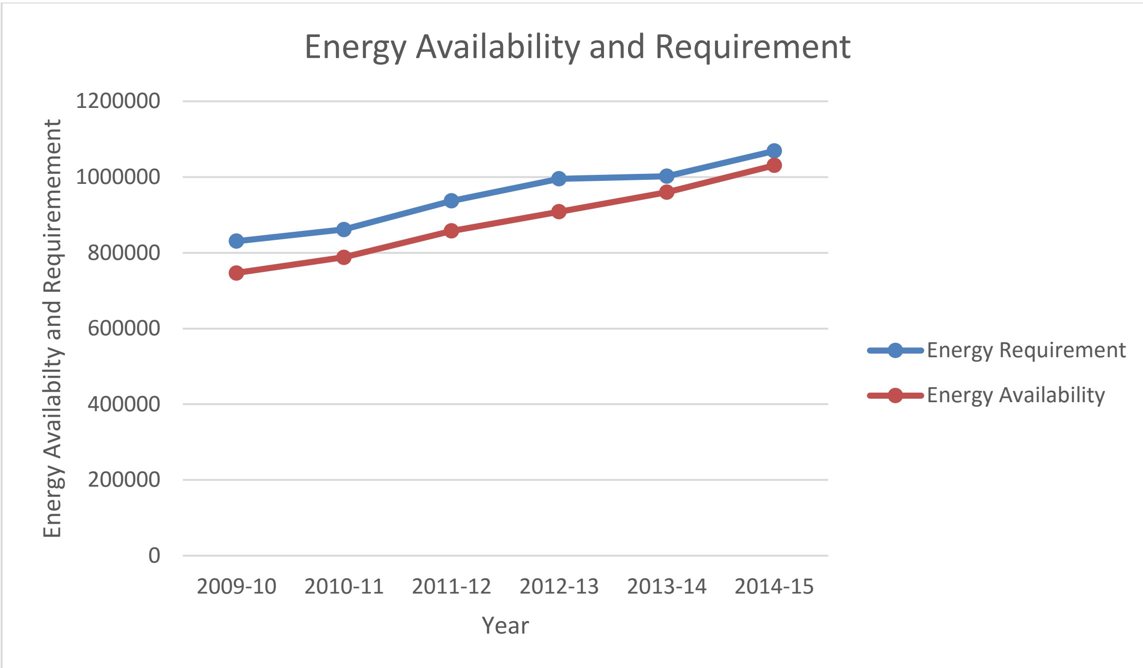
India is a nation with more than 1.2 billion people accounting for greater than 17% of world's population. It is the 7th largest country in the world covering the total land area of about 3,287,263 sq kilometers. India extends to about 3214 km from north to south and 2993 km from east to west. It has a border touching land of about of 15,200 km in length and a shoreline of 7,517 km. The country has about 28 states and 7 union territories and it faces an uphill test in providing enough energy to its residents at a realistic cost. India's GDP crossed the US $ 1 trillion mark in 2007-2008 which means that the yearly expansion speed of GDP during the period is at a surprising 18 percent. Therefore the energy challenge is of primary meaning. During the previous 6 decades, India's energy use has amplified to almost about 16 times and the installed electricity capacity has amplified close to 84 times. In 2008, India finished as the fifth highest energy consuming country in the world.

However, India as a large nation suffers from noteworthy energy paucity and enveloping electricity shortage. In current years, India's energy use has been growing at a rapid rate due to population increase and economic expansion, although the base rate may be fairly small. For an economy which is projected to grow at a rate of 8-9% per annum, swift urbanization & rapidly progressing standards of living for the millions of households of India, the demand is extremely prone to grow notably. According to the estimates made through the Integrated Energy Policy Report which was presented by the Planning Commission of India, 2006 which was that if the nation is to develop on the path of this persistent GDP growth rate during the coming 25 years, it would imply an increase of 4 times of its energy needs over the 2003-04 levels along with a 6 times raise in the want of electricity and again a 4 times increase in the requirement of crude oil. Keeping in view the challenge of supply, there are practical apprehensions that severe scarcity of energy may occur. The table given below gives the elaborate stats which present the picture of electricity sector in India over the years. The table and the graphs given below clearly show the deficit power which has to be met by us in the coming years which is possible only with the help of renewable energy, especially solar energy.

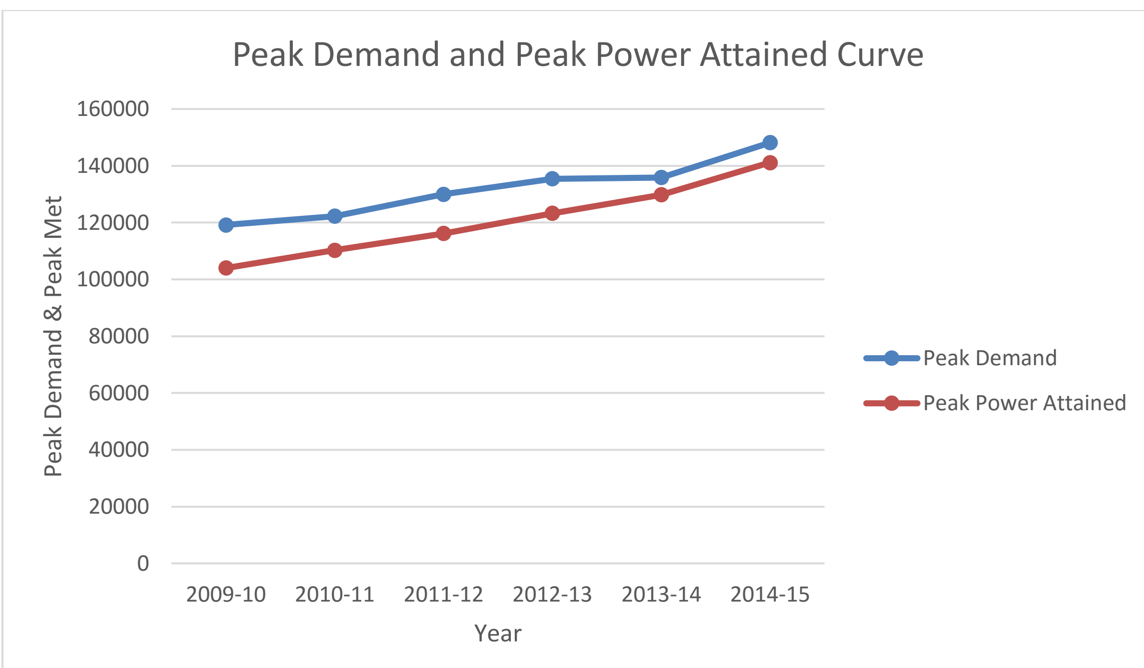
The table below shows the power demand and supply position in the country during 2009-10 to 2015-16 :

	Energy (MU – Million Units)				**Peak (MW – Mega Watts)**			
Year	**Requirement**	**Availability**	**Surplus(+)/Deficits(-)**		**Peak Demand**	**Peak Met**	**Surplus(+) / Deficits(-)**	
	(MU)	**(MU)**	**(MU)**	**(%)**	**(MW)**	**(MW)**	**(MW)**	**(%)**
2009-10	8,30,594	7,46,644	-83,950	-10.1	1,19,166	1,04,009	-15,157	-12.7
2010-11	8,61,591	7,88,355	-73,236	-8.5	1,22,287	1,10,256	-12,031	-9.8
2011-12	9,37,199	8,57,886	-79,313	-8.5	1,30,006	1,16,191	-13,815	-10.6
2012-13	9,95,557	9,08,652	-86,905	-8.7	1,35,453	1,23,294	-12,159	-9.0
2013-14	10,02,257	9,59,829	-42,428	-4.2	1,35,918	1,29,815	-6,103	-4.5
2014-15	10,68,943	10,30,785	-38,138	-3.6	1,48,166	1,41,160	-7,006	-4.7
2015-16	85,786	83,862	-1924	-2.2	1,40,212	1,36,658	-3554	-2.5

Table: Power supply position in India (Reference: website, Ministry of Power, Government of India) http://powermin.nic.in/power-sector-glance-all-india



Graph: Energy Availability and Requirement

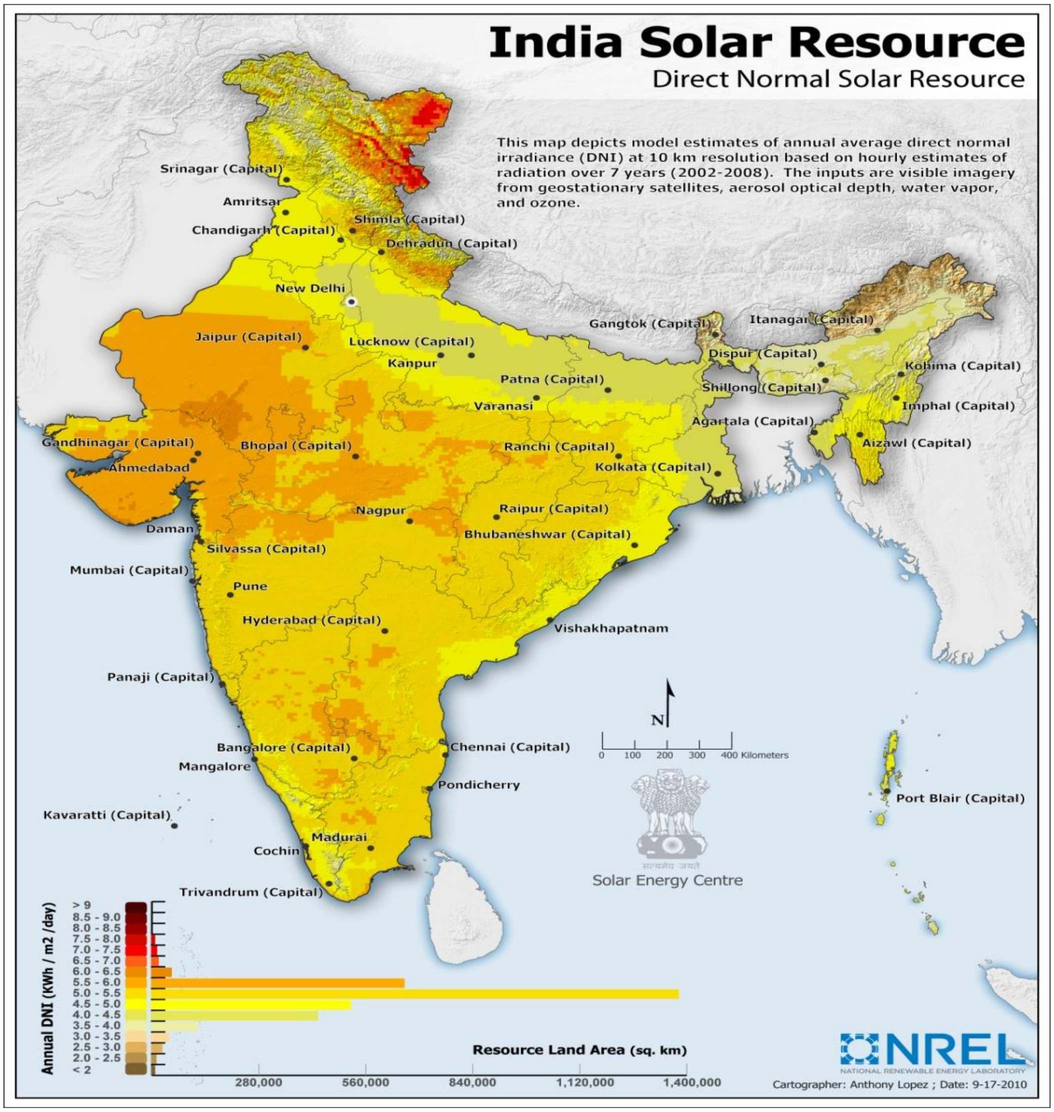


Graph: Peak Demand and Peak met

1.2 Solar Energy: The need of hour

The greenhouse emissions constitute about 38% of the total CO_2 emissions as a result of the electricity sector in India. This share of emissions is extremely probable to rise considerably in future as the per capita electricity expenditure levels drift towards those of the developed countries given India's low per capita electricity penetration. At the same time, attaining profound carbon emission slash in the power sector along with meeting the soaring electricity demand will surely prove challenging. To arrive at affirmed short and long-term electricity generation objectives, the Indian government has passed policies pushing the solar energy sector. Encouraging policies also strengthen the other renewable energy options. All the renewable energy sources jointly have the potential to decrease the Indian carbon emissions by 15% to 30% through the year 2050.

Amongst the various renewable energy resources known till date, India is bestowed with a very large solar energy potential. The solar map of India given below clearly displays that almost all parts of the country are blessed with superior quantity of sunshine throughout the year. There are close to 300 clear sunny days in a year in nearly all parts of the country. The standard solar irradiation incident over India fluctuates between about 4 kWh/day to 7 kWh/day. The solar radiation received over the entire Indian land region is forecasted to be about 5,000 trillion kWh per year. In the year 2008, in the month of June a ‘National Action Plan on Climate Change’ was announced, which proposed 8 chief national missions with 1 mission specifically dedicated to solar energy. This undertaking predicts a key step in the utilization of solar energy for power generation and for other important purposes such as heating and cooling of buildings. The ‘Jawaharlal Nehru National Solar Mission’ was launched by the Prime Minister of India in the month of January in the year 2010, with a target of achieving 20,000 MW grid connected solar power (based on solar photovoltaic (SPV) and solar thermal technologies), 2000 MW of standalone capacity including a target of 20 million solar lighting systems and a astounding 20 million sq.m. Area dedicated to solar thermal collectors by the year 2022. The mission and the targets which were set were planned to be implemented in 3 phases. The first phase was planned of a 3 year period (up to March, 2013), the 2nd phase was planned up to March 2017 and the 3rd phase would be continued until March, 2022. The target of 1,100 MW grid connected solar PV systems which include 100 MW of solar roof top photovoltaic systems and little solar PV installations and 200 MW capacity corresponding off-grid or standalone solar applications and solar collector area of 7 million sq. m for phase-I was to be set up. Novel architectures have been designed for the 1000 MW projects. These will be undertaken through PSUs such as NTPC Vidyut Vyapar Nigam (NVVN). NVVN would be trading the solar power to state utilities past normalizing the solar power with the corresponding capacity of thermal power. CERC (Central Electricity Regulatory Commission) has announced tariffs for the acquisition of solar power by NVVN. The tariff for PV for the year 2011 was Rs.17.91 per unit and Rs. 15.31 per unit for solar thermal power. The primary mission is to help arrive at solar power grid parity by 2022 and assist setting up of native solar power equipments manufacturing capacities.



Map: The Solar Map of India (Reference: http://www.nrel.gov/international/ra_india.html)

1.3 Solar Energy Policy in India

The solar market in India is rising at a rapid rate. The market recently surpassed 4 gigawatts (GW) of installed solar energy capacity and is drifting towards becoming one of the largest global solar markets. In order to reach the solar market's potential and bind investor interest, the government is elevating policy support. Augmented solar capacity, muscular policies, and mounting investor interest are a move in the right course. Yet, as the stakeholders and government know, even greater action will be required to attain India's wider renewable energy ambitions.

The Indian government formally accepted the novel solar target of 100 GW of solar energy which was announced last year. The National Solar Mission (NSM) now envisages the 2020 target to achieve the ambitious 100 GW of installed solar power capacity--a 5 times rise from the initial 20 GW solar energy target.

Within Indian frontiers, Rajasthan has emerged as India's foremost state for installed solar energy projects, showing an enormous capacity of almost 1.5 GW for a single state. Gujarat until that time was leading, and now is the runner up with a significant 957 megawatts of solar energy capacity. Mutually, these two states symbolize 50 % of India's installed solar capacity.

The Prime Minister Cabinet Committee on Economic Affairs (CCEA) initiated a liberal plan to install 2 GW grid connected solar photovoltaic (PV) power projects. The plan is probable to augment renewable energy employment, creating an approximate 12,000 job opportunities for inhabitants of both the urban and rural areas. It could also restrain the CO_2 emissions and produce sufficient solar energy to lighten nearly 1 million households in the country.

The CCEA plan makes use of a new trait; the "Build, Own and Operate" (BOO) model. Under Batch III, Phase II of the NSM BOO is a public-private partnership i.e. a PPP model in which the private party builds possessions bearing support from the government. The aim of the BOO model is to improve private venture in attainment of the very ambitious 2020 target.

According to the CCEA plan, the NSM will once again use Viability Gap Funding (VGF) as part of the plan. The VGF is held up by the National Clean Energy Fund (NCEF), a source that has established itself to be very effective in implementing the NSM initiatives. Several features of the plan include: 250 MW Domestic Content Requirement, using the solar PV cells and modules which have been produced in India and a 1,750 MW capacity of "Open Category" content, using solar PV cells and modules from any country. The location of projects can be selected by the bidders, which could engage placing of projects in solar parks which are created under initiatives of MNRE 13-month commissioning period, opening from the day when the Power Purchase Agreement (PPA) is sealed.

India also has a novel Renewable Energy Corporation of India (RECI), formerly known as the Solar Energy Corporation of India (SECI). The newly formed RECI has greater responsibilities and authority, which include the authority to possess and operate renewable plants and deal or trade renewable power. RECI's capacity to sell solar power may offer the desired aid for the stressed distribution companies (DISCOMs) in India.

1.3.1 Investor Interest & Financing

The investment in India's solar energy market has seen considerable expansion across the board. This can be attributed to the efforts made by the government of India in solar energy sector by organizing large scale events like RE-Invest 2015 which saw investors from across the globe. It was a direct consequence of the 100 GW target of solar energy set by the government of India to be met by the year 2022. Clean energy investments in India have risen to 59% in the first 3 months of 2015 singlehandedly, and are probable to exceed $10 billion prior to closing of 2015, which has been predicted according to the Bloomberg New Energy Finance.

Recently, SunEdison announced its ambitious plans to invest about $ 15 billion in the solar market of India by the year 2022. This great undertaking follows an agreement sealed in the month of January by Adani Group (India) and the biggie SunEdison and to assign $2 billion toward constructing a solar apparatus manufacturing unit in India.

This shows that India will need a considerable arrival in finance to realize the very ambitious 100 GW solar target--which will necessitate a figure of $100 billion in investments and generate up to 1 million jobs in the sector in India. By means of pioneering financing means such as green bonds and green banks which can provide help to the momentum that India requires to become a international leader in renewable energy. Renewable energy is an extraordinary prospect to offer the extremely needed clean energy admittance and power to India's rising economy.

1.4 Objectives of the present work

The steady rise in the advancement of solar cell manufacturing technology would certainly make the use of these technologies possible on an widespread basis than what the present scenario is. The use of the most recent photovoltaic power control mechanisms called the Maximum Power Point Tracking (MPPT) algorithms has led to a significant development in the efficiency of operation of the solar panels and modules and has thus contributed to the field of utilization of renewable sources of energy [3] [8]. But the MPPTs come with their own limitations that they track only the input power and pump that maximum power into the system. Hence there arises the need to efficiently collect the power at the output stage in order use that power for various applications such as pumping, battery charging or grid integration. The present thesis explores this subject which has remained relatively untouched but plays an important role in deciding the efficiency of power converters used.

The objectives of the present work in nutshell are given below as:

1. To study the effect of loading on the performance of Solar PV Standalone systems.
2. To study the effect of loading on the efficiency of Solar PV Standalone systems.
3. To simulate the effect of loading on various performance parameters in Solar PV Standalone systems.
4. To observe the effect of non ideality of buck converter on the solar PV systems.
5. To observe the most optimum operating range of duty cycle in solar PV standalone systems.
6. To study the basic characteristics of various batteries and find the most suitable battery for Solar PV applications.
7. To simulate a simple battery charging circuit for Solar PV applications.

Chapter 2

LITERATURE REVIEW

The topic of solar energy utilization has been looked upon by many researchers all around the globe. It has been known that solar cell operates at very low efficiency and thus a better control mechanism is required to increase the efficiency of the solar cell and researches have come up with new technologies for battery charging applications. In this field researchers have developed what are now called the Maximum Power Point Tracking (MPPT) algorithms.

M. G. Villalva, J. R. Gazoli and E. Ruppert F [1]-[2] in their both papers have presented a comprehensive method to model a solar cell using Simulink or by writing a code. Their results are quite similar to the nature of the solar cell output plots.

P. S. Revankar [9] has even included the variation of sun's inclination to track down the maximum possible power from the incoming solar radiations. The control mechanism alters the position of the panel such that the incoming solar radiations are always perpendicular to the panels.

Hung-I Hsieh et al. [23] proposed a high-frequency photovoltaic pulse charger (PV-PC) for lead-acid battery (LAB) guided by a power-increment-aided incremental-conductance maximum power point tracking.

Hairul Nissah Zainudin and Saad Mekhilef [5] have compared the 2 most popular Maximum Power Point Tracking Techniques for PV Systems using 3 converters viz. the buck, boost and the Cuk converter.

B. SreeManju, R.Ramaprabha and Dr.B.L.Mathur [25] have modeled the Standalone Solar Photovoltaic Battery Charging System by employing a buck-boost converter and controlled the battery charging by using the PI controller.

Huan-Liang Tsai, Ci-Siang Tu, and Yi-Jie Su [7] have developed a generalized Photovoltaic Model and have implemented the Solar PV model using the MATLAB/SIMULINK software package.

ArashShafie et al [26] proposed a novel MPPT algorithm primarily for applications involving battery charging which are considered constant voltage type loads for all practical purposes. This was achieved mainly with output current maximization.

Eduardo I. Ortiz-Rivera and F.Z. Peng [23] proposed an analytical Model for a Photovoltaic Module using the Electrical Characteristics provided by the Manufacturer Data Sheet.

E. Koutroulis and K. Kalaitzakis [14] proposed a new regulation system for battery charging in photovoltaic applications.

TrishanEsram and Patrick L.Chapman [27] compared the available Photovoltaic Array Maximum Power Point Tracking Techniques.

M. Berrera [28] has compared seven different algorithms for maximum power point tracking using two different solar irradiation functions to depict the variation of the output power in both cases using the MPPT algorithms and optimized MPPT algorithms.

Chetan Singh Solanki [22] has comprehensively explained the design of Solar PV systems in his book on Solar Photovoltaic Technology and Systems.

Katherine A. Kim and Philip T. Krein [6] have studied the various photovoltaic converter module configurations in order to achieve the maximum power point operation in solar PV systems.

C. Julian Chen [16] has analytically explained the guiding physics behind the solar e in his book about the physics of solar energy.

Paul A. Lynn [17] has explained the principles of physics behind solar PV technology in his book on introduction to Photovoltaics.

Robert W. Erickson & Dragan Maksimovic [13] have effectively explained a novel and comprehensive approach to converter design through their book on power electronics.

Mukund R. Patel [3] has explained the design process of standalone solar PV systems along with the process of interconnection of solar energy to the grid in his book on solar and wind power systems.

Heinrich Ha¨berlin [10] has laid down the latest design, layout and construction methods for entire PV plants in his book on solar photovoltaic system design.

Mohammed H. Rashid [8] has explained the power electronics involved in the solar energy conversion systems in his book on power electronics.

P.Sathya, G.Aarthi [29] have modeled and simulated the solar PV system specifically for PV system battery charging applications.

Chapter 3

THE SOLAR CELL

To understand the modeling of solar cells better, we should first delve into the semiconductors of solar cell as follows:

Lab Experiments prove that when light falls on a surface which is metallic in nature, electrons may be ejected (depends on the energy inside the light). The energy E of the freed or ejected electrons depends upon the frequency ν of the light which is incident on the surface. This phenomenon occurs according to the following equation,

$$E = h\nu - \phi,$$

In the above equation, h is the Planck's constant, and ϕ is the least or minimum energy which is required to free the electron from the metallic surface. These electrons which are ejected or freed from the metallic surface constitute an electric current (i.e. the movement of electrons through the circuit and the magnitude of the electric current solely depends upon the intensity of the light which was incident on the surface.

These results show that the exchange of energy occurs in discrete units which is in the form of discrete quantities of electrons and radiation. These discrete quantities of radiation are called **photons**. According to the traditional idea they are assumed to be massless i.e. having 0 mass. Each photon contains some energy which is given by the $h\nu$, and the intensity of the radiation is obtained by the obtaining the number of photons falling on the metallic surface per unit time.

3.1 The Electron Band Theory

Akin to the spectators sitting in movie theatre moving between the rows and seats of the theatre, electrons also change their places, which is according to the availability places or spaces for them to fit into. Each electron is characterized by a specific energy which depends on the shell in which it is placed and because it so happens that the shell level is very closely related to the amount of energy that an electron possesses, the "jumps" or "exchanges" between shells require some energy. If an electron jumps from a lower order shell to a higher-order shell, means that it has acquired some extra energy from a source. Using the movie theater analogy, it accounts for a rise in energy for a person who climbs to a greater height (moving against the force of gravity) to move to higher row of seats. Conversely, if an electron "jumps" to a lower shell emits some of its possessed energy, just like a person who is leaping down to a lower row of seats loses his potential energy and the disbursed energy converts into heat energy and sound energy. The jumps between various shells require a considerable exchange of energy and hence all spring overs between the shells are not equal.

It is the spread or thickness of the bands and their closeness to existing or prevailing electrons that decides the degree of mobility of these electrons when they will be exposed to an electric field. The bands with no electrons overlap over the bands which contain the electrons in case of metallic substances. It means the electrons would virtually need very less energy or no energy at all to switch states between the bands. As a result the outer electrons are free and ready to move as soon as the electric field is applied. This is the reason why metals are so good conductors of electricity.

The overlapping of bands don't occur in all substances as it is the inherent property of the material. In many substances a significant gap exists between the valence and the conduction band. Hence it is difficult to free the electron from the valence band to send it to the conduction band as it requires considerable amount of energy. These substances are referred to as insulators.

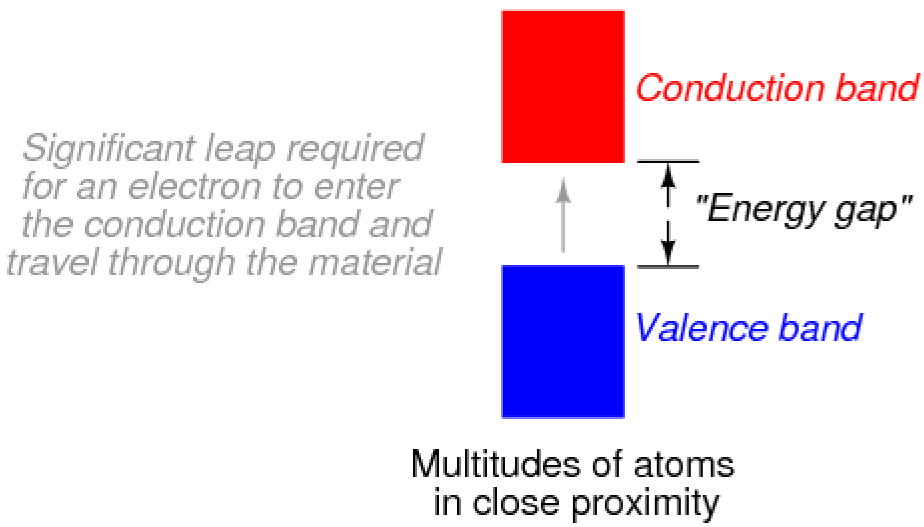


Figure 1. Electron band separation in insulating substances

There is another category of substances which have band gap between the conductors and the insulators. In these substances the energy that they require to drive an electron to the conduction band is moderate. These materials are referred to as semiconductors.

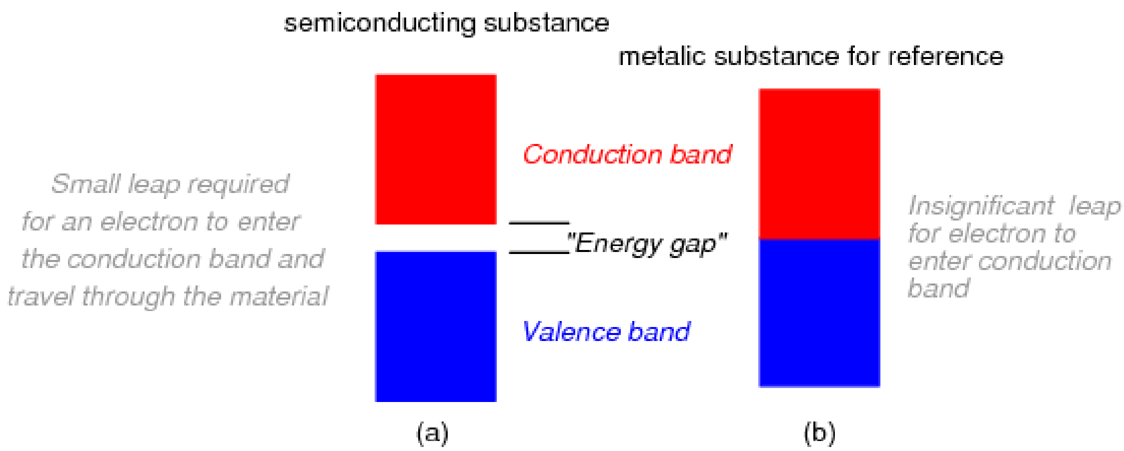


Figure 2. Electron band separation various substances, (a) Band gap diagram in semiconducting substances, they have a significant band gap, (b) Band gap diagram in metallic substances.

The conducting property of semiconductor varies according to temperature i.e. at low temperatures, less energy is accessible to force the electrons in the valence shell through this gap, and the semiconductor acts like an insulator. But as the temperature is further increased, the ambient energy itself is sufficient to push the electrons through the gap and hence the conduction of electrons increases. [1] [11]

3.2 Generation of charge carriers

One of the below situations arise when a photon strikes a semiconductor surface:

a. The photon can get absorbed by silicon crystal if and only if the band gap energy of silicon is lower than that of the energy of photon. This effectively generates an electron-hole pair sometimes even heat, which entirely depends on the band structure.
b. The photon can pass through the silicon — this happens in the (generally) case of photons with lower energy,
c. The photon can bounce back or reflect off from the surface of silicon,

If the silicon surface absorbs the electron then the energy of electron is transferred to the crystal lattice. This electron is unable to move because it is generally located in the valence band and is hence tightly bonded inside the covalent bonds of the substance with the adjacent atoms of the lattice. The energy which is transferred to the electrons elevates or throws it to the conduction band and it becomes free to roam. The atom which has become electron deficient due to this process is called as a hole. The electrons in adjacent atoms move towards the hole and complete the electron deficiency. In this way the hole propagates through the substance and is free to move inside the crystal lattice. Hence it is seen that the electrons which get assimilated inside the semiconductor create mobile electron-hole pair.[12]

A photon needs to have a greater magnitude of energy than the band gap energy in order to excite an electron from the valence to the conduction band of the material but it so happens that the frequency spectrum of the solar radiation in approximation is same as that of the spectrum (frequency) of a black body at an extremely high temperature of 5,800 K which is also the temperature of the surface of the sun, and most of the solar radiation which reaches the surface of the Earth comprises of photons which have energy greater than the band gap energy of silicon. As a result these electrons will be absorbed by the silicon material and the extra energy is converted into heat energy (or vibrations) which then dissipates inside the lattice and as result its temperature rises.

3.3 Charge carrier separation

The charge carriers separation occurs through 2 methods inside the solar cell:

a. **diffusion** of carriers due to the random motion exhibited by them
b. **drift** of carriers, when an electric field is established across the device

There is almost no electric field inside the active region of the cell and hence the governing mode of separation of charge carriers is diffusion inside the solar cells. This takes place due to the random motion (zigzag) of the carriers until the electrical field present inside the active region completely captures them. The diffusion length of minority carriers (i.e. the photo-generated carriers usually travel a particular distance before they can recombine) ought to be comparable to the thickness of the cell. Because of the existence of defects, the diffusion length of the minority carriers in thin film cells (such as the amorphous silicon) is too small and the dominant mode of charge separation hence is the drift, which is wholly driven by the electrostatic field present inside the the junction and which reaches to the full cell thickness.[16]

The minority carriers don’t return as soon as they swept across the junction. Before the carrier has a chance to be elastically dispersed back to its starting point it relaxes to a typically lower energy state and hence this sweeping is an irreversible process.

3.4 The p-n Junction diode

As the name suggests, the p-n junction is the junction between the p-type silicon and the n-type silicon. Needless to say the junction or association has to be made at the molecular level and not at the physical or macro level. They are made by diffusing the p-type dopant to the other side of the n type wafer and vice versa.

The electrons diffusion starts across the p-n junction as soon as the n-type silicon is put in close contact along with the p-type silicon. This diffusion occurs because of the concentration gradient across the regions i.e. a flow of electrons takes place from a region of high concentration of electrons (n-type junction side) to the region of low concentration (p-type junction side) and they readily recombine with p-type side of junction. However, the diffusion process doesn't continue for an indefinite time because the charges that accumulate on both the sides of the junction create an electric field which opposes the flow of electrons and finally balances out the diffusion of holes and electrons. The region where the diffusion across the junction has occurred is called as depletion region because it doesn't contain any mobile charge carriers. In this condition there are hardly any mobile charge carriers left close to the junction and a so - called *depletion region* is formed.This is called as the space charge region. [17]

3.5 Connection to Ohmic Load

Since the final aim of the solar cell is to produce electrical energy hence the current and voltage and creating power hence, Ohmic metal-semiconductor connections are created on the p-type and n-type sides of solar cell and subsequently to the electrodes which are then connected to an ohmic load (external). Electrons which are gathered by the junction and swayed to n-type side or have been formed on the n-type side move through the load through the wires till the time they arrive at the p-type side contact where they recombine with the hole which was either swept through the junction or created on p-type side as one of the electron hole pair.

The measured voltage equals the the difference between the quasi Fermi levels of minority carriers, i.e. holes on the n-type side and electrons on the p-type side.

3.6 Equivalent Circuit of a Solar Cell

It is very useful in engineering to create equivalent mathematical models (in this case electrical models) in order to comprehend the electronic behavior of the solar cell and precisely predict its response. We model the solar cell into its electrical equivalent model i.e. in the form of well known circuit elements like resistors, capacitors or diodes in order to analyze the cell. An ideal or perfect solar cell can be precisely modeled as a current source in parallel with a diode. In the realistic world no ideal solar cell exists and thus the series and parallel resistances are added in the circuit to account for the voltage, current and power drops in the solar cell.

As the name suggests the solar cell is a cell, just like the cells in the human body and hence is the fundamental building block of a solar panel. If a number of solar cells are connected together they constitute a module or a panel. We model the practical solar cell below which we call as the single diode model as it contains only a single diode.

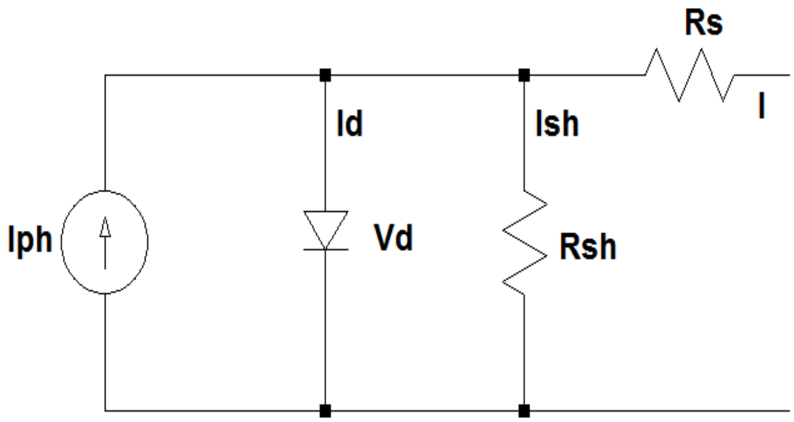


Figure 3. The single diode model of solar cell [1]

The characteristic equation for a photovoltaic cell is given as under,

$I = Ilg - Ios*[\ \exp\{q*V + I*RsA*k*T\} - 1\ ] - [\ V+I*Rs/Rsh\ ]$ [1][2] (1)

Where,

$Ios = Ior*\ (T/Tr)\ 3*\ [\ \exp\{q*Ego*\ \{(T\text{-}Tr)\ /Tr*T\}*A*k\}$ [1][2] (2)

$Ilg = \{Iscr + Ki*(T-25)\}*lambda$ [1][2] (3)

Ios : Reverse saturation current of the cell

V & I : Output voltage and current

q : Charge of an electron i.e $1.6*10^{-19}$C;

T : Cell temperature in Celsius;

lambda : Solar irradiation (W/m^2);

k : Boltzmann's constant, $1.38 * 10^{-23}$J/K;

Iscr : Short circuit current at the temperature of 25 degree Celsius;

Ki : Short circuit current temperature coefficient at Iscr;

A : Ideality factor;

Ilg : Light-generated current;

Ior : Cell saturation current Tr;

Ego : Band gap value for silicon;

Tr : Reference temperature;

Rs : Series resistance;

Rsh : Shunt resistance;

The characteristic equation of a solar panel is reliant on the quantity or number of cells connected in parallel and number of cells connected in the series configuration. It is observed from the experimental results that the variation in current is less dependent on the shunt resistance and is dependent more upon the series resistance [7].

$$I=Np*Ilg-Np*Ios*[\exp\{q*(V/Ns+I*Rs/Np)/A*k*T)\}-1]-[V*\{Np/Ns\}+I*Rs]/Rsh \quad [1][2]\ (4)$$

The I-V and P-V curves for a solar cell are given in following figure. It can be easily observed from the characteristics given below that the cell operates as constant current source at low values of operating voltages and constant voltage source at low values of operating current.

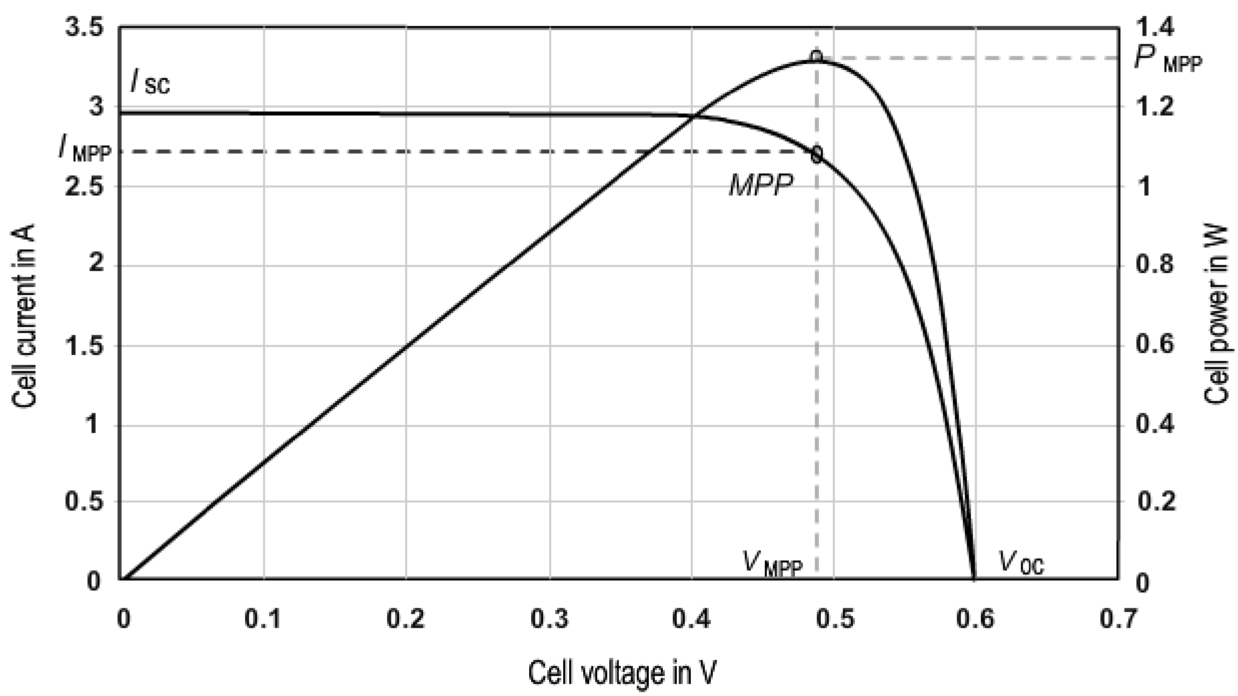


Figure 4. P-V and I-V curve of a solar cell at a given temperature and solar irradiation [10]

3.7 Effect of Variation of Solar Irradiation and Temperature

3.7.1 Effect of variation of Solar Irradiation

1. General viewpoint

The solar radiation incident on the atmosphere of the earth is comparatively almost constant but the radiation which reaches the surface of the earth widely varies because of:

- The latitude's location;
- local variations in the atmosphere, such as pollution, clouds and water vapours;
- the atmospheric effects, which includes scattering and absorption;
- the time of the day and the season of the year. [12]

The above mentioned effects have various effects on solar radiation which are received by the Earth's surface. These changes include variations spectral content of sunlight, the overall power received and the angle at which the light is incident surface of the earth. Additionally, the solar radiation at any particular location varies markedly as a key change which happens due to the above effects. The seasonal variation, the clouds and the other effects like the length of day at the latitude contribute to the variability. The variations in desert regions are less because of the local atmospheric conditions such as the clouds. Equatorial regions also have low variability between seasons.

2. Technical Viewpoint (Electrical parameters and their curves)

The P-V and I-V characteristics of a solar cell are highly dependent on solar irradiation values. As a result of the environmental changes solar irradiation keeps on fluctuating, but control mechanisms are available that can efficiently track this change and can change the working of the solar cell to meet the required load demands. Higher solar irradiation means that higher energy transfer to the silicon material and hence higher input energy which yield proportionally higher output power. The open circuit voltage rises to small extent with the rise in solar irradiation. This is because of the fact that when higher energy is incident on the solar cell, the electrons are supplied with a higher proportion of the excitation energy, and hence their mobility rises thus yielding more power. [13]

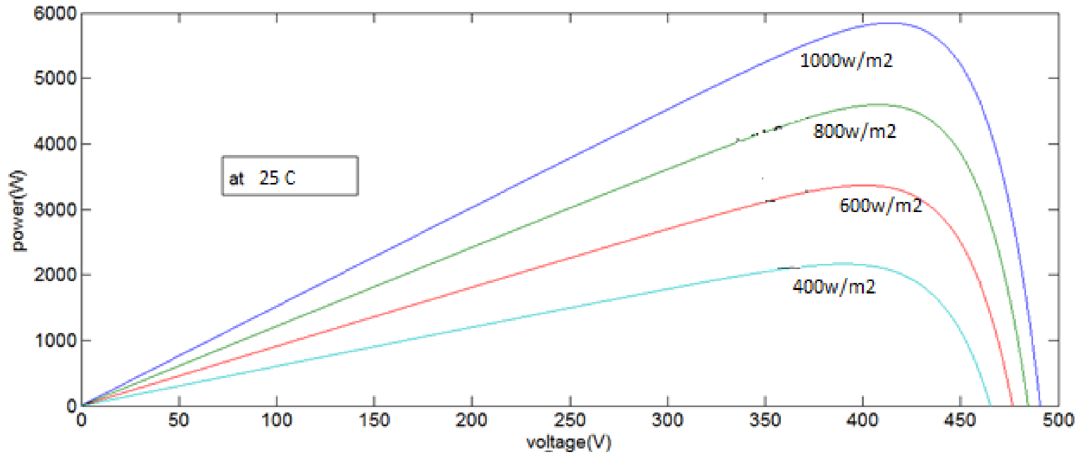


Figure 5. Variation of P-V characteristics with solar irradiation [8]

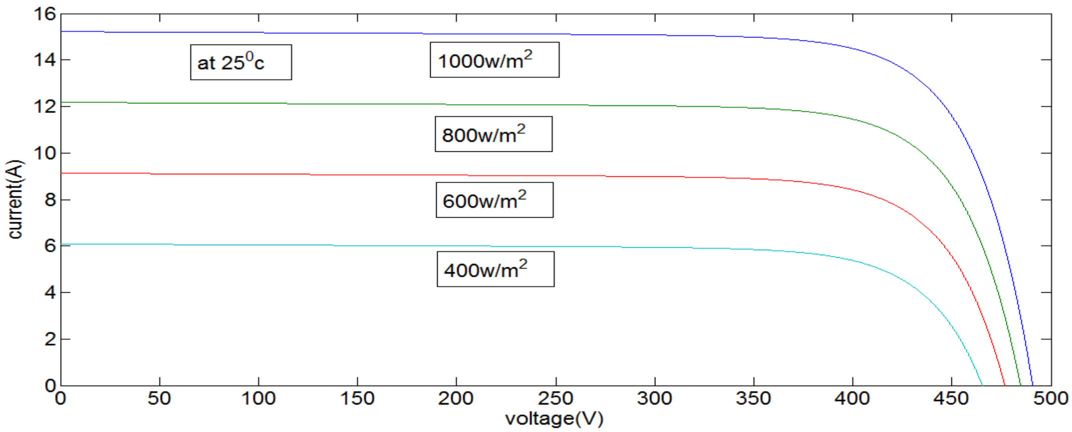


Figure 6. Variation of I-V characteristics with solar irradiation [8]

3.7.2 Effect of variation of temperature

The temperature rise around the solar cell has a counter effect on the power generation capability of the solar panels. The increase in temperature is accompanied by decrease in the open circuit voltage. Increase in temperature causes the band gap of the material to increase and hence more energy is required to cross this barrier. Hence the efficiency of the solar cell is reduced. [18]

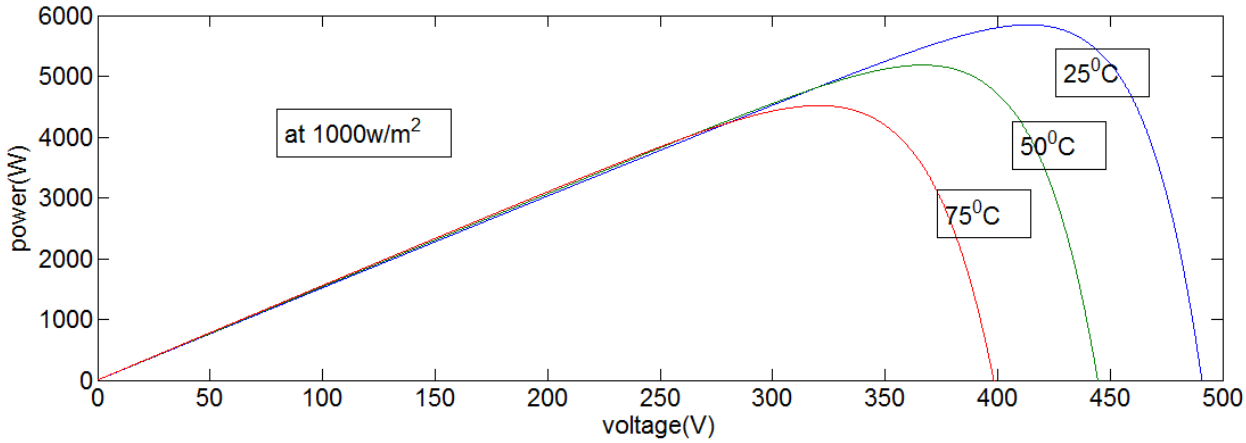


Figure 7. Variation of P-V curve with temperature [10]

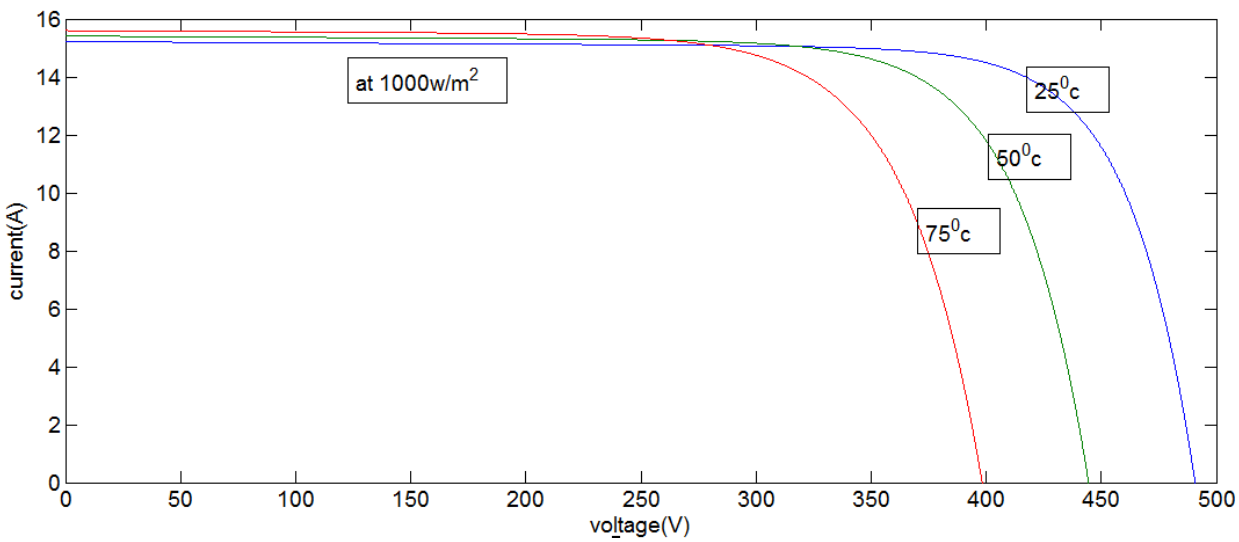


Figure 8. Variation of I-V characteristics with temperature [10]

Chapter 4

THE BUCK CONVERTER

The buck converter is a high efficiency step-down DC to DC switching converter. The converter uses a transistor switch, typically a MOSFET (Metal Oxide Semiconductor Field Effect Transistor), to modulate the pulse width of the voltage into an inductor. Voltage pulses are rectangular in nature which go into an inductor which results in a triangular current waveform as the inductor acts as an integrator. There are several equations for the voltage and current for a buck converter that define the relation between the inductance used in the circuit and the ripple current. For the sake of this thesis discussion we adopt that the converter is working in the continuous mode of operation, which means that the current through the inductor never goes to zero i.e. the inductor is never fully discharged.

A buck converter comprises of 3 components: a switching element (MOSFET), a diode and an inductor. The switching element is usually a Field Effect Type (FET) type transistor but any device that allows the external binary control of current flow can be employed. The diode is usually a Schottky type diode but most of the normal current-carrying type diodes will do the job. The inductor normally is a coil wound over a ferrite core, but may well be air-cored or so short so as to consist of just a loop of wire.

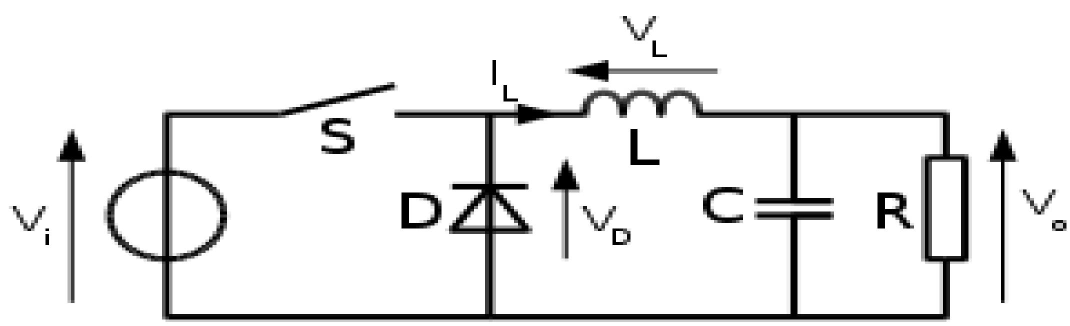


Figure 9. A Buck Converter schematic [19]

The switch is rapidly switched off and on in a controlled manner. When the switch is in conducting state, the current through the inductor increases and when the switch is turned off the current falls through the inductor leading to a triangular waveform as mentioned above. The inductor basically resists the change in current, so the current will not immediately rush in at the moment of switch-on and some current will continue to flow after the off-switching moment.

4.1 The Buck Converter Operation (Continuous mode)

A buck converter operates in the continuous mode of operation if the current through the inductor (I_L) never falls to zero. In this mode, the operating principle is described as follows:

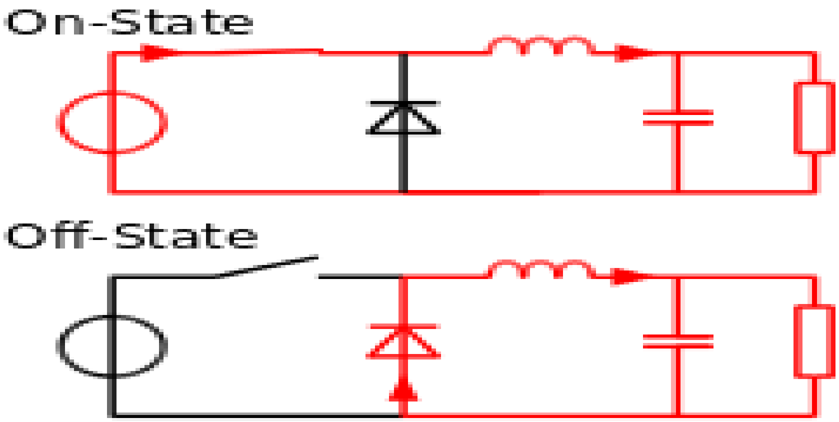


Figure 10. The ON & OFF states in a buck converter [19]

In the above figure the red lines denote the flow of current through the circuit and the respective elements which are involved in that state.

- When the switch (MOSFET or an IGBT) as above is closed (on-state switch, top figure), the voltage across the inductor (in red) is given by $V_L = V_i - V_o$. The current through the inductor rises in a linear fashion. As the diode (in black) is reverse biased by voltage source V (in black), no flow of current through the diode takes place;
- When the switch (MOSFET or an IGBT) is opened (off state switch, bottom figure), the diode (in red now, because it conducts) is forward biased. Thus the voltage across the inductor becomes $V_L = -V_o$ (by KVL, not accounting for the drop in diode) and current I_L dips.

The energy stored in inductor L is

$$E = \frac{1}{2} L \cdot I_L^2$$

Therefore, it can be easily seen that the stored energy in the inductor rises when the switch is turned ON (as I_L increases) and then reduces when the switch is turned OFF as in that case it becomes the power source in the circuit. Hence it is seen that inductor (L) is used to transfer the energy from the input to the output of the converter.

The rate of change of I_L can be calculated as:

$$V_L = L \frac{dI_L}{dt}$$

Here, V_L equals to V_L - V_o during the On-state and equal to $-V_o$ during the Off-state. Therefore, during the ON state the rise in current is given as:

$$\Delta I_{L_{on}} = \int_0^{t_{on}} \frac{V_L}{L}\,dt = \frac{(V_i - V_o)}{L} t_{on}\,,\ t_{on} = DT$$

Conversely, the Off-state decrease in current is given as:

$$\Delta I_{L_{off}} = \int_{t_{on}}^{T=t_{on}+t_{off}} \frac{V_L}{L}\,dt = -\frac{V_o}{L} t_{off}\,,\ t_{off} = (1-D)T$$

If we here assume that the converter operates in its steady state i.e. the transients have subsided, and the energy stored in each component at the end of the commutation cycle T equals the energy stored at beginning of the next or the same commutation cycle. It means that the current I_L is same at t=0 & at t=T as shown in the figure below.

So we can write from the above equations:

$$\frac{V_i - V_o}{L} t_{on} - \frac{V_o}{L} t_{off} = 0$$

The above integrations are graphically done more conviniently: In figure 4, $\Delta I_{L_{on}}$ is proportional to the area of yellow surface, and $\Delta I_{L_{off}}$ is proportional to the orange surface area, as these surfaces are defined by the inductor voltage (red) curve. As these surfaces are composed of simple rectangular shapes, their areas can be found by using the formula for area of rectangle i.e. $(V_i - V_o)\,t_{on}$ for the yellow rectangle and $-V_o t_{off}$ for the orange rectangles respectively . In order to ensure that the system operates in steady state, these areas must bear equal values.

As can be easily seen in figure below, $t_{on} = DT$ and $t_{off} = (1-D)T$. Where D is known as the *duty cycle* and it has a value between 0 and 1. This yields:

$$(V_i - V_o)DT - V_o(1-D)T = 0$$
$$\Rightarrow V_o - DV_i = 0$$
$$\Rightarrow D = \frac{V_o}{V_i}$$

From this equation, it can be easily seen that the output voltage of converter for a given duty cycle varies in a linear fashion for a given input voltage. Because of the fact that D i.e. the duty cycle is equal to the ratio between t_{on} and period T, it can't be more than 1. Therefore, $V_o \leq V_i$. This is why this converter is called as the *step-down converter*.

So just for an example, to step a 12 V voltage down to 3 V (output voltage equal to a 1 quarter of input voltage) would need a duty cycle of about 25% or 0.25, in our (theoretically) ideal circuit.

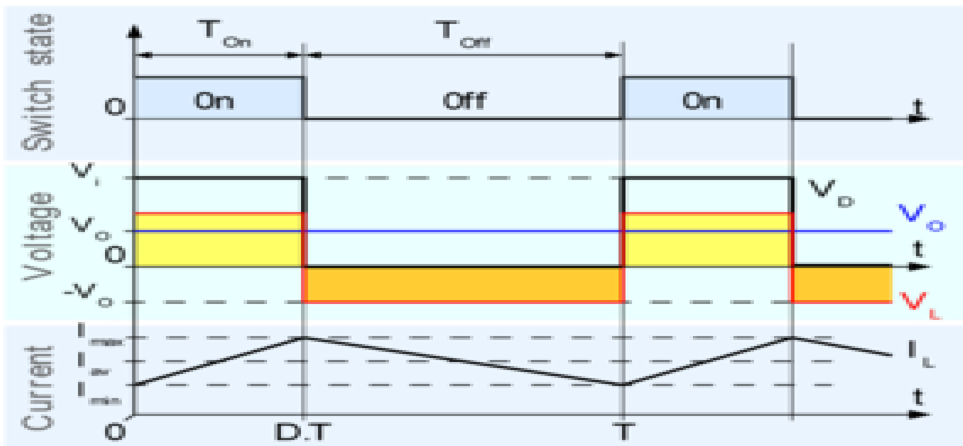


Figure 11. Voltage, Current and Switching state graphs in Buck Converter [19]

After the above mathematics concerning the buck converter we move towards the physical explanation of the working of the circuit.

As soon as the voltage Vi is applied in the reverse direction across the power diode, the MOSFET or the IGBT in the circuit turns ON. Hence as long as the switch remains ON the power diode remains OFF in the circuit. Therefore as long as the MOSFET is ON the power diode ought to continue as being OFF. The MOSFET switched ON state MOSFET always means the diode OFF state. Current I_L begins to go up as soon as the MOSFET is turned ON. The exponential growth of current I_L occurs because of the inductance (L) present in the circuit. The MOSFET is maintained in the ON state for the t_{on} interval, and OFF for the t_{off} interval of time.

I_L has a finite value which happens to be the maximum output current value through the first cycle as soon as the MOSFET is turned OFF. This maximum current takes place when the MOSFET turns OFF. The abrupt drop of I_L to 0 is prevented due to the presence of inductance L. The fall of the current I_L causes a $L.di/dt$ drop i.e. an induced voltage drop to materialize across the inductance L. Due to this voltage drop across the inductor, the diode is forward-biased and hence the circuit is cut-off from the source. The diode causes the flow of current to continue and fall exponentially. The flow of current in the circuit in this way exclusive of the help of a voltage source, but only because of the stored energy in the inductance L is commonly referred to as "Free-Wheeling". The power diode give the free-wheeling course for the MOSFET as soon as its turned OFF. Hence, the power diode automatically comes into ON state as soon as the MOSFET switches off because of the presence of the inductance with energy stored in it. The fall in I_L continues as long as the MOSFET remains in OFF state, which is for the duration of t_{OFF}. The minimum value to which the current decays to at the end of first cycle is labeled as the valley magnitude IV1 as it is the lowest value in the figure below. The IInd switching cycle starts when the MOSFET at the end of first t_{OFF} again is turned ON, and the current begins to rise again. Because of the original current IV1, the second maximum i.e. IP2 will be greater than IP1. As a result, the valley magnitude IV2 at the ending of cycle II will also be longer than IV1. In this way, the switching grows and both the maximum and valley (minimum) amounts gradually increase. After quite a few cycles, the difference between the consecutive cycles becomes insignificant. We say that the circuit conditions have attained the steady state.[20] This means that maximum current is effectively the same in successive cycles. An analogous statement is right for the minimum or valley current also. The relation between the duty cycle (D), input voltage (V_i) and the output voltage (V_o) is given by:

$V_o = V_i \times D$

Where,

$D = t_{on} / (t_{on} + t_{off})$

The duty cycle can be ideally changed in the range of 0 to 1 by the variation of ON time and hence the output voltage is at all times less than or equal to the input voltage and thus the name step down or buck converter. By the proper selection of inductor and capacitor values the ripple in output voltage of the DC-DC converter is minimized, which is given by

$L = D * [\ - V_o\ ] / (\ I_{ripple} \times f_s\ )$

$C = I_{ripple} / (8 \times f_s \times \Delta\ )$

V_i = Input Voltage of the Buck Converter,

V_o = Output voltage,

D = Duty Cycle,

f_s = Switching Frequency and

I_{ripple} is the inductor ripple current & is typically 30% of output maximum current. ∆V is the output voltage ripple and it is generally 1% of the output voltage. The ESR is defined as the effective series resistance of the capacitor, and is given in detail in the manufacturer’s datasheet (usually 0.03Ω). A capacitor with a low value of ESR will only help to reduce the ripple on the output voltage.

4.2 The Practical Buck Converter

Uptil now we have been considering the buck converter as ideal i.e. assuming no losses in the converter circuit. This assumption of an ideal converter helps to simplify the analysis and getting an insight into the working of the circuit. But in our practical world the circuits are non ideal and have many kinds of losses which have to be incorporated if we want to analyze the real circuits. We would not go into details of loss modeling as it is beyond the scope of this thesis but we would illustrate the models briefly so as to provide a base for the subsequent chapters.

Hence we now consider the practical buck converter with its losses in order to help us get an insight into the working of a practical buck converter.

The practical buck converter has a number of losses out of which the primary ones are given below as:

a. Inductor copper loss due to the ohmic resistance of the inductor

b. The MOSFET on resistance loss

c. Losses in the diode due to its forward voltage drop

d. MOSFET switching loss

These losses occur inside the practical buck converter and can reduce its efficiency significantly and hence they must be taken into account.

To model the inductor copper loss due to the ohmic resistance of the inductor, the model consist of R_L in series with the inductor and R_C in series with the capacitor. Additionally, the diode forward resistance can be effectively modeled as a voltage source in series configuration with the switch which becomes ON and OFF in the 2 intervals.

The figure given below illustrates a simplified diagram of the buck power stage with the inclusion of a drive circuit block. The power switch, Q1, is an n-channel MOSFET. The diode, CR1, which is typically referred to as the catch diode, or the freewheeling diode. The inductor, L, and capacitor, C, constitute the output filter. The capacitor ESR i.e. R_C (equivalent series resistance) and the DC resistance inductor i.e. R_L are included in the analysis. The resistor R, represents the load as seen by the output power stage.

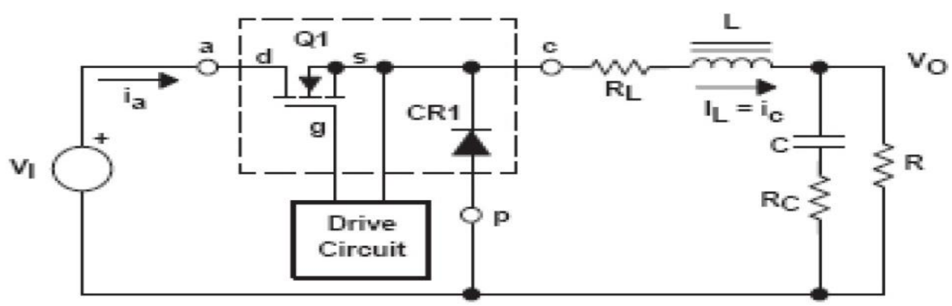


Figure 12. A Non Ideal Buck Converter [20]

All through the standard operation of the buck power stage, Q1 is constantly switched on and off with on & off times decided by the control circuit. A train of pulses is caused by this switching action at the junction of Q1, CR1, and L which is successfully filtered by the L/C output filter to produce a dc output voltage, V_o. A more detailed quantitative analysis is given below.

The explanation of the steady-state operation in a continuous conduction mode is given below. The steady-state means that the input voltage, output voltage, duty-cycle and output load current are invariable and not varying amid the cycles. In the continuous conduction mode, the Buck power stage supposes 2 states in each switching cycle. The ON state occurs when the Q1 is switched ON and CR1 is switched OFF. The OFF state occurs when the Q1 is turned OFF & CR1 is ON. A linear circuit can correspond to each of the 2 states in which the switches in the circuit are replaced by their individual equivalent circuits during each state. The circuit diagram for each of the 2 states is shown in the following figure.

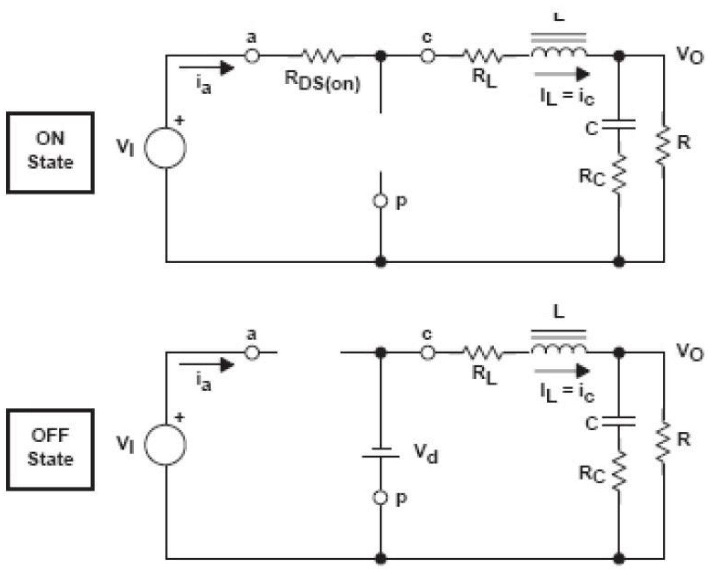


Figure 13. Non Ideal Buck Converter States [20]

The period of the ON state is $D \times T_s = T_{ON}$ where the D is the duty cycle, which is set by the control circuit, and which is given as a ratio of the ON time to the time of 1 complete switching cycle T_s . The OFF state duration is called as T_{OFF}. Since there are only 2 states in each switching cycle in the continuous mode, T_{OFF} is equal to $(1–D) \times T_S$. The quantity (1–D) is also known as D'. The inductor voltages in both cycles can be calculated and hence the output voltage using the volt- second balance.

$V_L = L\ (di_L / dt)$ and

$\langle V_L \rangle = 0$

The inductor current increase during the ON state is given by:

$V_{L1} = V_I – I_L.R_L – V_o$

The inductor current increase during the OFF state is given by:

$V_{L2} = V_d – I_L.R_L – V_o$

Using the Volt - Second Balance we get,

$D.V_{L1} + (1-D).V_{L2} = 0$

Solving we get,

$V_o = D.V_I – I_L.R_L – (1-D).V_d$

where, $I_L = V_o / R$

Finally we get,

$V_o = (DV_I – (1-D)V_d) / (1 + R_L/R)$

which we can see is far from the simple relationship which we calculated in the case of the ideal buck converter and which was

$V_o = DV_I$

We can easily see from the equations the impact of these lossy elements on the power output also because, $P_o = V_oI_o$ and $I_o = V_o / R$

Hence, solving we get

$P_o = (DV_I – (1-D)V_d)^2 . / [(1 + R_L/R)^2 . R]$

The expressions involve an element of the square of terms which decreases the output to a greater extent.

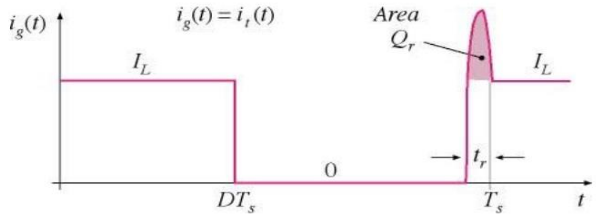
An interesting observation here is that the output power depends upon the duty cycle and hence the efficiency of the converter. Hence there arises a need to operate the system at an optimum duty cycle so as to reduce the losses in the system and to improve the efficiency.

Additionally, there are switching losses which are more even more aggravating than the ohmic losses.

So, we model the switching losses next.

Since the switching loss occurs due to the non ideal switching behavior of the switch, hence we assume that the input current waveform change from an ideal switching to an inclusion of effects due to diode recovery charge, Q_r and reverse recovery time, t_r.

The input current waveform considering the switching losses is given below.



$$\langle i_g \rangle = I_g = (area\ under\ curve)/T_s$$
$$= (DT_sI_L + t_rI_L + Q_r)/T_s$$
$$= DI_L + t_rI_L/T_s + Q_r/T_s$$

Figure 14. Input current waveform considering switching loss

Hence from the figure the value of I_g is

$I_g = (DT_sI_L + t_rI_L + Q_r)/Ts = DI_L + t_rI_L /T_s + Q_r /T_s$

If the switching losses were ignored then the t_r and Q_r values would have been zero and the expression would have reduced to,

$I_g = DI_LT_s / T_s = DI_L$

Hence we can see that the input current has reduced and hence the loss in power is apparent.

Since,
$V_o = DV_g$

$P_{out} = VI_L$ and $P_{in} = V_g (DI_L + t_rI_L /T_s + Q_r /T_s)$

$\eta = 1 / [1 + f_s (t_r /D + Q_r R /D^2V_g)]$

Hence we again see the strong dependence of duty cycle on the efficiency as was in the previous case of ohmic and forward drop losses.

This again reinforces the need to choose the duty cycle optimally and wisely.

Hence we on the way have developed a strong base which would help us get an insight into the working of buck converter employed in solar PV systems in subsequent chapters.

Chapter 5

MAXIMUM POWER POINT TRACKING

Presently, the efficiency of modern solar cells is usually too low. To increase the efficiency of solar cells, various methods are used. These method involve efficient matching of the source and load. One popular method which is used is known as the Maximum Power Point Tracking (MPPT). Maximum power point tracking (MPPT) is a technique or an algorithm (which typically runs on a microprocessor) that solar battery chargers, grid connected inverters and other similar devices make use of to obtain the maximum possible power out from 1 or more photovoltaic devices, which are typically solar panels, however optical power transmission systems can also take advantage from an analogous technology. Solar cells have an intricate connection among the solar irradiation, the ambient temperature and the entire resistance which produces a non-linear output efficiency which can be easily analyzed based on I-V curve of the solar cells. The purpose of the MPPT controller system is to efficiently sample or track the output (power) of the solar photovoltaic cells/panels/modules and to apply the proper resistance (load) to attain the maximum power for a certain environmental condition. MPPT devices are generally incorporated into an electrical power converter system that does the voltage or current conversion, filtering & regulation for driving various kinds of loads, including the electrical power grids, batteries or motors.

Solar inverters convert DC power to AC power and most of them incorporate the MPPT technique: These inverters sample the output power (I-V curve) from the solar cell and impel the system towards the best or the most optimum voltage and current on which the maximum power can be extracted from the solar panels.

MPP (Maximum Power Point) is the product of the MPP voltage (V mpp) and the MPP current (I mpp): some solar panels have a higher maximum power rating than the others.

The main advantage of this method is that this method can be efficiently used to acquire the maximum possible power from an electrical source which is varying with respect to time. In usual photovoltaic systems the I-V curve is of non-linear in nature, thus making it even more challenging to be used to power a certain load. This can be done by making use of a Buck converter whose duty cycle is changed continuously by using an MPPT algorithm. A Few of the most popular algorithms are listed below.

A Buck converter is used on the load side & a solar panel is used to power this converter.

Our particular application involves charging a battery through solar energy and the battery should be charged as fast as possible. Hence MPPT becomes even more important to charge the battery at as optimal rate as possible.

5.1 Various methods for MPPT

There are a number of methods which are used for maximum power point tracking out of which only some are listed as under:

- Perturb and Observe method
- Incremental Conductance method
- Constant Current method
- Constant Voltage method
- Parasitic Capacitance method

5.1.1 Perturb and Observe method

This method is the most commonly used method in all of the MPPT methods. In this method a very few number of sensors are employed. The operating voltage is sampled & the algorithm changes the operating voltage in the necessary direction i.e. towards Voc or zero voltage and samples dP/dV. If dP/dV is positive, then the algorithm escalates the value of voltage in the direction of the maximum power point until the value of dP/dV is negative. These iterations are persistent until the algorithm lastly reaches the maximum power point. This algorithm is not very suitable when the variation in the solar irradiation is high. In P&O the voltage actually never reaches an exact value but perturbs or hovers around the maximum power point (MPP). [4]

5.1.2 Incremental Conductance method

This technique uses the Photovoltaic array's incremental conductance dI/dV value to compute the sign of the quantity dP/dV. When dI/dV quantity is equal and opposite to value of I/V (where $dP/dV=0$) the algorithm knows that maximum power point has been reached & hence it ceases and returns the corresponding value of operating voltage for the maximum power point. An advantage of this method over the former is that this method tracks the conditions of rapidly changing irradiation in a more accurate manner than the previous P&O method. But the other side of this method is that the complexity which is involved in this method is that it requires a number of sensors to operate and hence is economically less effective.

P=V*I

Differentiating with respect to voltage yields;

$dP/dV=(V*I)/dV$ ………………… (5)

$dP/dV = I*(dV/dV)+ V*(dI/dV)$ ……………….(6)

$dPdV = I + V*(dI/dV)$ ……………. (7)

When the MPP is reached the slope dP/dV=0 .Thus the condition would be;

dP/dV=0……………….. (8)

$I+V*(dI/dV)$=0………….. (9)

which finally yields,

$dI/dV= -I/V$………….. (10)

5.1.3 Constant Current method

Similar to constant voltage method, this method is dependent on the relation between open circuit current and the maximum power point current. The ratio of these 2 currents is generally constant for a solar cell which is roughly around 0.95. Thus the short circuit current is obtained experimentally and operating current is adjusted to 95% of this value.

All these methods have their certain advantages and certain disadvantages. The choice is to be always made regarding which algorithm is to be utilized looking at the need of the algorithm and its operating conditions. For example, if the required algorithm is to be a simple one and not much effort is given on the reduction of the output voltage ripple then the P&O algorithm is suitable. But if the algorithm is to give a very definite operating point and the voltage fluctuation near MPP is to be reduced then the IC method is more suitable, but this would make the operation more complex and costly.

5.1.4 Constant Voltage method

This method which is not a so widely used method because of the inherent losses it carries during its operation is dependent on the relation between the open circuit voltage and maximum power point voltage. The ratio of these 2 voltages is generally constant for a solar cell which is roughly around 0.76. Thus the open circuit voltage is obtained experimentally & the operating voltage is adjusted to 76% of this value.

5.1.5 Parasitic Capacitance method

This method is an improvised version of incremental conductance method, with the improvement being that the effect of Photovoltaic cell's parasitic union capacitance is included into voltage calculation.

5.1.6 Flow Chart of MPPT Algorithms

Two of the most widely used algorithms for maximum power point tracking are studied here. The algorithms are

a. Perturb & Observe Algorithm.
b. Incremental Conductance Algorithm.

The flow charts for the two algorithms are shown below.

The Flow chart or logic for perturb & observe is given below:

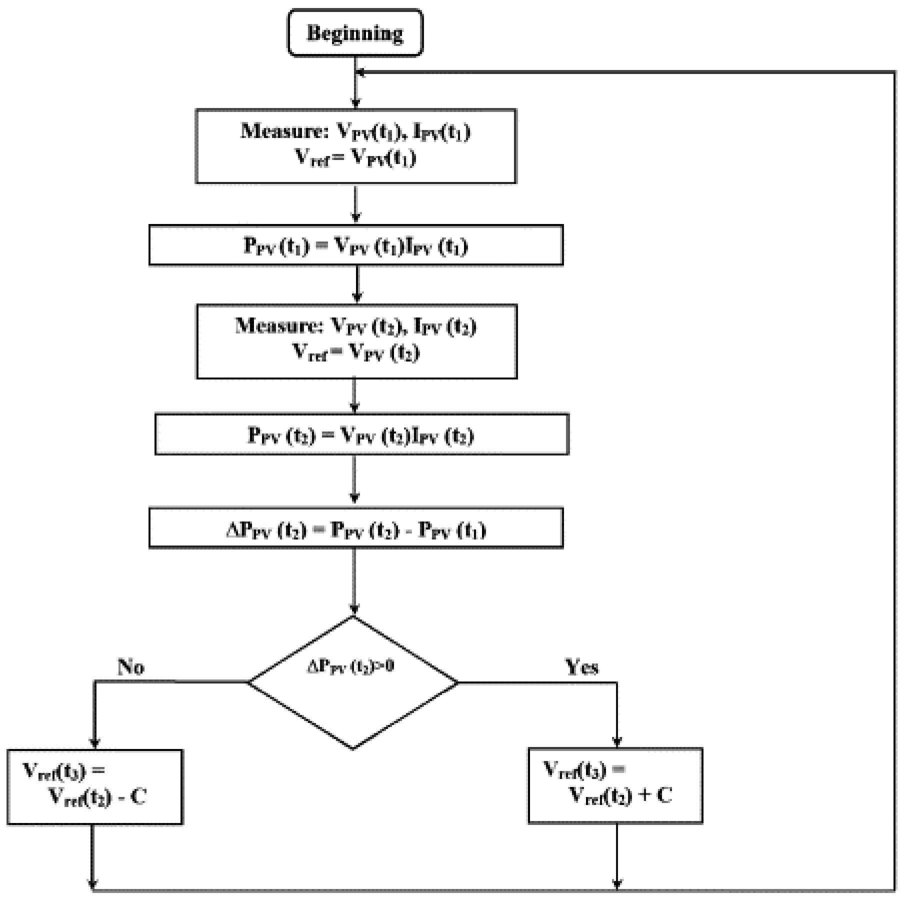


Figure 15. Flow chart of perturb & observe algorithm [5]

The Flow chart or logic of incremental conductance method is as follows:

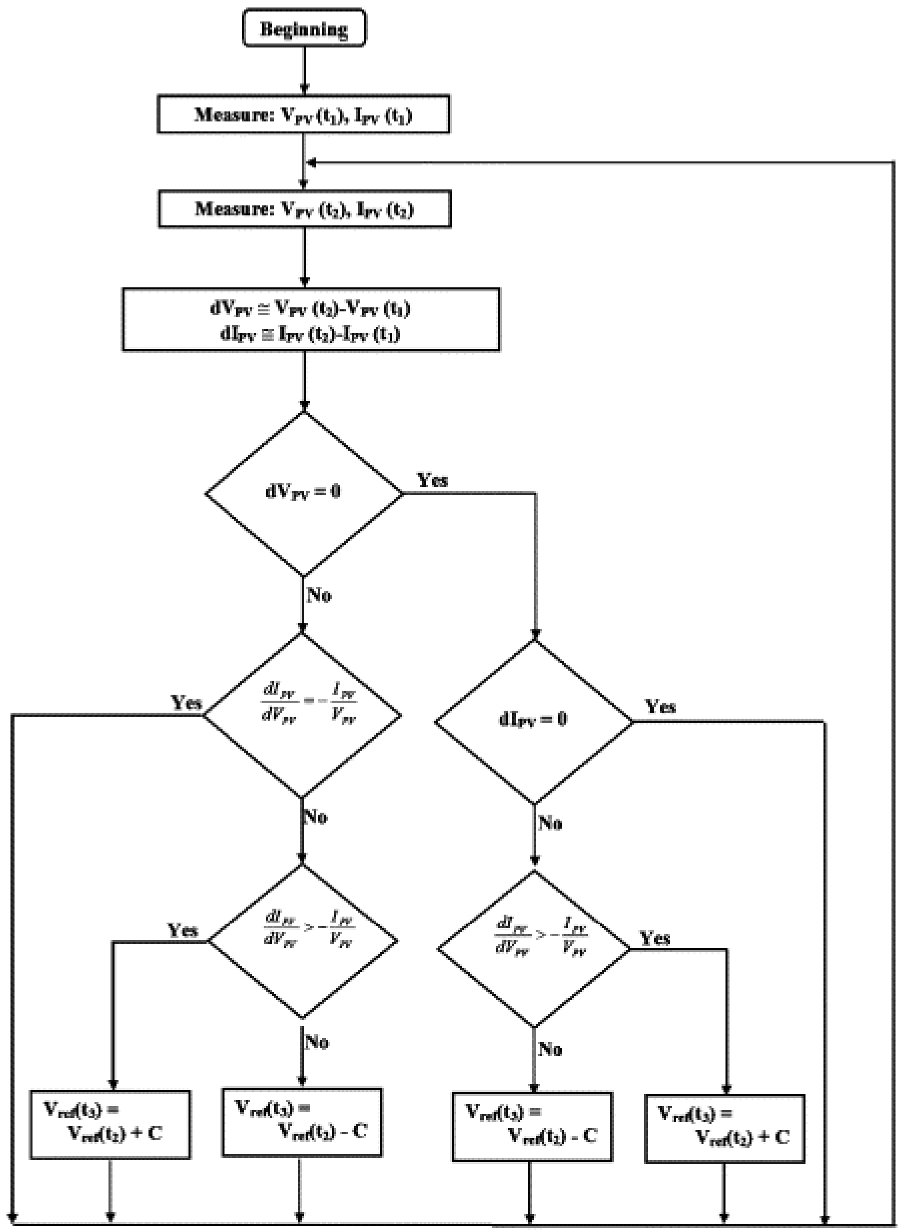


Figure 16. Flow chart of incremental conductance algorithm [5]

Out of these 2 algorithms we implement the Incremental Conductance algorithm using the MATLAB Simulink library, where the values are used to vary certain signals with respect to input signals. Incremental Conductance algorithm is chosen because we need minimum ripple in our output voltage as we want to charge a battery using solar energy & we don’t want to put the wavy voltage into the battery and eventually reduce its performance.

Chapter 6

EFFECT OF LOAD RESISTANCE ON OUTPUT POWER (Simulation & Results)

Up till now we have discussed about the maximum power point tracking in solar PV systems. The concept of Maximum Power Point or the extraction of maximum power has been talked about only in the context of the input power. According to this concept, it is seen that to extract the maximum power from the PV system the system has to be operated at a specific point on the I-V or P-V curve at which it gives out the maximum possible power. This is because of the peculiar nature of the Solar PV I-V curve and the dual behavior of the PV as a current source at low voltages as well as a voltage source at high voltages. We have to operate the PV system at the knee point of current and voltage source so as to extract the maximum power out of the PV system.

Hence the Maximum power is talked about in the context of input stage only.

It is obvious to say that the Solar PV system which is operating on the maximum power point delivers maximum power into the system and it has to be harnessed efficiently so that the maximum possible power is delivered to the load so as to operate the plant at a desirable plant load factor.

The PV system consists of the solar PV modules connected in a desired series-parallel configuration and the balance of system which includes the charge controller and an inverter stage if the load is an AC load. We have considered battery charging as our application where we charge the battery using the solar power. The charge controller controls the power flow to the battery and ensures that the system operates at the maximum power point at all times. The charge controller employs the Maximum Power Point Tracking by changing the duty cycle of the buck converter so as to operate the converter at an optimum duty cycle so as to transfer the maximum power into the system. The duty cycle is constantly monitored and varied using the P&O, I&C or other such algorithms which have described in detail in the previous sections. The operation of buck converter has also been described in the previous section.

It is very important to operate the system at the output maximum power point as is important to operate the system at the input maximum power point. We have used the terms input and output maximum power points to refer to the input and output stages of the buck converter.

There is an optimum output maximum power point to transfer maximum power to the load. This maximum power point consists of an optimum V/I ratio i.e. the output resistance at which the maximum power will be transferred to the load.

We illustrate this with the help of following analysis :

We know that,

$P_o = V_o * I_o$ and $P_i = V_i * I_i$

$V_o = D * V_i$ and $I_o = I_i / D$

Since in an ideal converter,

$P_o = P_i$ …………(1)

We know that for a resistive load,

$V_o = I_o * R$

Hence,

$P_o = V_o^2 / R$

Putting the value of V_o in 2 from 1 we get

$P_o = (D * V_i)^2 / R$

$P_o = D^2 * V_i^2 / R$

Hence we know that in an ideal converter output power depends upon the Duty Cycle (D), Input Voltage (Vi) and the Resistance (R) of the load.

Now we take certain live values as examples and find the Duty cycle associated with them.

We take 200 Wp module which has a Vmp = 26.3 V and Imp = 7.6 A as its maximum power ratings at Standard Test Conditions (STC) i.e. an irradiation of 1000 KW/m^2 and Temperature = 25^oC.

Here,
Wp – Watt peak
Vmp – Voltage at Maximum Power
Imp – Current at Maximum Power

We take an output resistance of 2 ohms which is a load resistance and is to be supplied by the PV system.

Then, putting values in the above equation we get,

$P_o = D^2 * V_i^2 / R$

$200 = D^2 * 26.3^2 / 2$

NOTE – We have put the above rated values in the equation because they are maximum power voltages and currents and we expect the system to operate at maximum power at all times.

Calculating the duty cycle we get,

D = 0.7604 OR D = 76.04 %

We take another example,

This time we change the output resistance to 0.8 ohm

$P_o = D^2 * V_i^2 / R$

$200 = D^2 * 26.3^2 / 0.8$

Calculating the duty cycle we get,

D = 0.4809 OR D = 48.09 %

Hence it is very much possible to calculate the duty cycle required to transfer the maximum power from the input side to the load.

We take yet another example,

This time we change the output resistance to 10 ohm

$P_o = D^2 * V_i^2 / R$

$200 = D^2 * 26.3^2 / 10$

Calculating the duty cycle we get,

D = 1.7004 OR D = 170.04 %

which is not practically possible because we know that the value of duty cycle ranges between 0 to 1 only.
It means that it is not possible to transfer maximum power to the load of value = 10 ohms.
Hence it means that there is a threshold resistance above which maximum power couldn't be transferred to the load from the input to the load side and we ought to find that critical value of resistance.

We now proceed to find that value of resistance.

We know that the maximum value of duty cycle i.e. D = 1

Actually the value is never 1 but it tends to the value 1.

Hence we can say that, $D \rightarrow 1$

$P_o = D^2 * V_i^2 / R$

This time we proceed to find the value of R rather than D in the previous cases.
We put value of D as 1

$200 = 1^2 * 26.3^2 / R$

Calculating the Resistance we get,

R = 3.4584 ohms

Hence we get the value of critical Resistance as 3.45 ohms.
In other words we can say that the value of critical resistance should not be greater than 3.45 ohms if we want to transfer the maximum power from the input to the output stage of the Buck converter.

We also know that the duty cycle is not controlled by us but it is controlled by the Maximum Power Point Tracking (MPPT) controller which adjusts the duty cycle so as to operate the PV arrays at maximum power point in order to extract the maximum power out of them.

But we saw here that the output resistance of the converter plays a key role here if we want to transfer that maximum power extracted by the MPPT (200W in our case) from the PV arrays to the output of the converter. The resistance acts as a deciding factor when we come to transferring that power from input to the output.

Hence the resistance should not be greater than 3.45 ohm for optimum operation.

Now,
We go back to that equation again.

$P_o = D^2 * V_i^2 / R$

We again put the values in this equation to inspect the things more closely.
This time we go back to the III case in which the value of R was equal to 10 ohms.
We are actually trying to find out the maximum power that is actually being transferred to the output in the R = 10 ohms case.

This time we put the values as,
$V_i = 26.3$ V
R = 10 ohms

Putting the above values we have the following equation,

$P_o = D^2 * 26.3^2 / 10$

Note that in the previous case we got the value of Duty cycle (D) as greater than 1 because of the values we put in the equation
But we very well know that the value of Duty cycle can’t be greater than 1

Hence the maximum value of D = 1

We put D = 1 in the above equation because it is the maximum that it can get.

$P_o = 1^2 * 26.3^2 / 10$

$P_o = 69.169$ W

Hence the maximum power transferred in this case was 69.169 W
This is an interesting observation that really solidifies our belief in the importance of output resistance and its dominance in deciding the maximum power transfer.

It means that the converter efficiency is very well governed by the output resistance connected to the output of the converter and we need to govern that in order to preserve the efficiency of the system.

Now, another interesting question arises from this calculation.

Where did the power go from the system?

It is important to remember that we initially assumed our system to be ideal and lossless and based all our calculations on this assumption.

Remember that in an ideal converter,

$P_o = P_i$

Hence the loss of power from the system seems surprising considering the above assumption.

To find the answer to this question we go back to the previous key equation which gave us the above results.

$P_o = D^2 * V_i^2 / R$

Hence to account for the loss in power we modify the above equation as,

$P_o = P_i + P_L$

Where, P_L = Power Loss in the converter

Putting the above value of P_o in the above equation we get

$P_i + P_L = D^2 * V_i^2 / R$

Hence we do away with the assumption of an ideal converter and delve into the practical world by considering practical converters which are lossy and we have to take into account their losses as well.

Hence we find the value of power loss as,

$P_L = P_o – P_i$

We had found,
P_o = 69.169 W and P_i = 200 W

Hence, $P_L = P_o – P_i$
P_L = 200 – 69.169
P_L = 130.831 W

which is a huge amount of power loss which occurs in the converter.

Hence the efficiency (η) of the converter is calculated as,

η = (Output Power / Input Power) * 100

η = (P_o / P_i) * 100

η = (69.169 / 200) * 100 = 34.5845 %

Hence we observe that the efficiency of the converter is only about 35 % which is very low which is why this topic becomes all the more important.

Hence we now plot a curve between duty cycle and resistance in an ideal buck converter and see the variation between these 2 parameters.

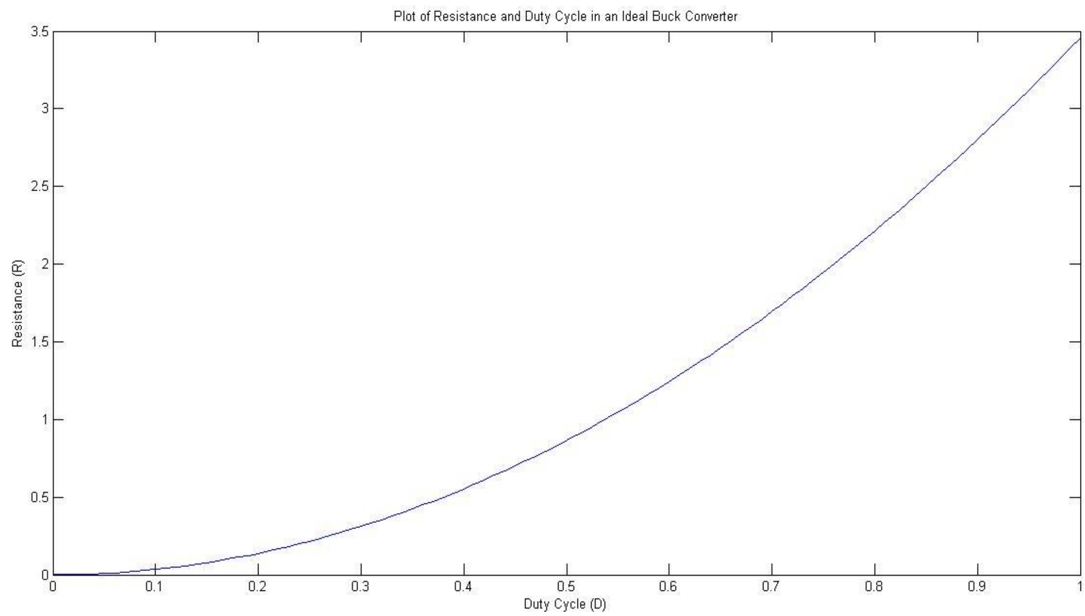


Figure 17. Variation between duty cycle and resistance in an ideal buck converter

Observe that the duty cycle axis is between 0 and 1 only as it is the range of duty cycle.

Hence we see that there is a direct relation between the duty cycle and the output resistance which governs the flow of power from the input to the output stage.

Let us see some results and compare our theoretical predictions from them.

We simulate the Photovoltaic system in MATLAB which we have been discussing and compare our results with those of the practically accurate results.

6.1 Modeling of the Solar PV system in MATLAB Simulink

We now simulate the following models in MATLAB Simulink:

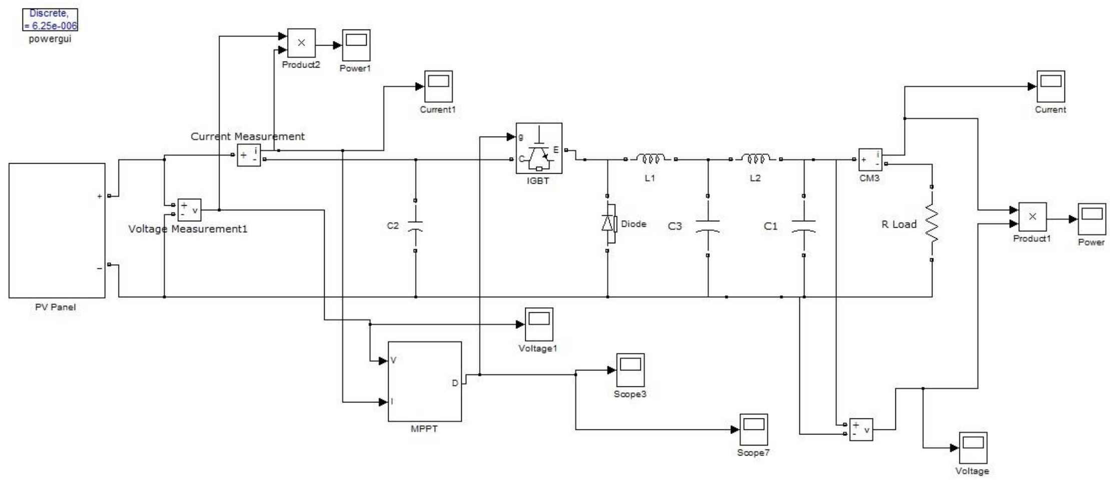


Figure 18. MATLAB Simulink model for PV system

In the above MATLAB Simulink model the solar PV system is modelled which includes the solar PV panel block which is a masked block and is explained below. Next to the PV Panel block, a buck converter is connected which bucks or steps down the DC voltage. The Buck converter contains the inductors L1 and L2 having the same value i.e. 5.85 mH and the capacitors C1 and C3 also have same values of 0.2564 mF. The buck converter also contains semiconductor devices such as the IGBT and the diode which are present in traditional buck converters. The IGBT gate signal is controlled by the MPPT controller which is responsible for Maximum Power Point Tracking.

Further, the Buck converter is controlled by a MPPT unit which takes the voltage and current of the PV panel as the inputs and tracks the maximum power by operating the PV panel at the voltage at which maximum power is extracted.

Finally, the output resistance is the load whose value is varied to study the effects on output power.

All quantities are measured and recorded using the ‘Scope’ block which is attached to the various quantities like the input voltage, output voltage, input power and output power.

A two stage filter i.e. 2 LC filters have been employed at the output stage to effectively smoothen out the ripples in output voltage, current and the output power.

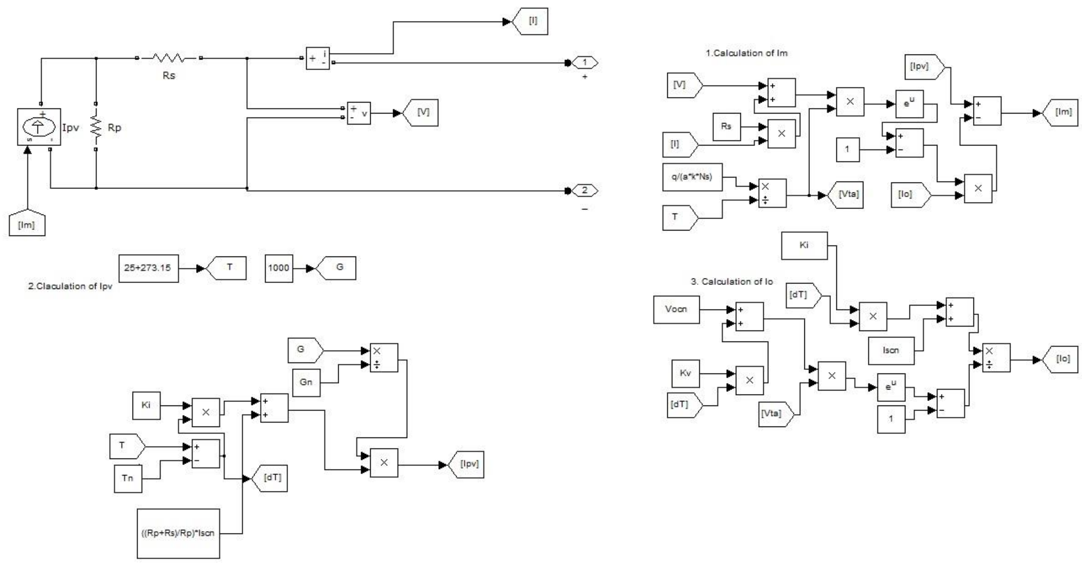


Figure 19. MATLAB Simulink model of Solar PV panel

The above MATLAB Simulink model unmasks the PV panel block which contains the modeling of a typical solar cell. The Ipv, Im and the Io of the solar cell is modeled using the equations (1) and (2) from the previous chapter on solar cells where the detailed formulas have been illustrated. The input quantities or parameters have also been illustrated in detail in that chapter.

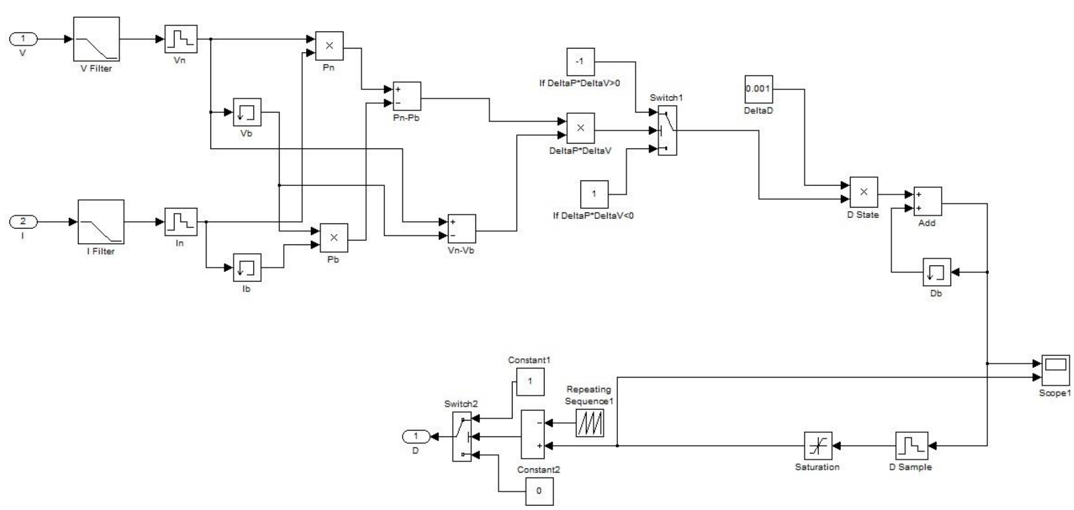


Figure 20. Modelling of MPPT (Incremental Conductance method)

6.2 Simulation Results

The Maximum Power Point Tracking - Incremental Conductance (I&C) method has been modeled using MATLAB Simulink in the above figure. The modeling has been done in accordance with the Incremental Conductance Algorithm illustrated in detail in the previous chapter on Maximum Power Point Tracking.

Now, we present the following plots for the various values of output resistances:-

a. Input Power (P_i)
b. Output Power (P_o)
c. Input Voltage (V_i)
d. Output Voltage (V_o)

We first consider the R = 2 ohms case:

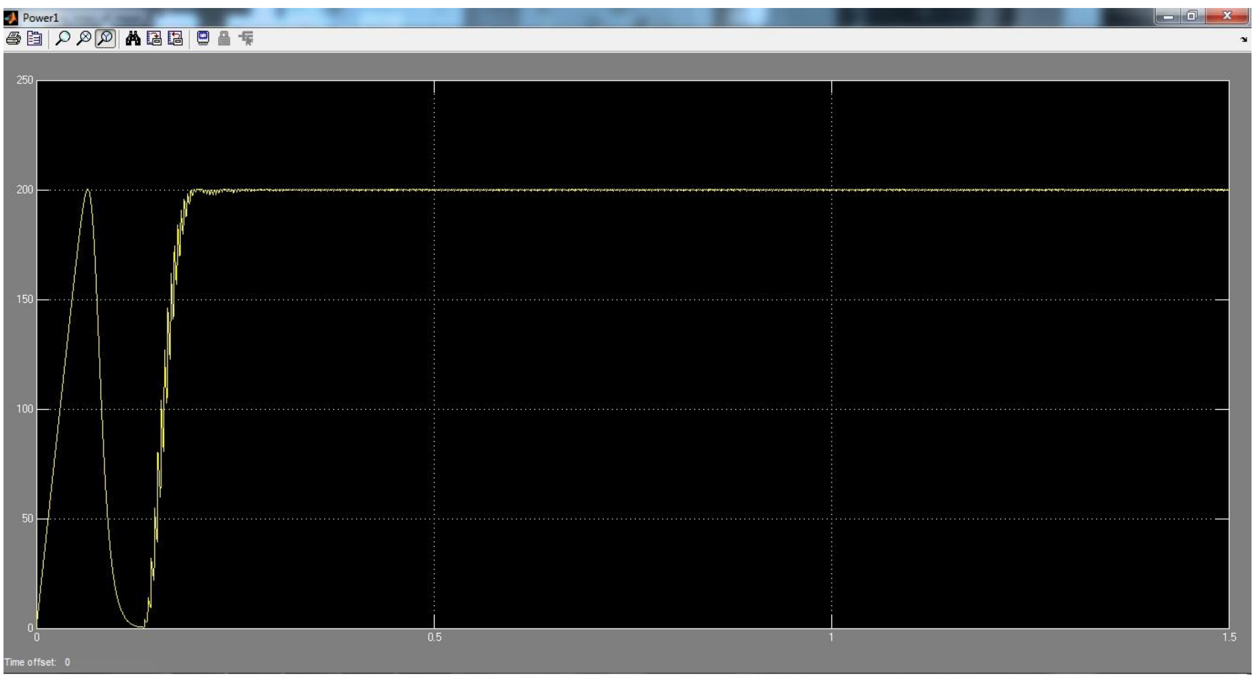


Figure 21. Plot of Input Power when R = 2 ohms

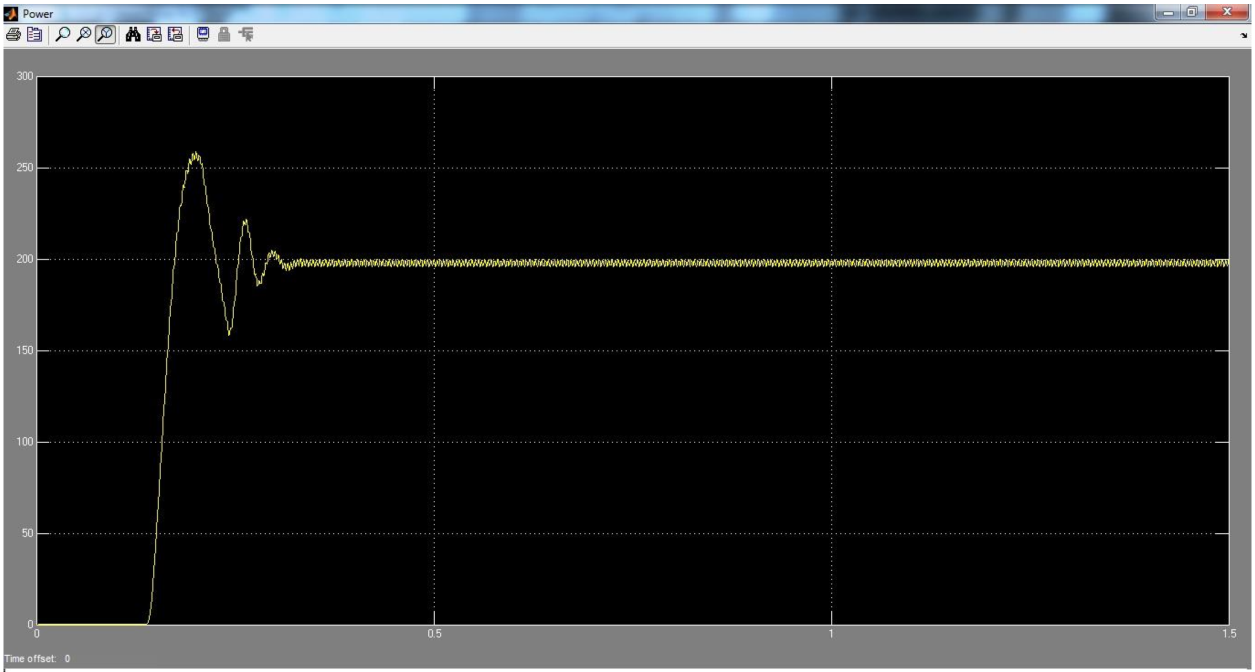


Figure 22. Plot of Output Power when R = 2 ohms

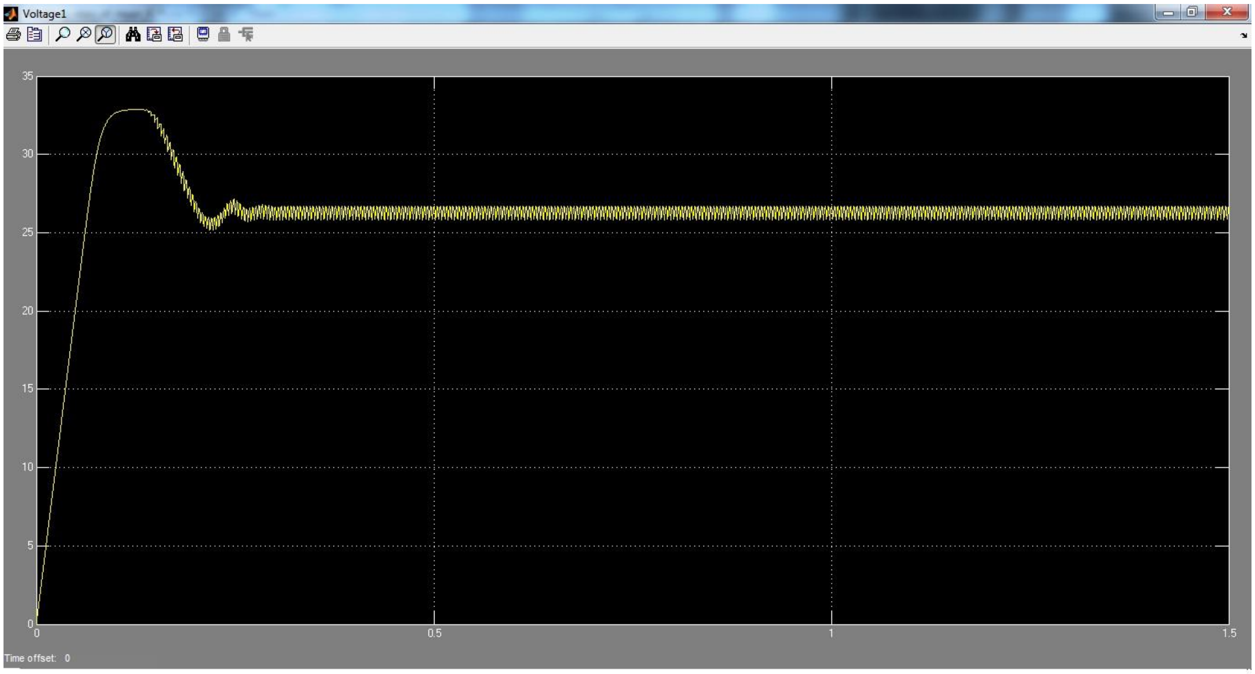


Figure 23. Plot of Input Voltage when R = 2 ohms

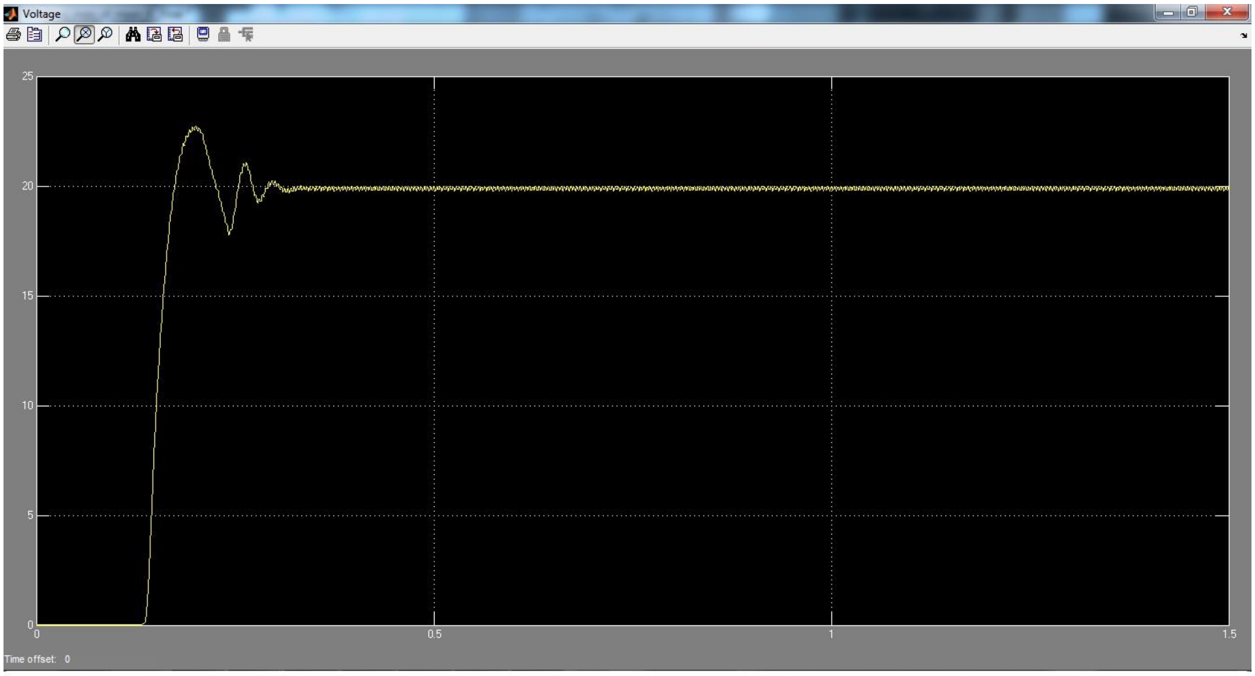


Figure 24. Plot of Output Voltage when R = 2 ohms

Hence at steady state the above plots have the values (averaged) as follows:

Input Power = 200 W
Output Power = 200W
Input Voltage = 26.3 V
Output Voltage = 20 V

Hence we get the Duty cycle as,
$D = V_o / V_i$
D = 20 / 26.3 = 0.7604

which is in really good consensus with our previous theoretical result which was 0.7604 also.

Also note the under damped response and the high maximum overshoot in the input and output power & voltage plots. This happens due to the low value of output resistance (i.e. 2 ohms). The low value of resistance influences the choice of circuit components like the inductor, MOSFET and capacitor which have to be chosen according to the peak voltage and current values.

Now we consider R = 3.45 ohm which we calculated as the borderline case.

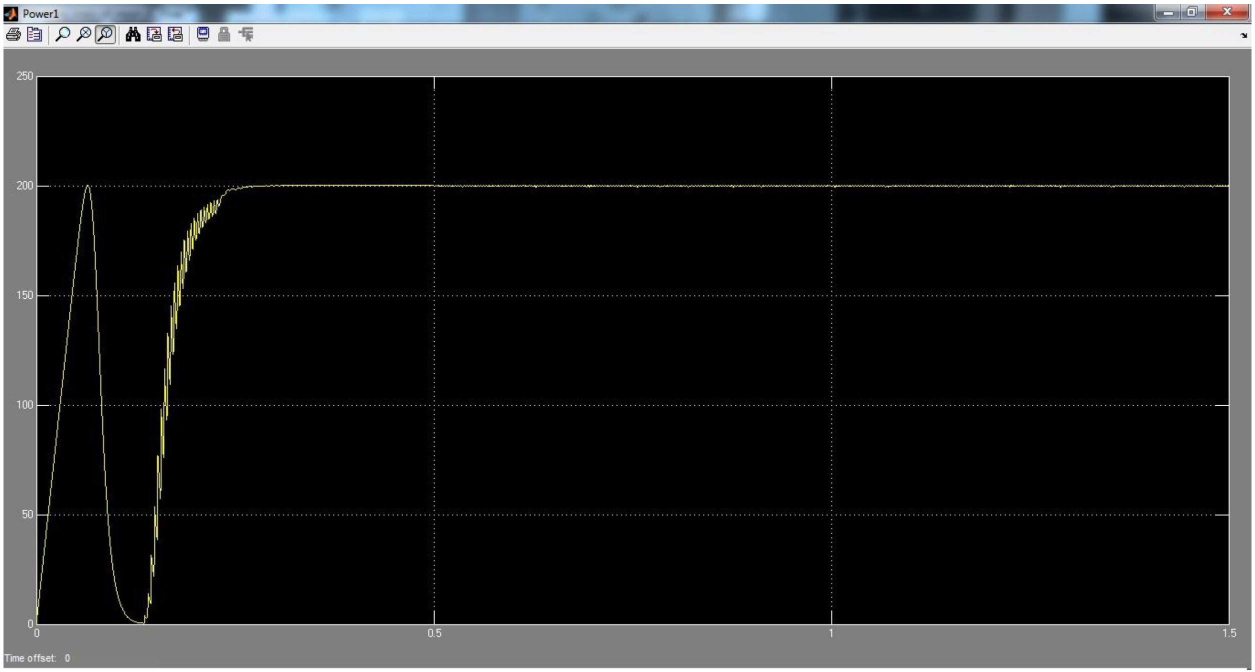


Figure 25. Plot of Input Power when R = 3.45 ohms

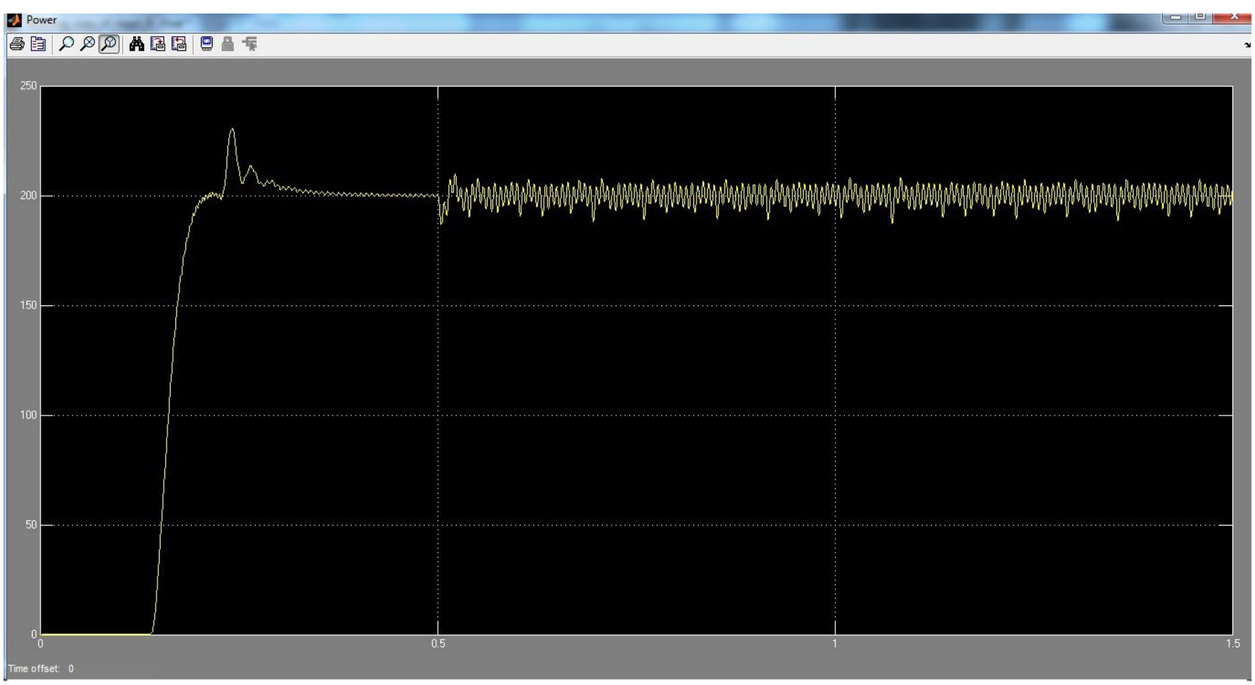


Figure 26. Plot of Output Power when R = 3.45 ohms

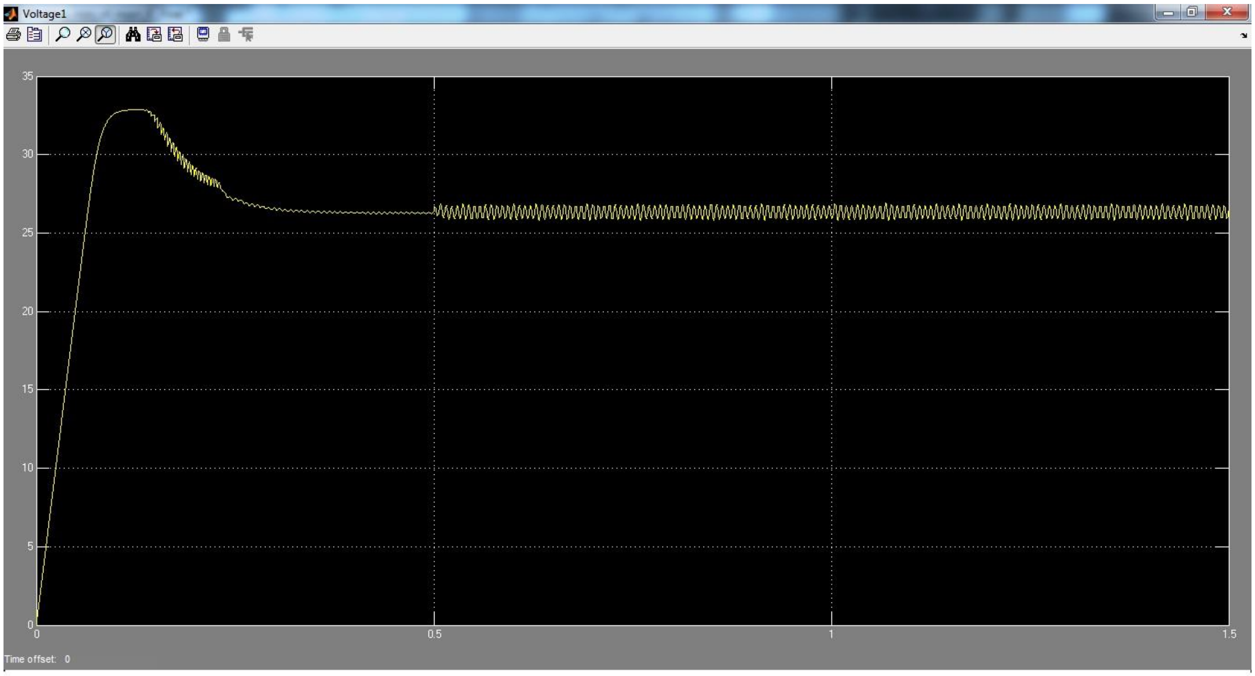


Figure 27. Plot of Input Voltage when R = 3.45 ohms

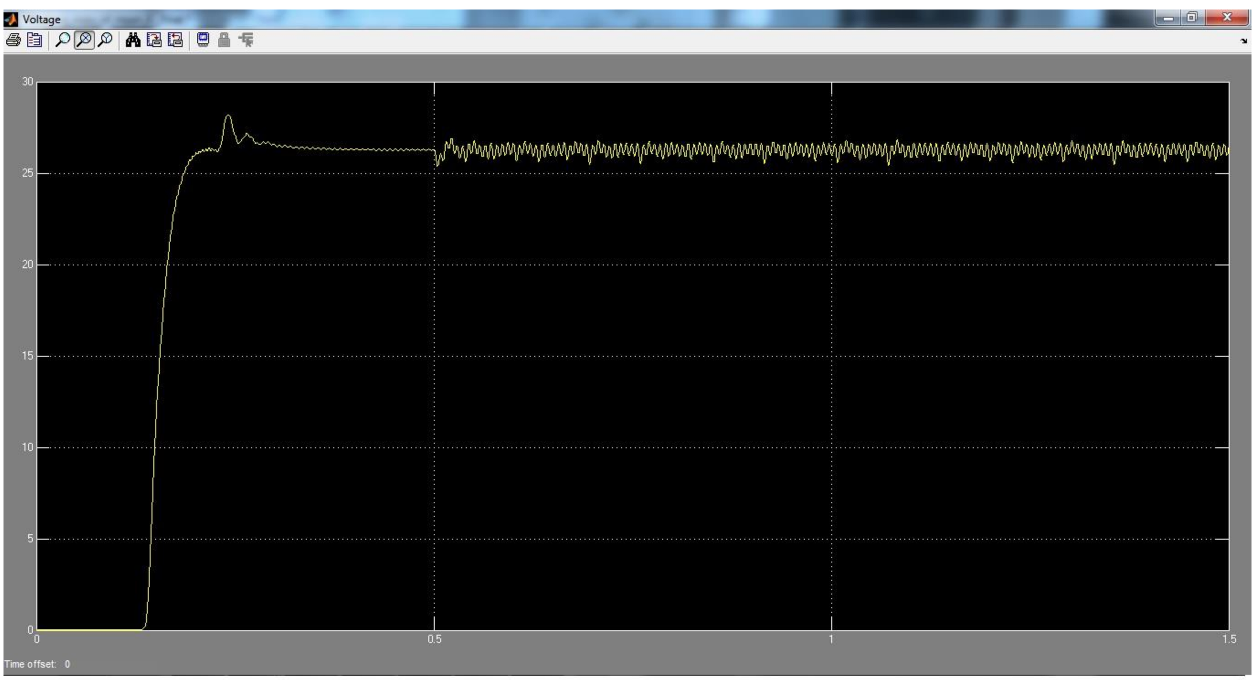


Figure 28. Plot of Output Voltage when R = 3.45 ohms

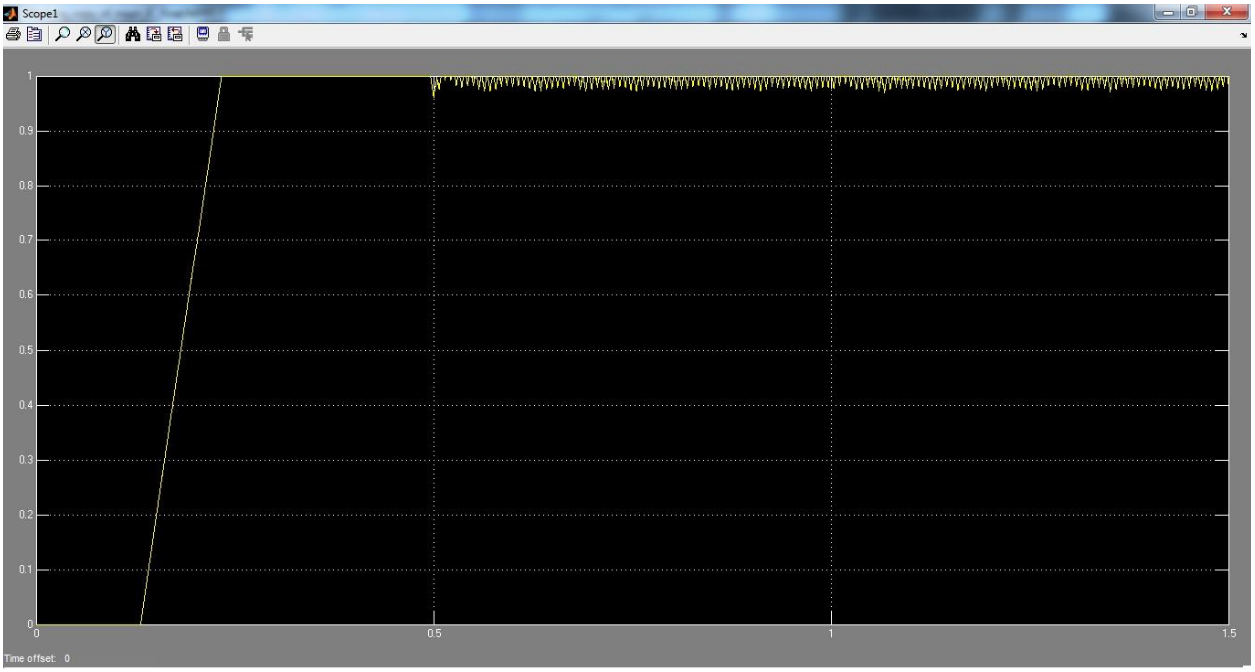


Figure 29. Plot of Duty cycle when R = 3.45 ohms

Hence at steady state the above plots have the values (averaged) as follows:

Input Power = 200 W
Output Power = 200W
Input Voltage = 26.3 V
Output Voltage = 26.28 V

Hence we get the Duty cycle as,
D = V_o / V_i
D = 26.28 / 26.3 = 0.9992 which is equivalent to 1.00

Hence we see that the both the results are in close consensus with each other. Since this case is a borderline case therefore it effectively yields a duty cycle of 1.

The high frequency oscillations in the output voltage are due to the oscillations in the duty cycle (around the value 1) and they can be effectively filtered to yield a smooth output.

Note that the under damped response from the previous 2 ohms case has changed and improved to an overdamped response and the high maximum overshoot in the input and output power & voltage plots has also reduced. This happens due to the increased value of output resistance (i.e. 3.45 ohms). This value of resistance influences the choice of circuit components like the inductor, MOSFET and capacitor which have to be chosen according to the peak voltage and current values.

Now we consider the 10 ohm case.

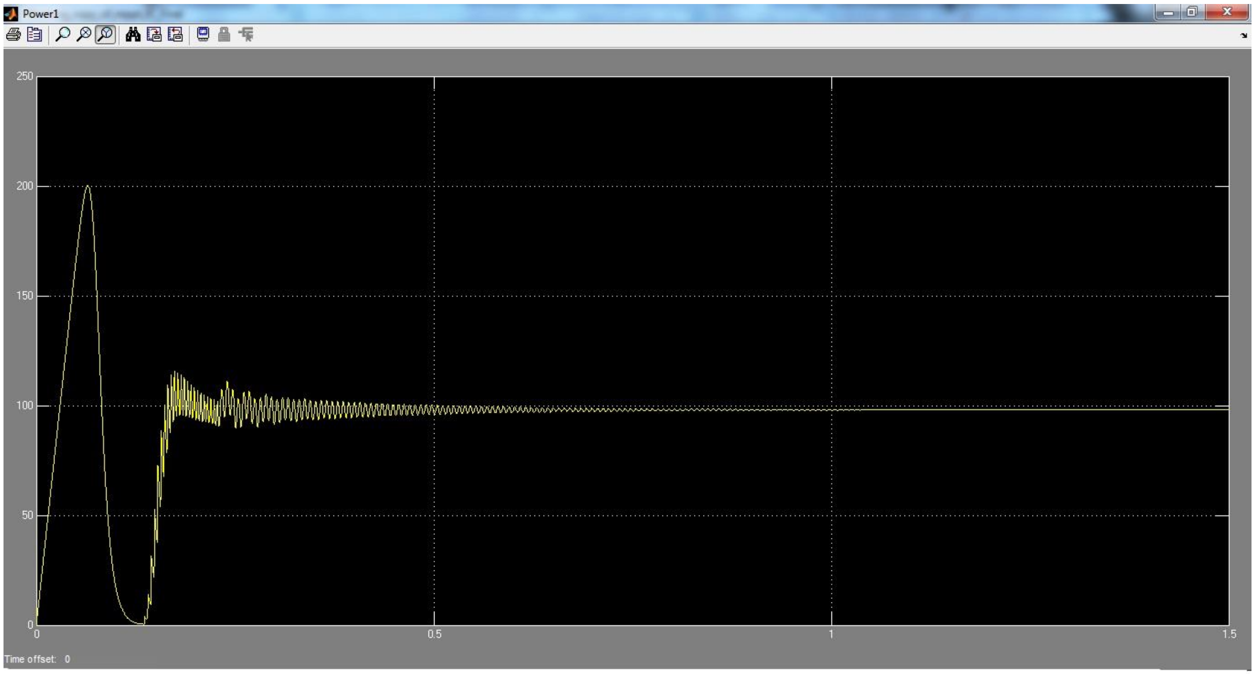


Figure 30. Plot of Input Power when R = 10 ohms

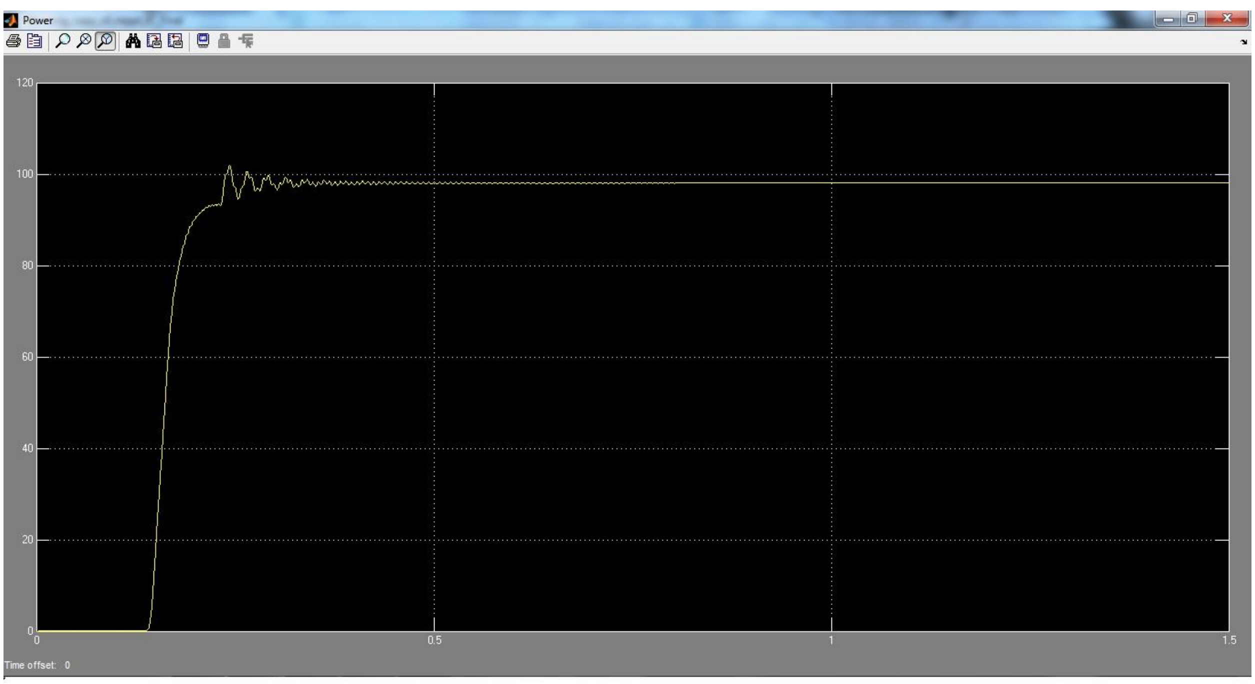


Figure 31. Plot of Output Power when R = 10 ohms

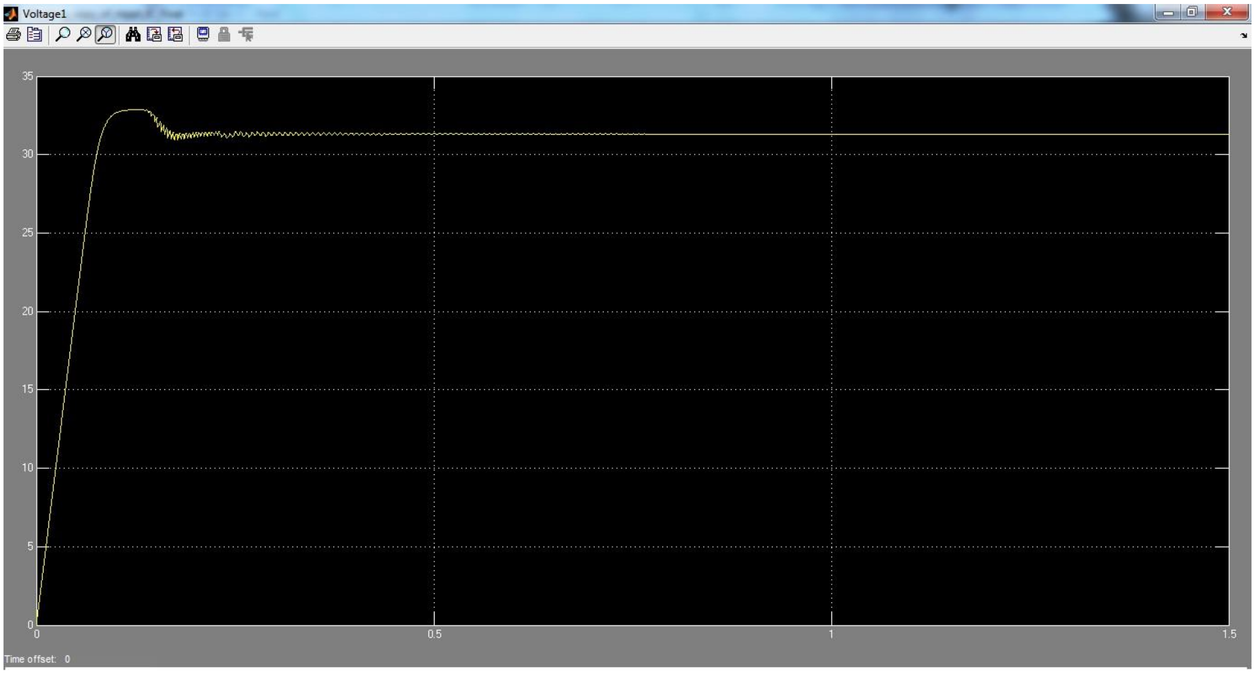


Figure 32. Plot of Input Voltage when R = 10 ohms

Figure 33. Plot of Output Voltage when R = 10 ohm

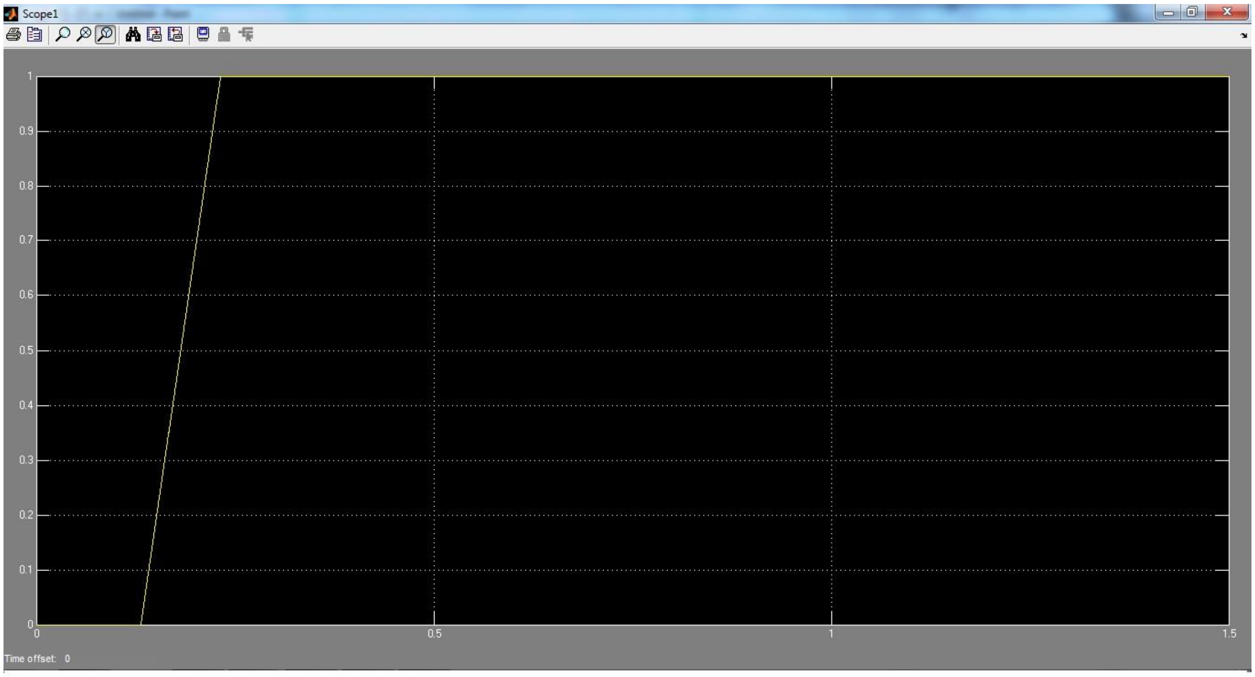


Figure 34. Plot of Duty cycle when R = 3.45 ohms

Hence at steady state the above plots have the values (averaged) as follows:

Input Power = 98.05 W
Output Power = 98.04W
Input Voltage = 31.314 V
Output Voltage = 31.311 V

Hence we get the Duty cycle as,
$D = V_o / V_i$
D = 31.311 / 31.314 = 0.99990 which is equivalent to 1.00

This case is interesting as we observe that the duty cycle didn't rise from 1.00 (which it cannot anyway) but the output has come down to less than 50% of the maximum power.

We see that both the results don't match at all because we had initially calculated the duty cycle as 170% (or 1.70) which is not practical. So the system would operate at the maximum duty cycle of 1.

The input power and the output power too don't match because we had calculated the output power as 69.169 W taking the maximum duty cycle (i.e. 1) but here the input and output power has value of about 98 W.

This case has interesting physical implications.
In this case the MPPT tried to track the maximum power but it failed in doing so because it would require a duty cycle of 1.70 which is impractical. Hence the duty cycle saturated at its maximum value of 1. The output powers also don't match because the MPPT in order to track the maximum power, increased the input voltage (& hence the output voltage because duty cycle is about 1) to

31.11 V (and hence the power) and we in our calculations had considered the input voltage to be at its Vmp of 26.3 V as in the previous cases.

Hence we conclude that the MPPT is more intelligent than us !!

Nevertheless, our derived formula still holds true even for this case provided we put in the right values i.e.

$P_o = D^2 * V_i^2 / R$

Here,
$D = 1 \quad V_i = 31.11$ V and R = 10 ohms

$P_o = 1^2 * 31.11^2 / 10$

Calculating we get,
$P_o = 96.79$ W

which is quite close to our value of 98 W.

Note that the under damped response from the previous cases has improved to a great extent and the output has become very smooth. The high maximum overshoot in the input and output power & voltage plots has almost disappeared. This happens due to the increased value of output resistance (i.e. 10 ohms). This value of resistance influences the choice of circuit components like the inductor, MOSFET and capacitor which have to be chosen according to the peak voltage and current values.

So we also observe that the choice of resistance plays a role in deciding even the system response. If the output resistance is too low then we may get a good output but in the same place we may also get an undesirable response .And if the output resistance is too high then we may get a good response but the efficiency may suffer to a great extent. Hence we have to make a trade off and choose the optimal values like the middle case of a 3.45 ohm resistance which combines both, a good response and a good efficiency. This holds true even in the case of non ideal converters in which, at low duty cycles even the efficiency goes low due to the switching losses which we will discuss later.

Therefore even in variable output resistance systems we should try to maintain the resistance at the critical resistance so as to get the desired output.

Hence we see that the output resistance plays an important role in deciding the system performance and a system could deliver 200 W at the right choice of resistance but the same system's output could reduce to less than 50% as in the above case if the output resistance is not accounted for.

The ideal converter gives us the privilege of 0 loss i.e. throwing the whole input power to the output stage. So in this case the MPPT just tracks the maximum power and only the "lossless" transfer occurs inside the converter (apart from varying the voltage and current levels). However things are not so simple in the non ideal world and the analysis becomes complex in case of non ideal buck converter.

We now consider the converter as a non ideal buck converter and have a look at their results which would help us get an insight into the practical converters employed in PV systems.

We plot the curves between the efficiency and duty cycle in a non ideal buck converter for different values of output resistances.

Even though the input voltage is dependent upon the Maximum Power Point Tracking (MPPT) (which controls the duty cycle) controller, we have considered the voltage as independent of duty cycle in order to simplify the process and get a rough insight into the variation of efficiency and the duty cycle.

We consider the values of forward voltage drop as 0.6 V, the ohmic resistance of the inductor as 1 ohm and the input voltage of the converter as at the maximum power point i.e. 26.3 V.

From the analysis of non ideal buck converter done earlier we get,

$P_o = (DV_I – (1\text{-}D)V_d)^2 . \; / [(1 + R_L/R)^2 . R]$ and
$P_i = V_I I_g$

Here V_I is the input voltage and the I_g is the input current
$I_g = DI_L$ and $I_L = V_o / R$

We get,

$\eta = (1\text{-} (1/D – 1) (V_d/V_I) / (1 + R_L/R)$

Hence Taking R = 2 ohm case we get the plot as

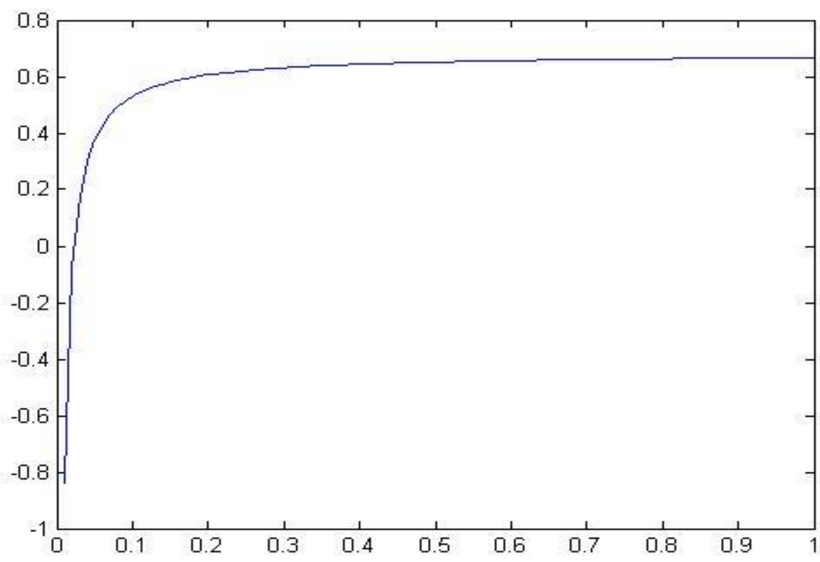


Figure 35. Plot of Efficiency vs Duty cycle for R = 2 ohms

Hence we see that the maximum efficiency that can be extracted from the system is around 65% only which is too low.

Below is a plot taking R = 3 ohm,

Hence we see that the maximum efficiency rises to near about 80% which is better than the previous case of R = 2 ohm.

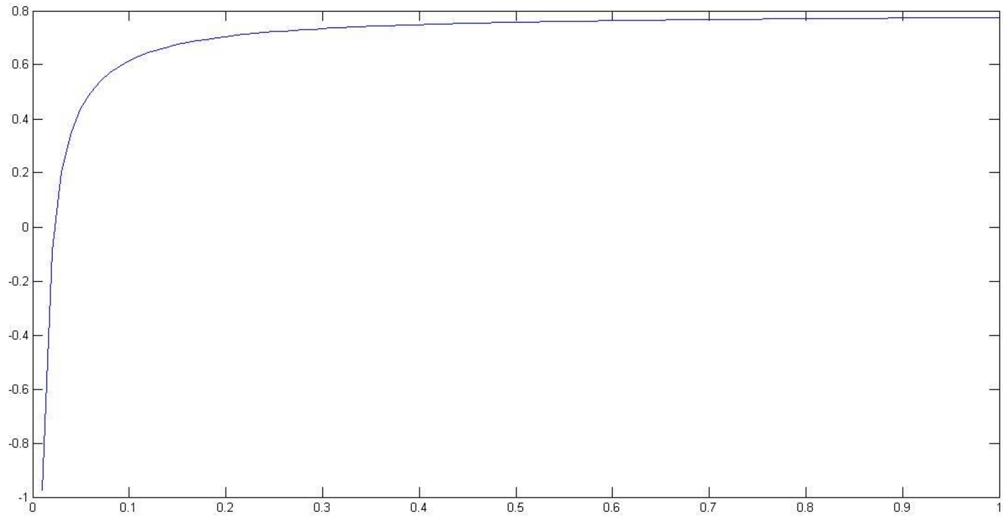


Figure 36. Plot of Efficiency vs Duty Cycle for R = 3 ohms

Thus, the choice of output resistance plays a major role in deciding the efficiency of the solar PV system which is evident from these results and it should be chosen carefully.

Chapter 7

ENERGY STORAGE IN PV SYSTEMS – BATTERIES

An electric **battery** is a device which stores the generated electrical energy in the form of chemical energy and vice versa as and when required consists of multiple (2 or more) electro-chemical cells that change the amassed chemical energy into electrical energy. Each cell constitutes a positive terminal (which is referred to as cathode) and a negative terminal (which is referred to as the anode). The current is produced in the battery because of the electrolyte which allows the stream of ions in the cell in amid the battery terminals and the electrodes.

Primary batteries, also known as disposable batteries or single use batteries are those batteries which are can be used only once and are then discarded because of the irreversible changes in their electrode material during their discharge. Some common examples of such batteries are alkaline batteries which are very commonly used in flashlights and a huge number of other portable or mobile devices. Secondary (rechargeable batteries) batteries, on the contrary, can be simply charged, discharged and then even recharged an abundant number of times because the innate composition of the electrodes can be established back by back or an opposite current which flows during the time of charging. Several familiar examples include the lead-acid batteries which are applied in motor vehicles, automobiles & lithium ion batteries which are widely used in mobile or transportable electronic devices.

Batteries appear in abundant sizes and shapes, from the tiniest of the sizes which are so commonly used to power hearing devices and calculators to battery banks of the magnitude of big rooms that are crucial to provide reserve power for computer data centers and telephone exchanges or places where even the smallest power outages are not acceptable.

Batteries have very small specific energy (energy per unit mass) than fuels which are in popular or common use such as gasoline, diesel etc. This is to some extent balanced by the high efficiency electric motors which perform mechanical work when they are measured up to to combustion engines.

7.1 Principle of Working

Batteries directly convert the energy amassed in the form of chemical compounds to a further useful form of energy i.e. electrical energy. A battery comprises of a number of voltaic cells. Each cell contains 2 half cells which are attached in a series arrangement by a conductive electrolyte which include anions and cations. 1 half cell comprises of the negative electrode, i.e. the electrode to which the anions (negatively charged ions) migrate and the electrolyte and the additional half-cell comprises of the positive electrode to which cations (positively charged ions) and the electrolyte. Constant oxidation and reduction reactions occurring in the battery are the source of power. Cations are the ions which are reduced i.e. electrons are added to them and they become neutral at the cathode throughout the charging process, while the anions are the ions those are oxidized i.e. the electrons are detached from the anions at the anode through discharge. These electrodes are not in a direct contact with each one, but are electrically linked to each other through the electrolyte present in the cell. Some cells use dissimilar electrolytes for each one of the half cell. The separator there in the cell permits the ions to stream amidst the half cells, but it avoids the assimilation of both the electrolytes.

Each one of the half-cell has an electromotive force (or emf), which is decided by its capacity to drive the electric current from internal to the external of the voltaic cell. The total electromotive force of the cell is calculated by taking the difference between the electromotive forces of their respective half-cells. Hence, if the electrodes have their electromotive forces as E_1 volts and E_2 volts respectively, then the total emf is given by E_2 - E_1 volts; in further words, the net electromotive force is the subtraction amid the reduction potentials of both of the half reactions.[14]

The electrical driving force is given by ΔV_{batt} and if taken across the terminals of the cell is known as the *terminal voltage (difference)* and it is measured in the units of volts. An extremely important parameter of the cell is its open circuit voltage and is the voltage across the cell when the cell is both discharging nor charging is known as the open-circuit voltage and it equals the electromotive force of the cell. Each and every practical (non-ideal) cell has an internal resistance and hence the terminal voltage dips during the discharging phase because of the voltage drop across the internal resistance while the terminal voltage is more when the cell is in the charging mode.

An ideal cell has a very small internal resistance which could be neglected, so it would retain the terminal voltage of the constant value of E until it gets exhausted, which will then suddenly drop to zero. If such a cell maintained a voltage of 1.5 volts and stored 1 coulomb charge then the work it has performed were 1.5 Joules on complete discharge of cell. In real cells, the internal resistance of the cell rises during discharge and the open circuit voltage plunges all through the discharge condition. If the resistance and voltage are plotted on the graph paper with time on the X-axis, the graphs attained are a curve, then the figure of curve obtained is due to the picky chemistry of the cell and the internal arrangement of the cell which has been utilized.

The voltage which is built up across the terminals of the cell directly dependent upon the energy emitted by the chemical reactions between the electrolyte and electrodes. The zinc–carbon cells and alkaline cells have diverse chemistries, but have about the same electromotive force of 1.5 volts. In the same way, NiMH and NiCd cells have dissimilar chemistries, but they have about the same electromotive force that is equal to 1.2 volts. The high electrochemical potential changes which occur in the reactions concerning the lithium compounds give lithium cells an electromotive force of 3 volts or more than that.

Most of the energy storage applications, such as in solar PV systems require deep cycle batteries. The Lead-acid battery is also available in a sealed "gel-cell" version with additives, which turns the electrolyte into a non spill able gel. The gel-cell battery, therefore, can be mounted sideways or upside down. The high cost, however, limits its use in military avionics. [3]

7.2 Types of Batteries

Batteries are classified into primary and secondary types:

- *Primary* batteries change the chemical energy to electrical energy irrevocably. When the reactant supply is exhausted out, energy cannot be carried back readily to the battery.
- *Secondary* batteries can be re-energized again and again, because their chemical reactions can be reversed by applying an opposite voltage to supply energy to the cell almost re-established back their native composition.

Some primary batteries which are employed, for example, in telegraph circuits, by replacing the electrodes the electrodes were restored back to their operation. Secondary batteries are not for an indefinite period rechargeable because of dissipation of the active materials, internal corrosion or loss of electrolyte.

7.2.1 Primary batteries

Primary batteries, or primary cells, can generate current instantly as soon as they are finished assembling. These are the most usually used batteries in moveable devices and they have less current drain or are used only occasionally, or are used if the power source is considerably far away from, such as in communication circuits or alarms where the electric power is only intermittently accessible. Disposable primary cells are not reliable as they can't be constantly recharged, because the chemical reactions can't be simply reversed and the vigorous materials may not come back to their original forms. Battery manufacturers in general, never recommend attempting the recharging of primary cells. [15]

Primary batteries have much higher energy densities than their counterpart rechargeable batteries, but the disposable batteries do not deliver great performance under applications involving high-drain i.e. with loads under 75 ohms (75 Ω).

The most common types of disposable batteries are zinc–carbon batteries and alkaline batteries.

7.2.2 Secondary batteries

Secondary batteries, also known as *secondary cells*, or *rechargeable batteries*, are charged before first use and they can be recharged and discharged again and again for subsequent uses. They are typically put together in discharged state with active materials. Rechargeable batteries can be very well (re)charged by applying an electric current, in order to reverse the chemical reactions that occur during discharge/use process. Battery chargers or chargers simply, are the devices which supply the appropriate current for charging these batteries.

The most primitive or the oldest rechargeable battery type is the lead–acid battery. This technology is a very old technology which contains the liquid electrolyte in an unsealed container, and it requires to keep the battery erect and the area should be well aerated to make sure the safe dispersal of hydrogen gas which is formed during the chemical reaction and which evolves during overcharging. The lead–acid battery has low energy density i.e. it is comparatively very heavy for the quantity of electrical energy that it can store or supply. But the most attractive characteristics which it possesses are its high surge current levels makes it universal where its capacity (over approximately 10 Ah) and the low manufacturing cost which are very important and even more important than the handling and its weight issues. Its common application is the most common, car battery, which can in general, deliver a peak currents of the order of even 450 amperes.

The sealed valve regulated lead–acid battery (VRLA battery) is well established in the automobile industry as it is great substitute for the lead–acid wet cell. The immobilized sulfuric acid electrolyte which is used in the VRLA battery, extends the shelf life of the battery and even diminishes the chances of leakage. VRLA batteries typically immobilize the electrolyte. The 2 types of VRLA batteries are:

- *Absorbed Glass Mat* (AGM) batteries which in a special fiberglass matting absorb the electrolyte.
- *Gel batteries* (or "gel cell") which uses a semi-solid electrolyte.

Several sealed dry cell types are the other portable rechargeable batteries that are very helpful in applications such as laptop computers and mobile phones. Cells of this type include lithium-ion (Li-ion) cells, nickel metal hydride (NiMH), nickel–zinc (NiZn), nickel–cadmium (NiCd) (listed in their order of respectively decreasing cost and power density). Li-ion batteries comprise the maximum share of the dry cell rechargeable market. NiCd battery has been replaced by the NiMH battery in nearly all applications due to its higher energy capacity, but 2 way radios, medical equipment and the power tools still use NiCd batteries.

Fresh growth in the meadow of batteries consist of batteries with embedded electronics such as the USBCELL, which allows the charging of an AA battery through a nanoball battery, USB connector, which permit for the discharge speed of about 100 times larger than the batteries used currently, and smart and intelligent battery packs with monitors and battery protection circuits which play a crucial role in preventing damage to the battery in the event of over-discharge. Low self-discharge (LSD) (which is still a challenge) permits secondary cells to be charged before shipping the batteries.

7.3 Batteries used in Solar PV applications

Now we see the batteries and their types which are used in Solar PV applications:

7.3.1 Lead Acid

Lead acid batteries are still very extensively used in automobile applications and they are automobile batteries in which the electrodes comprise of grids of metallic lead which enclose lead oxides that differ in composition in both the charging and discharging stages. The most extensively accepted electrolyte is dilute sulfuric acid.

Even after more than a 100 years of discovery of the lead acid batteries, they are still the most accepted choice for about 99% of power backup systems and solar PV applications. By means of an improved accessibility during the previous few years of the novel AGM (Absorbent Glass Mat) batteries and the true deep-cycle batteries, not much need of using any other type of battery has been felt. Batteries prepared for use in various industries can last as long as for about 20 years with a practical care, and even the distinctive deep cycle batteries, such as the ones which are used in the golf car, should last for 3-5 years. Intermediate batteries and other batteries also should even last from 7 to 12 years.

7.3.2 Nickel Cadmium

Alkaline storage batteries are the batteries in which nickel oxide comprises the positive active material and cadmium constitutes the negative material.

Important Features:

a. Low efficiency (65-80%)
b. Very expensive to dispose of after use - Cadmium is considered very hazardous.
c. Very expensive
d. Non-standard voltage & charging curves may make it difficult to use essential equipment, such as standard inverters and chargers.

Conventional pocket plate NiCd batteries have many good points apart from the limitations given above such as non-freezing, low self-discharge etc. but their cycle life is almost equal to, if as good as the properly chosen lead-acid battery. In other words, they have long life in terms of time, but not in the terms of cycles. This pushes them as a great option for emergency/standby systems, but not very great for systems involving daily charging and discharging cycles, such as in household applications. Hence they are not very much recommended for most solar PV applications or power backup systems.

7.3.3 Nickel Iron

Alkaline-type electric cells which use potassium hydroxide (KOH) as the electrolyte and cathodes made up of nickel plated steel wool substrate with active nickel material and anodes made up of steel wool substrate with an active iron material. This was invented by Edison and is the original "Edison Cell". They have a very long life and has an energy storage density of about 55 watts per kilogram.

These cells have as many limitations or drawbacks as the number of advantages when they are compared to their counterpart lead-acid type batteries. It is strongly suggested that the potential alkaline users should evaluate the economics and performance claims of the product seller cautiously to decide the appropriateness of the battery being considered.

Important Features:

a. Very high rate of self-discharge
b. High internal resistance which means the voltage drops can get large across the series cells.
c. Low efficiency – which can be as low as 50%, usually 60-65%.
d. High specific weight/volume
e. High gassing/water consumption

Can decrease the by and large efficiency of the solar system as much as about 25%.

This also points towards the variation of output voltage with the load and which charges much more than the other batteries. If an inverter is being used, the inverter must be designed keeping these voltage swings in mind. Also, NiFe's may not be used if the system depends on a stable voltage, for example if certain common DC appliances such as a refrigerator have to be run directly off the batteries. Also while using NiFe's to power DC lighting, fluctuation in light intensity is normally observed. A voltage regulator could be very well used to feed those appliances, but that would mean decreasing the efficiency to an even further extent.

It shows that the lead acid batteries although being an environmental hazard have stood the test of time and are the most suitable battery type for solar PV applications after the NiFe battery. The best cost factor of lead acid batteries doesn’t let them go obsolete even in the 21st century. But we have to search for better solutions because today sustainability is also a very important issue. Hence there is a lot of scope for research in various battery technologies so as to come up with a better alternative which has lower losses and is not an environmental hazard. Until then, the high losses in charging and discharging will add to an extra 25-40% to the dimension of the solar panels you will require for the same energy usage.

In short, despite the hype about long life and thousands of cycles, it is felt that overall these batteries are not a very ideal choice for all solar power applications.

Other Technologies:

There are other types of batteries also there in the markets, but most are far too expensive for any but for the most specialized application - such as space shuttles.

7.4 Battery Charging in PV Systems

As explained in the previous section, there are a number of battery types and chemistries which are in present in the market. Batteries are an integral part of PV system. The importance of batteries shows up at night when the solar PV system stops working due to the absence of sunlight. Hence we have to provide some backup or storage so as to meet the load demand at night time as we do by using the solar energy during the daytime. [30]

In the earlier sections we had discussed about the effect of resistance on the converter. In practical solar PV systems there may not be an actual resistance attached to the output of the converter. But there is always an output voltage and an output current which is measured at the output terminals of the converter. Hence the output resistance can be effectively calculated by the V=IR relationship and the ideas developed above can be applied effectively even when there is no actual resistance connected.

For using the battery as an energy storage medium we would have to know about some of its electrical characteristics.

Hence we introduce some electrical parameters which are commonly used in battery charging.

7.4.1 Battery Capacity

A battery's *capacity* is defined as the quantity of electric charge that can be delivered by the battery at the rated voltage. The battery capacity is dependent on amount of electrode material i.e. more electrode material enclosed within the cell, the greater will be the battery capacity. A smaller cell has lower capacity than a bigger cell both having the same chemistry, even though they build up the same open-circuit voltage. Energy stored in the battery is measured in units of kilowatt-hour (kW·h) and the battery capacity can be measured in units of amp-hour (A·h)

The rated capacity of the battery is typically articulated as the product of time which is equivalent to 20 hours multiplied by the current that a fresh battery can constantly supply for 20 hours at the temperature of 20 °C (68 °F), whilst lasting over a specific terminal voltage per cell. For example, a battery which has a capacity rating of about 100 A·h can deliver a current of 5 A over a 20-hour period at room temperature. But this doesn't convey that it can supply only a current of 5 A. It typically means that the product of the time and current cannot be larger than 100 A-h. As another example, it can even supply a current of 25 A its maximum duration will be maximum of 4 hour only. But practical batteries have a ceiling over the maximum current that they can deliver and hence that current must not be exceeded.

The fraction of stored quantity of charge which a battery could deliver depends on a lot of factors which includes taking into account the rate of delivery of charge (current), battery chemistry, required terminal voltage, ambient temperature, the storage period and other such factors.

The higher will be the discharge rate, the lower the will be the capacity. The relation between the current, the capacity and the discharge time for a lead acid battery is estimated (over a typical range of current values) by Peukert's law which is given by:

$$t = \frac{Q_P}{I^k}$$

Here,

I is the current drawn from the battery (A).

Q_P is the capacity when the battery is discharged at a rate of 1 amp.
k is a constant whose value is around 1.3
t is the amount of time (in hours) that the battery can sustain.

Batteries that are discharged at little fractions of their capacity or which are stored for a longer period of time or which lose capacity because of the existence of irreversible *side reactions* that use charge carriers without producing the current. This occurrence is referred to as the internal self-discharge. Additionally, other side reactions can occur when batteries are recharged, reducing the battery capacity for following discharges which will be there in the future. After sufficient recharges, practically all battery capacity is lost and the battery discontinues producing any power. Hence there are a restricted number of cycles that the battery can uphold.

Limitations on the rate of passage of ions through the electrolyte and the internal losses in energy cause the efficiency of the battery to differ. Over a least threshold, a lower rate discharging delivers more battery capacity than at a higher rate of discharge.

Batteries installations involving differing A·h ratings does not influence device operation (but it may have an effect on the interval of operation) rated for a definite voltage unless the limits on the load are exceeded. Digital cameras constitute the high-drain loads which can reduce the total capacity, which happens with alkaline batteries. For example, a battery which is rated at 2 A·h for a 10 or 20 hours of discharge wouldn't maintain a current of 1 A for complete 2 hours as its declared capacity implies.

7.4.2 C rate

The quantity of rate at which the battery is getting discharged is called as the C-rate. It is defined as the discharge current divided by the theoretical current drawn, under which the battery would deliver its nominal rated capacity in one hour. For an example, a 1C discharge rate will deliver the battery's rated capacity in 1 hour. Similarly, a 2C discharge rate implies that it would discharge at a rate which is 2 times as fast (i.e. 30 minutes). In the same way, a 1C discharge rate on a battery of 1.6 Ah rating means a discharge current of 1.6 A. Similarly, a 2C rate would mean a discharge current of 3.2 A. Normal standards for rechargeable batteries usually rate its capacity more than 4 hour, 8 hour or a still extended discharge time. Due to the voltage drop in the internal resistance and the chemical processes occurring inside the cells, a battery hardly ever delivers the capacity which is nameplate rated in just an hour. The types intended for special purposes, such as in uninterruptible power supplies used in computers, which may be rated by the manufacturers for the discharge periods which are a good deal less than 1 hour. [21]

We see a small case for the most widely used batteries in the solar PV systems which are the classic lead acid batteries. The open circuit voltage of a lead acid battery (i.e. when they are neither supplying the current nor they are being charged) will differ according to the state of charge of the battery. The graph given below corresponds to a usual 24 volt lead acid battery which is neither yet charged nor did it have any current drawn from it for about 2 hours.

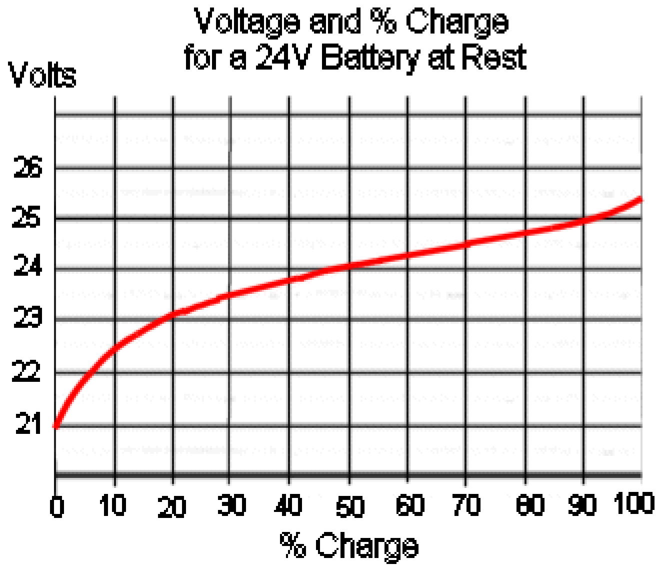


Figure 37. Volt-Charge characteristics of lead acid battery [21]

7.4.3 State of Charge

State of charge is a very important parameter of the battery as it tells us the amount of energy which is left in a battery evaluated with the energy it had when it was fully charged which gives the user an clue of about how much longer time the battery can continue to perform before it needs to be recharged. Hence, using the fuel tank analogy of an automobile, the State of Charge (SOC) estimation is often known as the "Fuel Gauge" or the "Gas Gauge" function.

The State of Charge (SOC) is defined as the existing capacity that is expressed as a percentage of some reference, more likely the current but sometimes also its rated (which was at the latest charge-discharge cycle) capacity but this uncertainty can sometimes lead to errors as a result of confusion. It is not typically an absolute measure in coulombs, kWh or Ah of the energy left in the battery which can be less confusing.

7.4.4 Battery Discharge Characteristics

A battery which is charged to the full will have a voltage of about 25.5 volts. As the current is drawn off from the battery & as the the charge level reduces, the voltage at first, decreases very rapidly and again it would become a necessity to stop drawing current from the battery for a couple of hours so as to become able to measure the true voltage of the battery. As further more current is drawn off the battery, the rate of voltage drop slows down and reaches a voltage of about 24V it is when the battery can be perceived at being about half the capacity.[21]

As the battery reaches a state of full discharge, the voltage starts to fall down even more quickly again.

It is extremely important for a battery to never reach the full discharged state, because if that happens, the inverter will automatically disconnect the supply when the voltage reaches around 22 volts in order to prevent the over discharging of battery.

A very interesting practical point to which can be made here is that, since the terminal voltage drops when some power load or an inverter is drawing a heavy current from the battery, this very simply means that the battery should be someplace at least over 50% charging in order to avoid the inverter cutting out the supply due to the low voltage.

The bigger the battery, the lesser this voltage drop will be, and a bigger percentage of charge will be obtainable at times of drawing heavy currents from the battery.

7.4.5 Battery Charging

If a voltage is applied to the terminals of the battery which are which has a value greater than the voltage of the battery, a current will flow through the battery in the opposite direction of its direction of supplying current, and the battery will be in its charging mode and it will charge.

The rate of charge or current that flows through the battery depends upon the difference between the external voltage which is applied to it (from solar panels etc) and the voltage of the battery. The solar panels which are intended for a 24 volt system are usually capable of producing over 30 volts because solar being an intermittent source can supply less or more energy depending upon the irradiation. This voltage makes sure that the panels are capable of fully charging the battery.

While it is beneficial for the good performance of the battery and its extended life that it ought to be charged fully on a regular basis, however if the battery has reached 100% SOC or a battery has been charged to its full capacity, it is essential not to continue the charging process as this can damage the battery. That is why a Charge Controller is necessary to ensure that the battery present in the system is never over charged.[21]

7.4.6 Battery Efficiency

The Lead Acid battery is not a 100% efficient battery for storing electricity – i.e. the energy that we obtain will never be equal to the amount of energy that is put in when charging. Usually, an efficiency level of approximately 85% is assumed frequently. The efficiency level of the battery depends on a number of factors which include the rate of charging or discharging.

The higher the rate of charge or discharge, the lower will be the efficiency. The state of charge of the battery will also affect the charging efficiency. If the battery is charged to about half or less, then the charge efficiency may be over 90%, dropping to about 60% value when the battery is more than 80% charged.

However it is found that if the battery is only charged partially, efficiency may be decreased with each cycle of charging and if this situation continues (the batteries never reaching full charge), the life of the battery may be further reduced.

Now we model a simple battery charging technique using the MATLAB Simulink interface.

7.5 Battery Charging Simulation and Results

In this section we model and simulate a simple battery charging technique using the MATLAB Simulink interface.

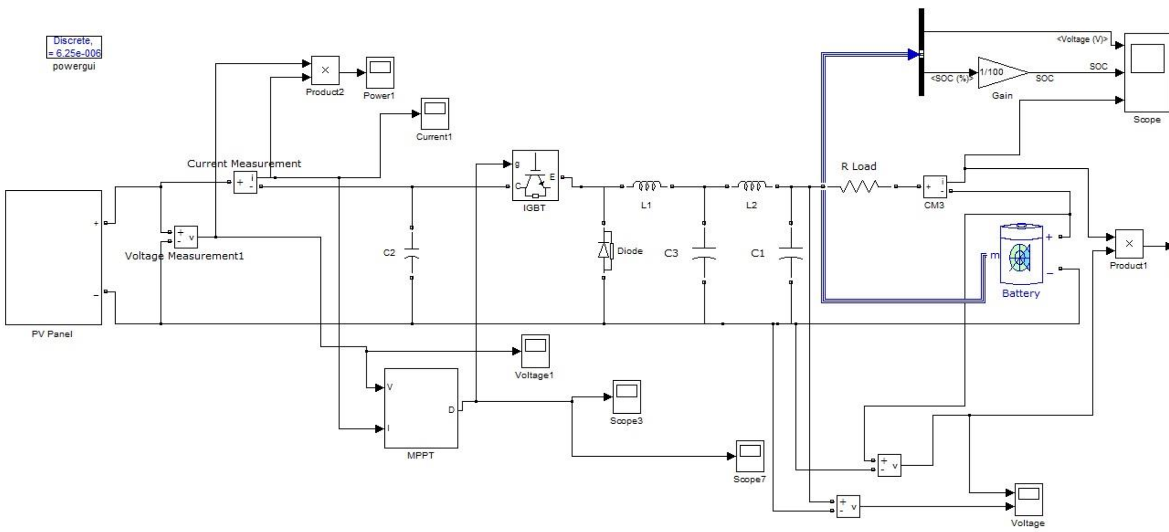


Figure 38. Modeling of Battery Charging using MATLAB Simulink

Using the MATLAB Simulink interface, we have successfully modeled a simple battery charging circuit. In the above Simulink model, a lead acid battery is charged using the resistance having a value of 1 ohm. The top right corner scope is used to record the battery voltage, State of Charge and the battery input current.

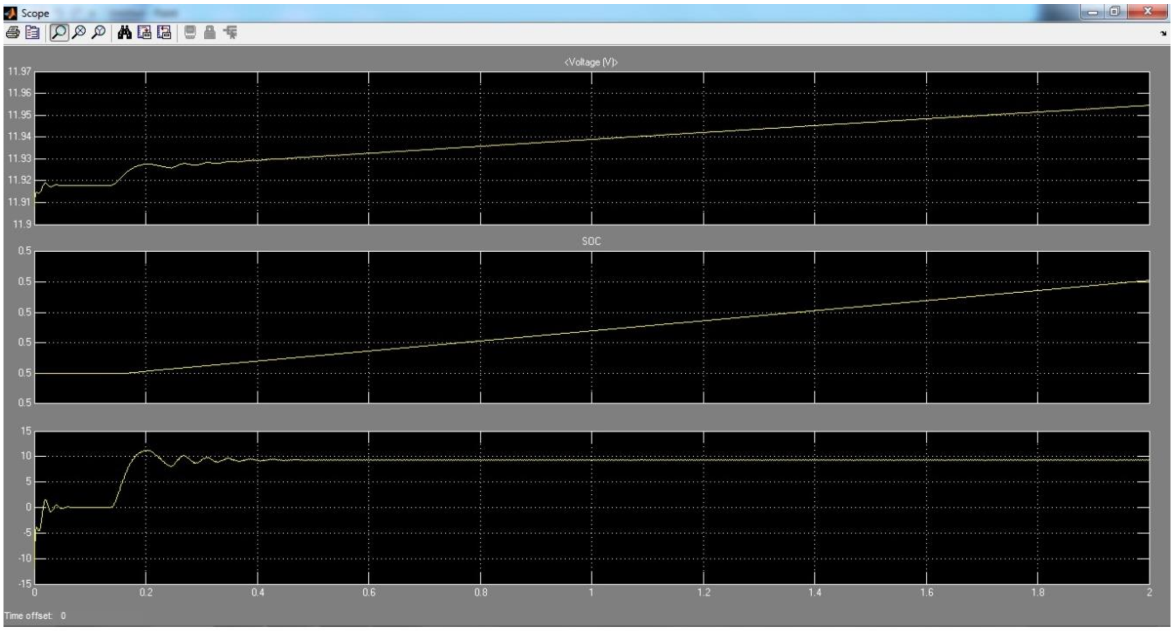


Figure 39. Plots of Battery Voltage, State of Charge and Battery Input Current

The most important battery parameters like battery voltage, State of Charge and the output current are recorded using the top right scope and are shown in the figure above. We observe that the output voltage and the State of Charge (SoC) increase and hence it shows that the battery is successfully being charged by the solar PV system.

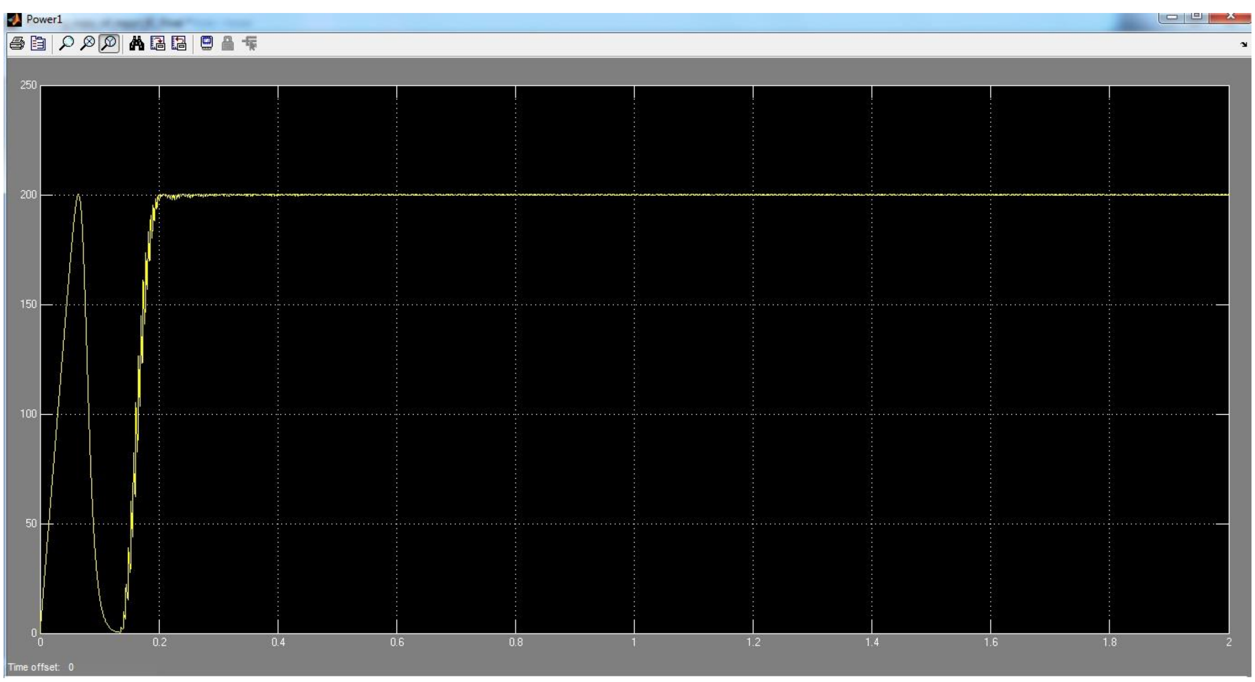


Figure 40. Plot of PV Input Power

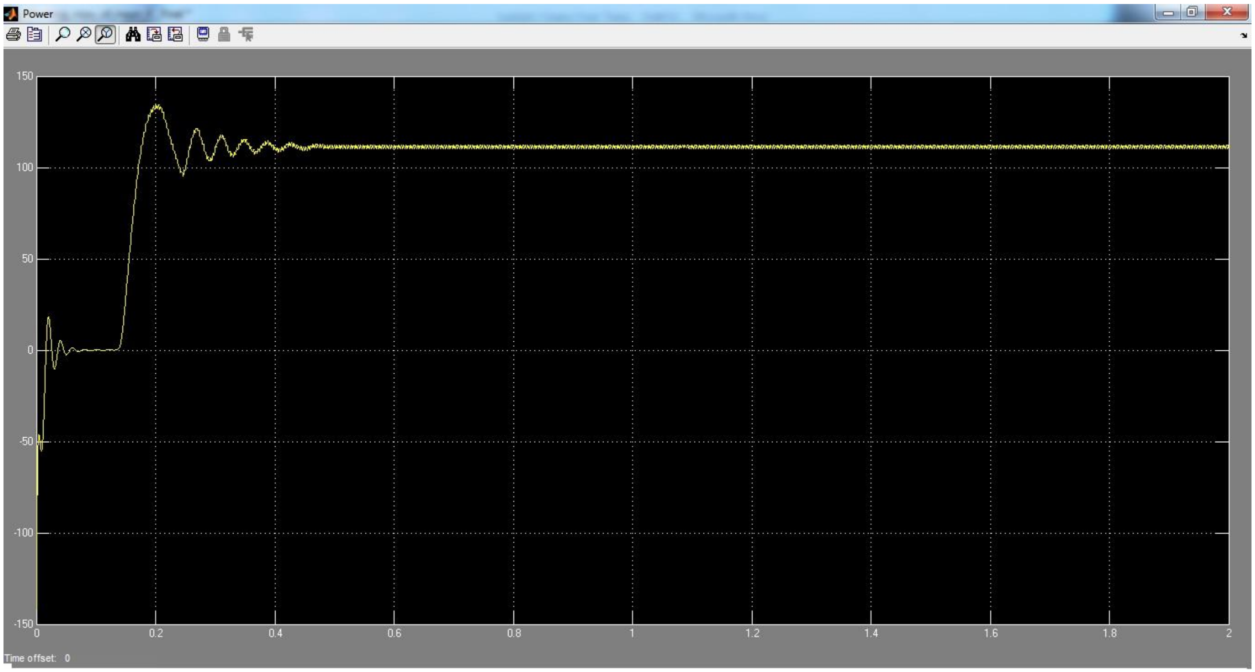


Figure 41. Plot of Converter Output Power or Battery Input Power

The plots of input power and output power have been illustrated above.

We observe that while the input voltage is at 200 W but the output power is only about 110 W which means that 90 W of power is lost. This difference in powers can be well attributed to the resistance of 1 ohm which is used between the output of buck converter and the battery. This coupling voltage drops the voltage across it and and hence the power is lost in I^2R loss which occurs due to the resistance.

We observe from the plot of battery input current that the value of current is about 9.3 A. Hence using I^2R formula we calculate the power loss in the resistor.

$P_L = I^2R = 9.4^2 * 1 = 88.6$ W

This almost coincides with the 90 W value which we calculated above.

Hence it can be easily seen that this circuit is a very simple circuit and can be used in applications where efficiency not an issue like solar powered radio or other communication equipment used for communication during disasters. Due to the simplicity of the circuit, these battery chargers are very cheap but on the other hand they are not efficient enough and they should be replaced by other sophisticated battery charger circuits in applications where efficiency is a real issue.

CONCLUSIONS AND RECOMMENDATIONS

It can be well observed from the above thesis that the efficiency of the solar PV system is decided by basically 2 key controlling parameters or levers i.e. the duty cycle of the buck converter and the load connected at the output of the buck converter. The duty cycle is controlled by the MPPT controller which is an algorithm that tracks the maximum power which can be extracted from the Solar PV system by operating the system at an optimum voltage. The system gives out maximum power over the full range of duty cycle i.e. from 0 to 1 but only for a specific range of values of load resistance. Like in our case maximum power is delivered only for a range of resistances which is from 0 to 3.45 ohms only. If the load becomes greater than 3.45 ohms the MPPT is not able to track the maximum power, it even stops operating at the Vmp (voltage at the maximum power point) which is given along with the panel. Moreover, the choice of load greatly affects the transient response of the system. This behavior of the solar PV system seems roughly analogous to the 3 phase induction motor characteristics whose slip at maximum power point also keeps shifting with increasing values of rotor resistance. Hence the loading should also be taken into account while designing the converter system for solar PV systems as it strongly influences the performance of the system. Towards the end of thesis, a simple low cost battery charging circuit is also modeled, simulated and analyzed which can be very well used for battery charging in applications not requiring high efficiency like mobile chargers, emergency communication systems used during disasters etc.

Future work

Improvement to this work can be further carried out by constantly tracking the output resistance of the system. The output resistance should be controlled by employing requisite circuits and should be maintained between the given limits in order to ensure best performance and efficiency of the system. The above work can be improved by tracking the maximum power under varying environmental conditions and in that case simultaneous variation in the load will be needed in order to ensure minimization of losses. Further work can be carried out on an experimental system whereby experimental values will be compared with the simulated results. Any discrepancies will be taken into consideration and further correction can be made on the simulated values.

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