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1. CHAPTER 1

INTRODUCTION

1.1 General Introduction

The increasing demand of entire world's energy requirement and consumption is resulting in emission of dangerous gases like Carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O). These are substantially increasing and this increase puts earth's ecological stability in danger, making it a threat for future generation's society both in social and political aspects. The energy production is mainly dependent on energy sources like natural gas, oil and coal. As the world's energy consumption and need is growing at a higher rate and the fossil fuels reserves are depleting slowly thus the need of renewable energy resources has gained higher demand and more important researches are being done in this area.

India being the world's second largest populous country and ranked fourth in terms of GDP depending upon purchasing power parity is well known as rapidly emerging economy in present times. India's energy requirement is met mainly by fossil fuels and only a small portion of the requirement is met by renewable energy sources.

1.2 Sources of power production

The Government of India's Central Electrical Authority report [dated 31-1-2016] gives information that, Coal shares the highest percentage in sources mix for power sector industries and also in country's core sector industries with 61% share, followed by hydroelectricity source at 15%, Natural gas energy source at 9%, Nuclear energy source by 2% and the rest required 13% is met by other sources [Figure 1.1].

In India, coal has been used as primary source of energy since long. Initially the use of coal was limited to house hold uses and other commercial uses. The advent of industries made a huge demand of coal and thus raised the mining of coal in large scale, usually the thermal plants in India use coal for production and also many applications like steel industry, iron industry, railways and locomotives used coal in large scale.

India being one of the largest producer of coal in world even imports coal to meet its needs. The production of coal in the previous financial year [2014-2015] is said to be 494.24 Million tonnes as per Coal India limited. Perhaps the disadvantages of usage of coal is also in large scale and preservation of coal will really play an important role for future generation to come.

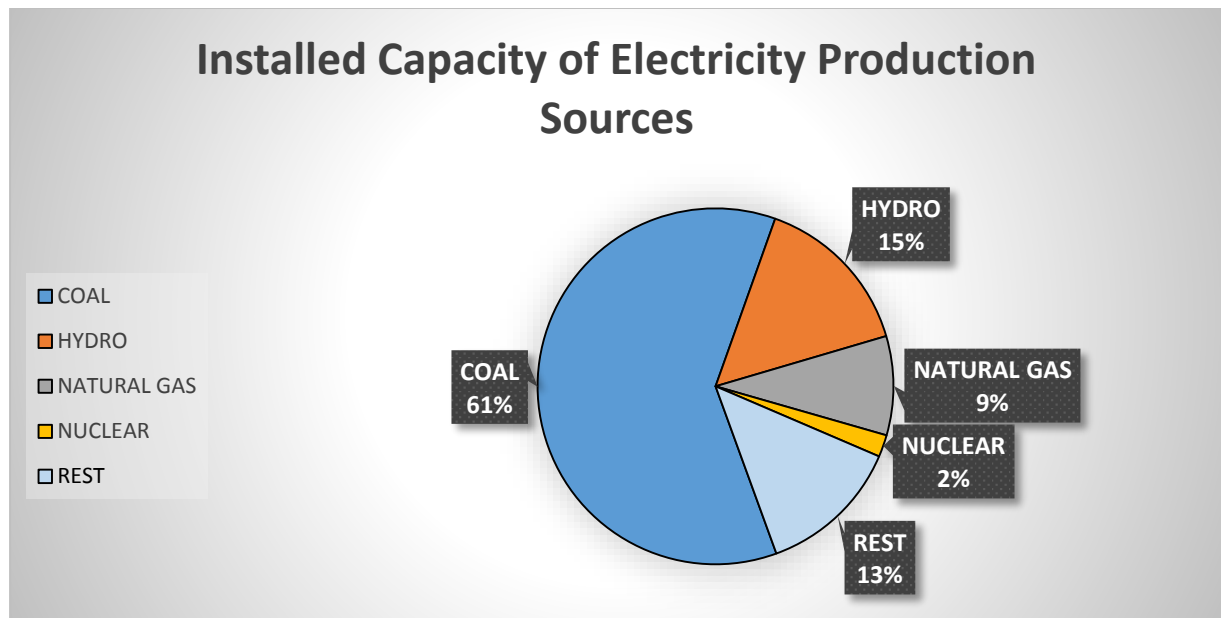


Fig 1. Installed capacity of Electricity Production sources in India

Natural gas is a compound of hydrocarbon gas mixture having methane, but having other alkanes too. It is produced as the by-product during production of oil. Most of the gas production is done in west coast of India, and maximum gas based production is done in south India. The gas based power production was 24.2 GW during the year 2012. Most of natural gas production are yet to come up.

India on the global platform has significant projects going on for technology and usage of nuclear power. Although nuclear energy amounts to 2% of entire power production in India, its energy extraction can be made to meet many soaring needs of power. India imports nuclear fuel – Uranium as per safeguards instruction from International Atomic Energy Agency. Uranium reserve are very much limited in India but there are sources of thorium which can provide energy far more than uranium for the same amount of fuel. On the contrary dealing with nuclear power, energy extraction and disposing of its waste and everything associated with nuclear energy is quite a risky affair.

The production and consumption criterions do not at all match in terms of energy sources, thus creating concerns about security and future needs of energy. As per Central Electrical Authority report India's per capita generation of electricity was 1,010 kWh and consumption was 746 kWh, yet the per capita electricity consumption of India is very less compared to many developed countries of the world regardless of low electricity tariffs.

Renewable Energy can be defined as the naturally obtained energy which is the repetitive and has a persistent source of flow of energy, occurring in the environment. Solar, wind, hydro are classified in this. Geographically India is being placed at very advantages position for tapping and using of many renewable energy sources, perhaps it's depended upon how wise the government and people will turn out to be, so as to tap the energy sources efficiently and use them. Among the sources like photovoltaic, hydro power, wind energy, photovoltaic energy holds the high potential to meet our energy demands constantly.

The era of wind power installations began in 1986 by setting up few on the coastal parts of Tamil Nadu, Maharashtra and Gujarat. The capacity of power production by wind power has been increasing since then. The installed power production by wind farms is 26,866.66 MW that accounts to 62.7% of the total share of power production [Figure 1.2], as per data given by central Electricity Authority. Many other states like Rajasthan, Karnataka, Madhya Pradesh, and Kerala have also started the wind power projects recently. Many of the western countries are using the wind power up to their full potential.

The sun and its energy is a non-polluting resource responsible for the sustained life on earth and it can give us efficient renewable energy thus creating a chance of producing a clean and high potential energy reserve. With increasing concern for depletion of fossil fuel reserves and global warming, the world is looking ahead at sustainable energy solutions in order to preserve earth for future generations.

Many countries in the world have started the photovoltaic energy installation. A report by International energy agency [Global Photovoltaic Markets, 2015] gives the data of few countries having large capacity on installed PV.

Table 1.1 Countries with maximum installed photovoltaic capacity

Countries	Installed Photovoltaic capacity (MW)
China	43,530
Germany	39,700
Japan	34,410
United states of America	25,620
Italy	18,920
United Kingdom	8,780
France	6,580
Spain	5,400
Australia	5,070
India	5,050

Many industrialized nations of the world have installed large capacity of solar power into their electrical grid system in order to provide an alternative chance to conventional energy sources. Even an increasing number of developing nations have also installed the solar power to reduce their dependence on most of the expensive fuels that are imported. The greater advantage is that the long distance transmission permits remote renewable energy resources to replace the consumption of fossil fuel.

Talking about the solar power potential of India. India is located at a region between Tropic of Cancer and Equator and substantially always has temperature ranging from 25°C – 27.5°C. This indicates the potential of India for tapping the solar energy, it gets the solar radiations almost throughout the year in most of the places in the country.

The calculation shows that India gets almost 300 hours of solar radiation. This would amount approximately to 5000 trillion kWh of power if we could tap the entire of it, in case. States like Gujarat, Madhya Pradesh, Maharashtra, Andhra Pradesh, Tamil Nadu, Punjab and Rajasthan have more potential. The total power production by solar power is 6,762.85 MW accounting to 15.8% of total share of production as on 31/3/2016.

The renewed data by Ministry of New and Renewable Energy, Government of India states the State wise Installed solar power production capacity as follows [as on 31/5/2016]:

Table 1.2 State wise Table 1.3 details of installed solar power capacity.

State	Installed Solar Power Capacity (MW)
Rajasthan	1285.932
Tamil Nadu	1267.414
Gujarat	1120.363
Andhra Pradesh	864.192
Telangana	785.843
Madhya Pradesh	780.37
Punjab	430.063
Maharashtra	385.756
Karnataka	146.462
Uttar Pradesh	143.495
Chhattisgarh	93.580
Odisha	66.920
Uttarakhand	41.145
Jharkhand	16.186
Haryana	15.387
Delhi	14.280
Kerala	13.045
West Bengal	7.772
Chandigarh	6.806
Andaman & Nicobar	5.100
Bihar	5.100
Tripura	5.000
Daman & Diu	4.000
Lakshadweep	0.265
Arunachal Pradesh	0.025
Others	58.311
Total	7,564.863

The rural areas would get electrified by this solar power production units as most of the population resides there. A few electronic devices are even available in market that is used extensively by people in remote area. In short the increasing trends in production of energy by solar would electrify every nook and corner of the country where electricity is not able to reach by cables.

Biomass has been an important source of energy since ages in India. It is very widely available and even neutral from carbon. Most of villages are dependent on it till date for energy needs. Even the government has also identified the potential and started many program to make efficient use of this source. The Biomass energy is produced by a number of sources like solid,

liquid and municipal waste collected from residential areas, animal farms, sugar cane factories and many more sources. Since most of the country is agrarian based the collection of manure, rice husk, bagasse from sugarcane factories coconut shells, saw dust remain as source of production till date.

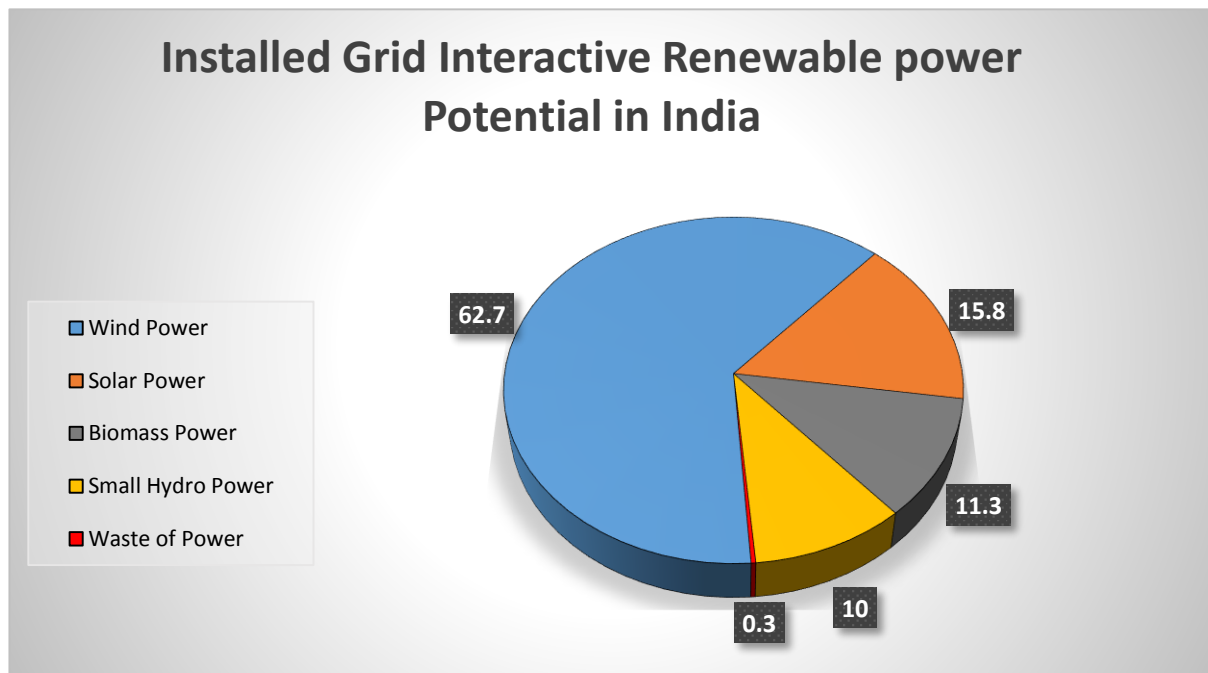


Fig 1.2 Installed Grid Interactive Renewable power Potential in India

The biomass is doesn't have the certainty of being available through the year, as some of the agriculture biomass is available only after the harvest season. Yet some of the sources can be manageable from animal manures. Karnataka, Andra Pradesh and Maharashtra are the leading biomass energy producers in the country. Its total production is estimated to be 4,831.33 MW, around 11.3% of the total share.

The country gets abundant rainfall during monsoon thus many rivers flow up to their full extent and many of check dams, dams, reservoirs get full and this flow of water is tapped to produce power in large as well as small scale in many of the states. The Hydro power plants are mainly classified in to small hydro power plants and large hydro power plants. All those with power production less than 25 MW of power production capacity are classified as small hydro power plants.

It is found that these small units of hydro power play an important role in improving the overall energy production and even in being the source of energy for remote areas in the country. Some remote places do have a micro hydro power plants just enough to fulfil their energy requirement. India is ranked 5th in global ranking for exploiting the potential of hydro power. Hydro power account to 4,273.47 MW of total power production in the country, almost 10% of the share. Many more projects are yet to come up but a few planning are discontinued in order to save the submerging essential biospheres and agricultural lands, but hydro power has always played a promising role for better service for power production.

1.3 Conclusion

India is emerging to be one of fastest growing economy in the world and Power sector plays a key role in economic development process of the country. All the villages and remote areas will be able to get electric supply only after India gets capacity to produce such large demand. As the world is getting technologically advanced India on its part has to get on toes to improve the standard of living for people and for every sector to grow electric power tends to be a basic need. In order to make world a better place for the future generations, we need to opt for environment friendly Power generation sources and this can only be achieved by advent and opting the renewable resources.

The introduction is focused on energy production and its importance. The closed loop controlled converters can be further modified as the PV emulators, which in turn can be used as a power sources. Thus the complete work is based on closed loop control of buck control but our emphasis is also on emulator as both have more similarities, perhaps a modified version of closed loop converter for various voltage values would be emulator indeed.

2. CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

By the form of accessible literature, it is concluded that the photovoltaic module could be efficiently made use of with DC-DC converter for industrial as well as for commercial use, the use of types of controllers also plays an important role in enhancing the results of the designed module and this affects the overall performance of the application system.

2.2 Literature review

India being the world's second largest populous country and ranked fourth in terms of GDP depending upon purchasing power parity is well known as rapidly emerging economy in present times. India's energy requirement is met mainly by fossil fuels and only a small portion of the requirement is met by renewable energy sources [1]. The various data of the power sources is given out in the form a report annually by the central electricity authority under ministry of power.

Rupesh wandhare and Vivek agarwal discuss about a PV system of low cost and weight. The system they talk about also has the ability to reconfigure itself depending upon the type of connection of the PV panels .i.e. either series or parallel. They also present the emulator designed with galvanically isolated type of power transformer [2].The system they have discussed is implemented with fly back converter, perhaps the system is designed to handle higher amount of voltages.

S.H.Lloyd, G A Smith and D G infield have presented a PV system taking in to the consideration of instability in the system as the load exceed beyond certain point. Even though the power is fed to the inverter it merely depends upon the range of load impedance [3]. The work they presented clearly under further investigation, there work be beneficial in case they use an auto tuning compensation to the circuit.

Kuang Tang discussed about realising the closed loop converter circuit in the Pspice software and solar pro, he talks about the system demonstrating the various output characteristics of I-V and P-V curve. He give idea about implementing the system for both series and parallel configuration the PV module array [4]. Isaac Flory presents his work of designing the closed loop buck converter having features like portable and inexpensive one. It is designed to be of light weight and plug and play type of front end device to emulate the PV module [5].

The Power and smart grid technology is ever changing in order to make the system more error or lag sustained. One such technology on research front is the smart grid technology and many applications following it. In order to incorporate the renewable energy sources in to the smart grid would make it energy efficient and using the closed loop converter technology or designing the emulator to work efficiently as per needs of grid is a difficult task [6]. Edin Golubovic and Baris talk of such innovation to be designed in smart grid applications field.

The design of closed loop converters faces a number of parameters to be focused on and taken under consideration in order to have a better output from the system, hence a variety of solar power variation are studied thoroughly and the system is to be designed [7]. Prabath Binduhewa presents such a system and talks about the manual variation of parameters as the drawback of the system designed.

Jaya Agrawal and Mohan Aware speak about having designed a system which uses the real time algorithm to be executed and the generating the output scale of AC-DC power supply [8]. The system is designed by using the lab view software and it is implemented to be interfaced with data acquisition. The system is also checked for the MPPT processing and this system to designed to handle the error quite precisely and the information and technicality they present is found to quite useful.

A profound information on designing the closed loop converters for higher power applications is a needful idea to be presented and this work of idea is presented by C.Roncero. The system is real time testing enabled for better operation [9]. Matlab/Simulink is used for the realising the circuit and maximum power point tracking is also checked for higher efficiency, and even the desired condition of temperature and irradiance.

Denis Pelin presents a case study on the PV converter system, to able to be used for laboratory purposes for the course of renewable energy sources and also for the standby power supply systems [10]. He also presents the way for DC programmable sources for the sub systems to be made used off. Dale Dolan and Joseph Durago also talk about the system design and simulation of the circuit simulation in a very simplified manner. The ideas they put forth are very simple yet knowledgeable in nature [11].

Rutu Shah and Ankur rana discuss about designing a system capable of performing well with a linear as well as non-linear loads. [12] Perhaps this would similarize the real time condition since loads keep varying as system might fail to meet the expectation. Although the system they discuss about has a few ripples that could eliminated by varying the size of the used filter inductor and capacitor.

Maurizio and Maria present the idea of implementing the system by using a DSP board of low cost. The designed system they talk about is designed to ensure the required dynamics and stability [13]. The system is evaluated to work in steady as well as in transient state. Hence they present a system to meet effectiveness of the proposed model. Hayrettin Can presents a system implemented using the power system block set using matlab software [14]. It is designed to handle the real time variation of the sun and change accordingly.

S. Armstrong and C.K.Lee propose a model designed to handle the harmonics of PV system and also make use of maximum power point tracking approach. They discuss about designing a system using the harmonic detection method in order to investigate the power point tracking methodology [15]. Ankur rana and Hiren Patel present a system of PV emulator based on buck converter being controlled by the current variation. Although it quite different, yet it gives a commendable idea to simulate the circuit in order to get a proper output and to remove system uncertainties [16]. They have worked the system with varieties of converters so as to get a in deep analysis of the system performance.

Qingrong and Pinggang discuss about testing the designed model in controlled environment and various control systems to be implemented in order to have better understanding and performance parameters of the system [17]. At the same time Houda Abidi and Daniel propose a model of PV array, the entire system is implemented using the electrical sensors to get better

level of the real time. The use of sensors make it more reliable and the real time parameters are better recorded, to support the system to perform better comparatively [18].

Balakrishna and Sandeep discusses about the microcontroller based design the control element being the current and they discuss about the system difficulties and having used the matlab as designing software it quite helpful in get better understanding of the system[19]. Ankur proposes a model of PV emulator designed to be controlled using the current and voltage. He expresses his view of emulator designed to be controlled by current as quite a better system since the produced ripples are less [20]. Even the loading conditions of the designed module as matters upon its performance levels. Iqbal and Tariq provide the insights about the systems control strategy and having designed the system in matlab, it gives the designer a wide variety of facility to implement and get outputs of better performance every time they simulate [21].

Viera biolkova and Kolka give insight classical study on the steady state analysis of the system of converters. They also discuss and propose a simplified case of general equation of switching converters which determines the response to harmonic input signal in the frequency domain [22]. The state space analysis method gives precise results since its A1 and A2 matrices are similar in all the switching phases.

C.T.Rim and G.B.Joung propose the state space analysis applied for the non-ideal DC-DC converters. The effect of changing the switching time due to current on the designed system provides an extension on the effect of storage time modulation [23]. They express that the primary converters like boost and buck-boost converter show a decreases in operation due to switching losses and they express their idea that buck is superior to other in terms of DC gains and stability of the system.

W.M.Polivka, P.R.K.Chetty and R.D.Middlebrook provide us the insight on modelling switching converters. The analytical descriptions of all the converters is done briefly. The conventional circuit of the converter is modified in order to include the new term [24]. They provide indeed a complete package of simplified idea on how to consider the operation of parasitic and also the modulation of the storage modulation of the converters.

J. Mahadvi, A. Emaadi, M. D. Bellar give a detailed explanation about the power electronic converter and the periodic time variant systems. They also talk about the switching operation of the converters. The generalized state space averaging method is a way to model converters as time independent systems and to be defined by a unified set of differential equations which are able to represent the exact operation. Therefor it can be considered as convenient approach for designing the required controllers to be applied to switching converters for application.

2.3 Conclusion

The literature review gives a basic knowledge of very detail in the specified area of research. It gives a widespread idea of the control strategy and the merits and demerits of every modelled system. Thus it gives a complete idea of the performance analysis and the design strategy for a better system design.

3. CHAPTER 3

PHOTOVOLTAIC CELL AND EMULATOR TECHNOLOGY

3.1 Introduction

Photovoltaic technology offers us an opportunity to generate electricity in a quiet, clean and most reliable manner. Photovoltaic systems consists of photovoltaic cells, the component that converts the light energy in to electricity directly. Since the primary source of light is sun, the devices are often called as solar cells. The technical word photovoltaic is a Greek word wherein “photo” means light and “voltaic” which refers to unit of electro motive force, which again is derived from name of Italian physicist Alessandro Volta.

In short the photovoltaic process means, “The process of producing electricity directly from the sunlight” by using the solar cells, also called as photovoltaic cell. Perhaps solar cell are the one used as basic component in solar modules. Silicon based semiconductors are the most common type of semiconductors used to make solar cell. The solar cell can be designed of any measurements and these are usually covered by Anti Refection Coating (ARC) which would reduce the loss of light due to reflection on the surface of cell.

Here in this chapter on Photovoltaic cell and Emulator technology we will discuss about Photovoltaic cell , its working principle, types of Photovoltaic cell, its equivalent circuit and also about emulator. We are basically showing interest on emulator since a more developed version of any of the closed loop converter can be called as emulator and its merits are of wide range.

3.2 Photovoltaic cell

Solar cells are made up of semiconductor materials as mentioned earlier. These are especially treated by an electric field. It has the Positive on one of its side usually at the back and negative is always facing toward the sun [Figure 3.1].

When the photons from the sun's energy hits the solar cell, the electrons from semiconductor material are released by the atoms of the material thus creating the electron-hole pairs.

When the electrical conductors are attached to Positive and negative terminals, it forms an electrical circuit thus the electrons flow in the form of electric current i.e. Photocurrent.



Fig 3.1 Photovoltaic cell

A typical Photovoltaic cell is made up of crystalline silicon material that is 0.25 mm thick and diameter of 12 cm, when there is complete availability of sunlight, it would generate 4 amp of dc current at 0.5V or electrical power of 2 watts.

3.3 Photoelectric Effect

When light falls on the surface it tends to absorb energy from electromagnetic radiations, that are of short wavelength usually like visible or UV light. The electrons are emitted from by the surface due to this absorption of energy [Figure 3.2]. The surface can be gas, liquid, metal or non-metallic. This effect is termed as Photoelectric effect.

The Electrons emitted in this entire process are Photoelectrons. During his experiments with spark gap generator, Heinrich Hertz first observed the photoelectric effect in 1887. Later in 1905, Albert Einstein published the photoelectric experimental data in a paper. In this year 1921, Albert Einstein was awarded Nobel Prize for his discovery of Photoelectric Effect.

Photons required for photoelectric effect should have energy ranging from 0 to 1MeV, for core electrons in some elements having higher atomic number.

The emission of conduction electrons from some metals usually needs energy of few electron-volts, depending upon the type of light either it is ultraviolet light or visible light of short-wavelength. The Study of photoelectric effect led to many steps and theories in understanding the electrons and quantum nature of light and this study also influenced the theory of concept of wave – particle dual nature of light.

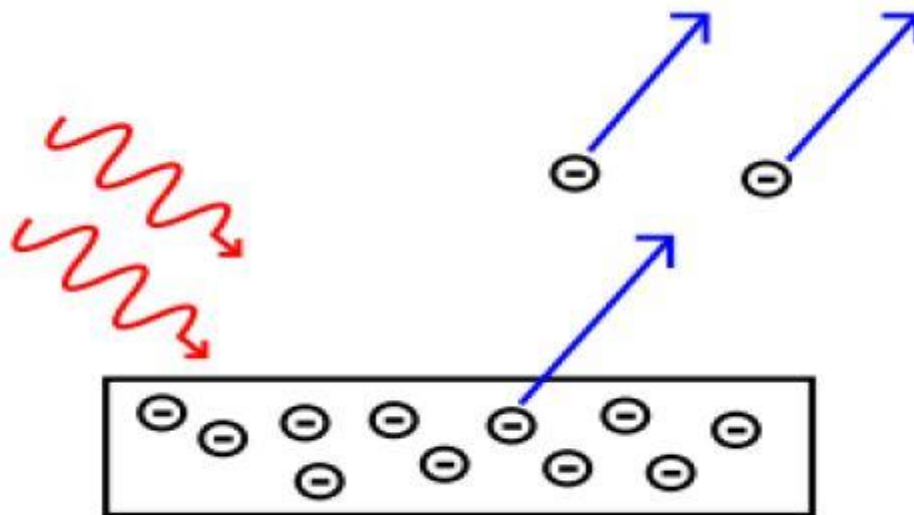


Fig 3.2 Photoelectric Effect

The Photoemission can happen on any material but it is more easily observable in case of metals or any conductors because the process of photoemission produces an imbalance charge, and if this imbalance in charge is not neutralized by flow of current, the potential barrier of atoms to emit increases until the emission current halts.

It is also possible to have the emitting surface in vacuum condition, because the gases delay the photoelectrons flow and make it tedious to observe. Further, the energy barrier for photoemission is generally increased by using a thin oxide layer on the metal surface in case

the metal has been unsheltered from oxygen, thus most of practical experiments, devices based on the concept of photoelectric effect are categorized to prefer clean metal surfaces when used in vacuum.

3.4 Working Principle of Solar Cell

A solar cell has a semiconductor material that is doped. The doped semiconductor material produces two different regions that are separated by a p-n junction. Electrons and holes being the two types of charge carriers, will be able to cross through this p-n junction. Thus in this process the region of their origin is depleted and their charge is transferred to the new region.

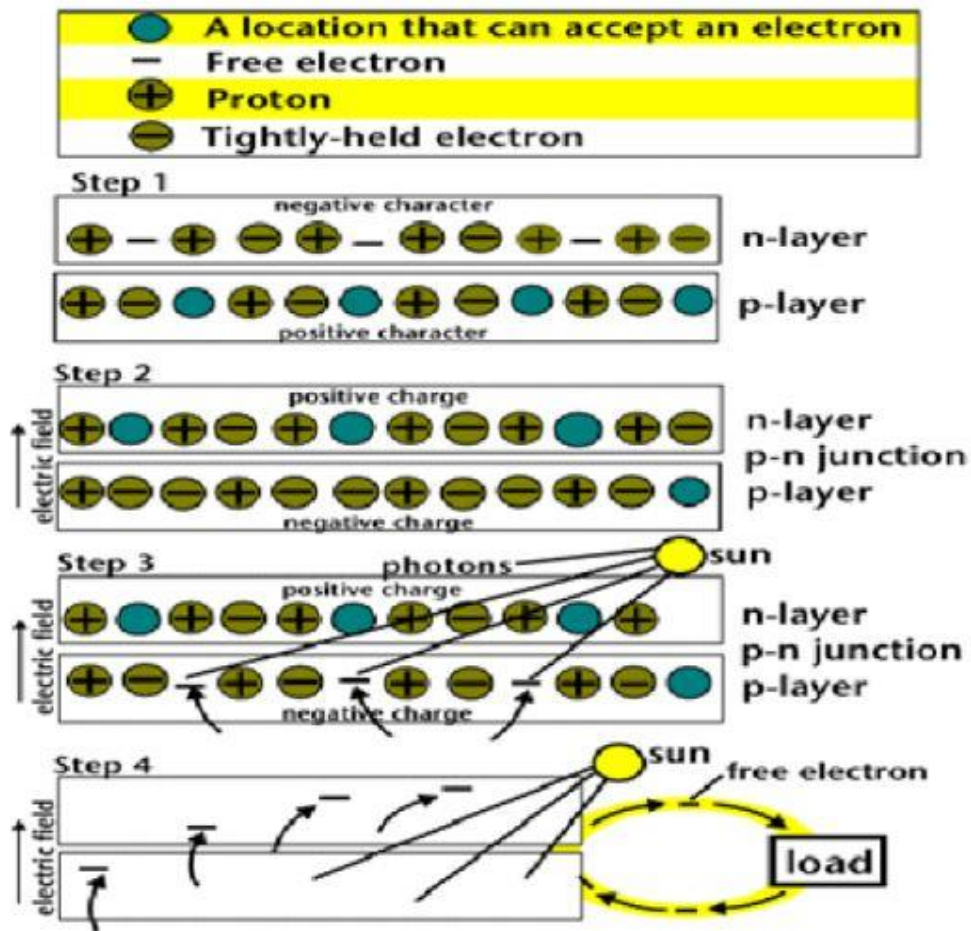


Fig 3.3 Step by step movement of charge carriers

The movement of these charges results in formation of potential gradient or say electrical slope, this is where the charge carriers tend to slide to the other side as they approach the junction barrier. When the sunlight falls on the surface of solar cell, the atoms of the cell are hit by the

particles of light called photons and this bombardment results in emission of electrons. As the electrons moves out of the atom, it creates a hole that has charge of equal and opposite magnitude.

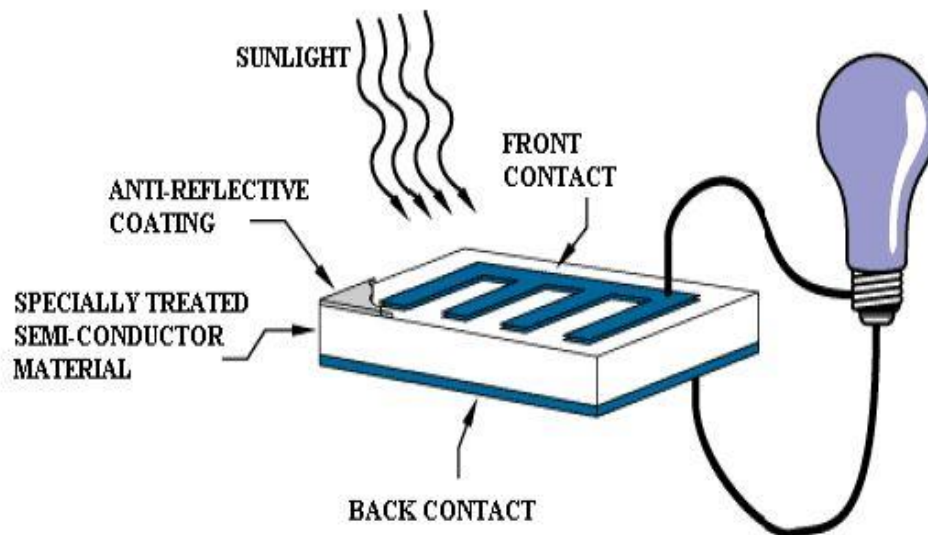


Fig 3.4 Operation of photovoltaic cell

When either of the carriers moves across the junction, the nature of the semiconductor material and its field discourage the carrier charge from re-crossing the junction in solar cell. A portion of carriers that move across the junction can be efficiently harvested by completing the circuit from the grid on cell surface to a collector. In short when the light falls on the solar cell, it pumps out the electrons out from one side of the cell, to pass through the circuit and again back to the other side of the cell, thus energizing any electrical device that is connected along the way.

3.5 Types of Photovoltaic cell

There are two types of photovoltaic materials namely crystalline and thin-film. Crystalline photovoltaic materials are further classified into two types:

They are Mono crystalline cells and Polycrystalline cells.

- Mono crystalline Cells: This type of cells are made out of a cut from a silicon of single cylindrical crystal. Mono crystalline cells avail the chance of getting higher efficiency (conversion rate of incident sunlight on the cell is 18% approximately), the complex process of manufacturing makes this type of cell comparatively more expensive.
- Polycrystalline Cells: This type of cells are made by cutting the fine micro slides from the lump of silicon which is molten and recrystallized. This type of cells are cheaper to produce, but efficiency has to be slight compromised (conversion of incident light is 14% approx.). The thin photovoltaic film is made by laying out photovoltaic material onto a substrate in the form of ultra-thin layer. The most common type of thin-film photovoltaic material is made by using a Si (amorphous silicon), but plenty of other materials such as CIS (copper indium selenide), CdTe (Cadmium Telluride), CIGS (copper indium/gallium selenide) are used.

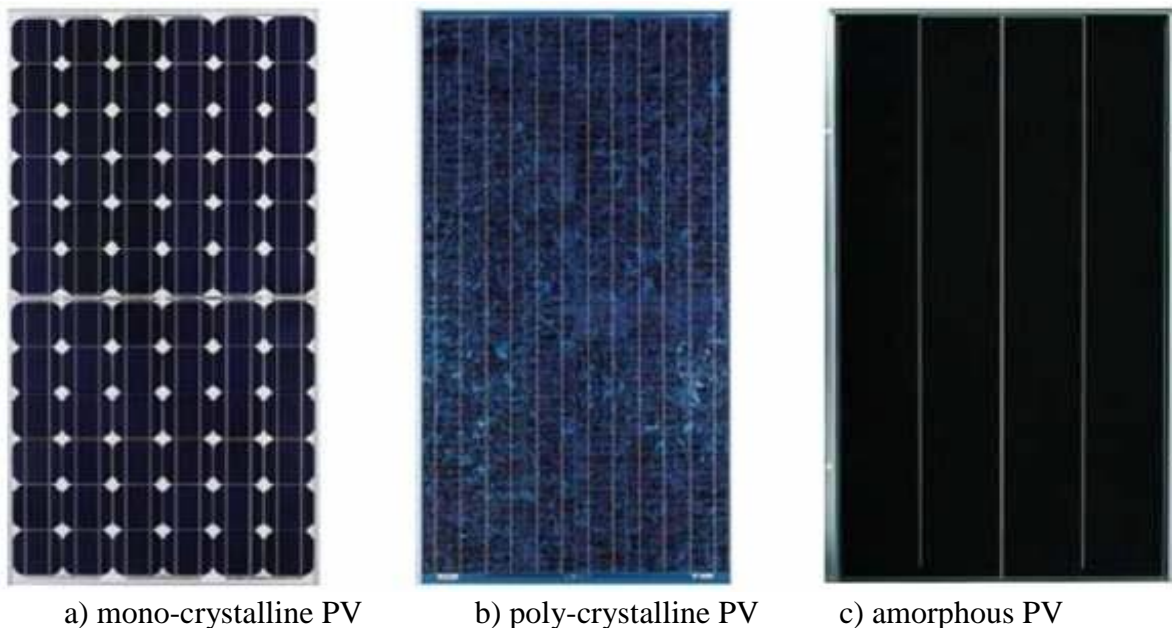


Fig 3.5 Types of industrialized PV technologies.

Amorphous silicon cells: Amorphous silicon photovoltaic cells are made by laying out a thin uniform layer of silicon on a substrate instead of creating a rigid crystal structure. Amorphous silicon has a property of absorbing light more effectively than crystalline silicon, hence the cells can be made thinner and so it is called as thin film PV. Both rigid and flexible substrates can be deposited by amorphous silicon, thus making it ideal for curved surfaces and also for directly bonding onto roofing materials. This technology of photovoltaic cell is less efficient

comparatively. It has the efficiency of around 6%, but it turns out to be too easier and cheaper to produce and install.

3.6 Design Orientation of Photovoltaic cell

A series of solar cells which are electrically connected to one another and are mounted in supporting frame is called as a photovoltaic **module**. The Modules are generally designed to produce and supply the electricity at a certain specified rating of voltage, like 12 volts system for example. The rating keeps varying as per the designed size of module. The power produced by the module is directly proportional to the magnitude of light that strikes the module.

Multiple number of modules can be arranged and wired together to form an array of modules. The Photovoltaic modules and arrays designed set up produces direct-current (*dc*) electricity. These can be designed to be connected in both parallel and series sequential electrical arrangements in order to produce any required amount of voltage and current quantity.

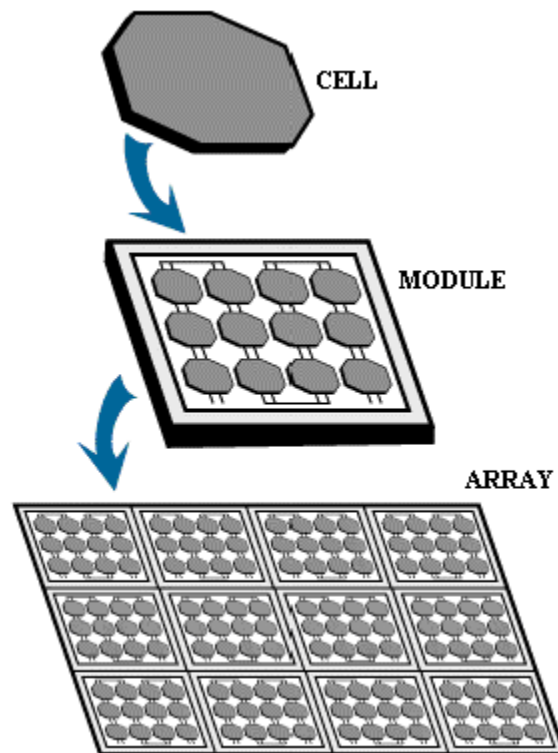


Fig 3.6 Design orientation of solar cell

The solar cell consist of a P-N junction semiconductor which produces currents by photovoltaic effect. The array of PV cell are designed by many solar cells connected in series or parallel.

The designed PV cell is a diode of a large area which is forward biased by a photo voltage. The characteristic of a solar cell is derived and represented as follows by its equivalent circuit [Figure 3.6]:

$$I = I_{ph} - I_D$$

$$I = I_{ph} - I_0 \left[\exp \left(\frac{q(V + I R_S)}{A k_B T} \right) - 1 \right] - \frac{V + I R_S}{R_{Sh}}$$

Where

I_{ph} = Photocurrent,

I_D = Diode current,

I_0 = Saturation current,

q = Electronic charge 1.6×10^{-19} ,

A = Ideality factor,

k_B = Boltzmann's gas constant (1.38×10^{-23}),

T = cell temperature,

R_S = Series resistance,

R_{Sh} = Shunt resistance,

V = Cell voltage,

I = Cell current,

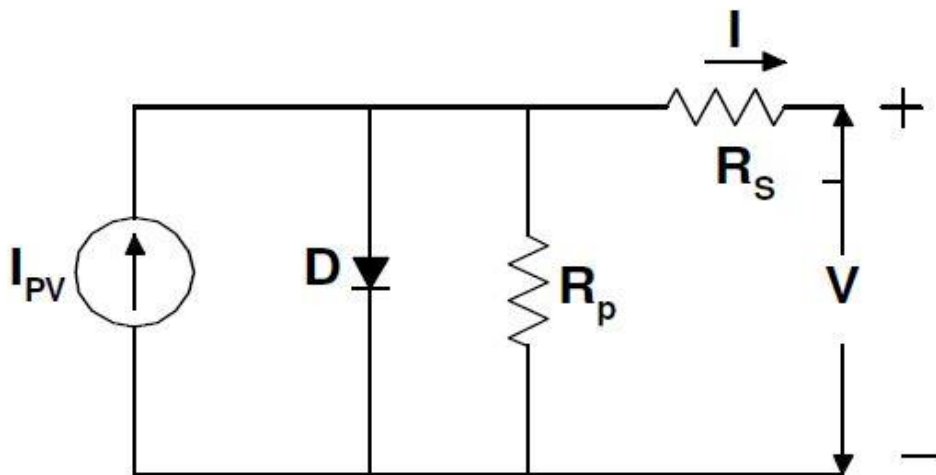


Figure 3.6. Equivalent circuit of PV cell

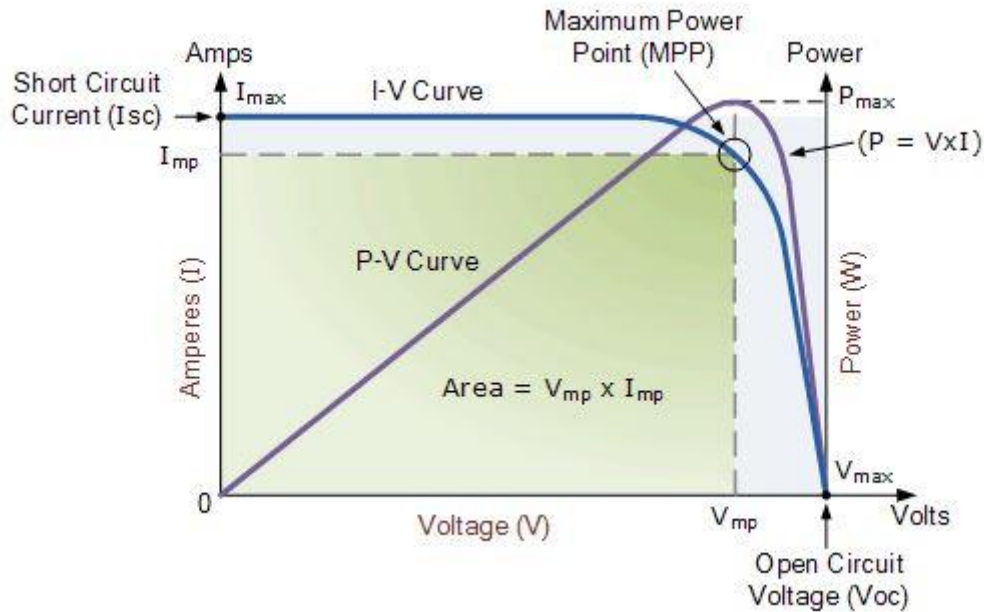


Fig 3.7 characteristic curves of PV cell I-V, P-V

The solar cell's output power can be modified quite effectively as required by using the tracking mechanism in order to place the PV device always facing the sun directly, else by using lenses or mirrors to concentrate the sunlight for maximum output. However, there are certain limits to this mechanism, due to the some complexities of the process, and the need to cooling of the cells. The current output of the device remains stable at higher temperatures relatively, but the voltage gets reduced, thus leading to a drop in power output as the temperature of the cell increases.

3.6.1 Short Circuit Current (I_{sc})

Short circuit current refers to the condition of the circuit when the impedance is low. It can only be calculated, when the voltage equals to zero (0).

$$I_{sc} = I \text{ (at } V = 0\text{)}$$

At the beginning of the forward-bias sweep, I_{sc} can be obtained. In the power quadrant, it is the maximum current value. For an ideal PV cell, this value of maximum current is the total current that is produced by photon excitation in the solar cell.

$$I_{sc} = I_{max} = I_1 \text{ for forward-bias in power quadrant.}$$

3.6.2 Open Circuit Voltage (V_{oc})

The open circuit voltage of PV cell can be obtained when there is no current passing through the PV cell.

$$V \text{ (at } I = 0) = V_{oc}$$

V_{oc} can also be termed as the maximum voltage difference across the PV cell for a forward-bias sweep in the power quadrant.

3.6.3 Maximum Current at P_{max} (I_{mp}), Maximum Voltage at P_{max} (V_{mp}), Maximum Power (P_{max})

Along $I-V$ sweep, the total power produced by the PV cell can be easily calculated in Watts by the equation, $P = VI$. At the points V_{oc} and I_{sc} , the calculated power will be zero and the maximum value for power happens to occur between the two. At this maximum power point voltage and current are denoted as V_{mp} and I_{mp} respectively.

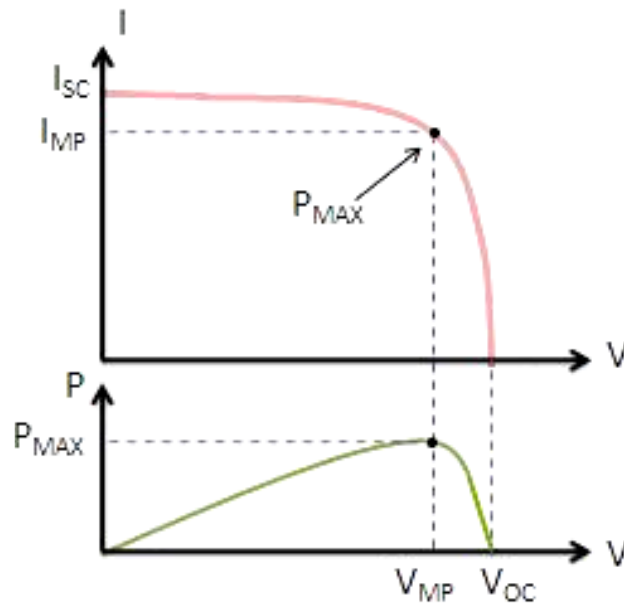


Fig 3.8 Maximum powers for an I-V sweep

3.6.4 I-V Curves for Modules and Arrays of PV cells

The shape of the I-V curve characteristics does not change for a module or an array of PV cells. Typically, it is calculated based on the number of cells connected in series pattern and in parallel pattern of design. If the number of cells connected in parallel is m and the number of cells connected in series is n and V_{oc} and I_{sc} are values for individual cells. The described pattern of PV curve is shown in Figure 3.9.

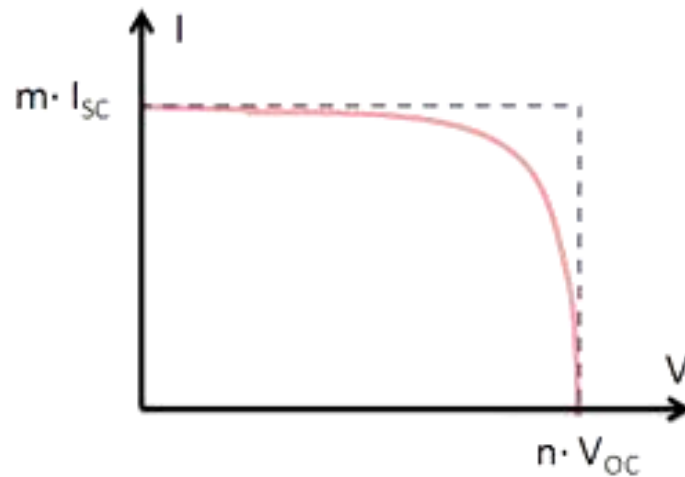


Fig 3.9 I-V curve for modules and arrays of PV cell

3.7 Photovoltaic Cell Emulator

A photovoltaic emulator is an electrical setup which gives the output power supply with similar current and voltage characteristics as that of PV panel. This emulator setup uses an existing power supply which can be manipulated by using microprocessor to emulate a photovoltaic panel and its characteristics. Based on the user specified design parameters of PV panel, the emulator calculates a current-voltage (I-V) curve, temperature and irradiance of the cell.

When a change in load occurs, the power supply changes magnitude of current and voltage to track the designed and calculated I-V curve, in order to mimic a solar panel characteristics. A PV emulator setup provides a controlled and manipulative environment which is not affected by any external factors such as weather and temperature. This design advantage allows recurring conditions on which the PV equipment can be tested, such as inverters. It also provides many control conditions to test a PV system overall.

3.7.1 Need for a Photovoltaic Cell Emulator

There has been intense and yet increasing growth in installed photovoltaic (PV) systems since the past decade. The Utility scale photovoltaic systems installations have always had an increasing pattern of growth. This increased penetration of PV systems in the field of energy production and utility has caused many new problems for photovoltaic equipment users and the PV setup manufacturers. Some of the issues that are encountered with the increasing PV penetration are unintentional islanding, the role of photovoltaic cells in voltage regulation of power system, coordination with existing protection systems against electrical hazards and providing transient stability during a fault through power transmission mechanism thus a more sophisticated way of testing PV equipment and its protection is required.

Presently, when using the photovoltaic equipment setup as inverter, the inverter can either be directly connected to real PV modules setup or a separate programmable power supply can be used. The problem with connecting photovoltaic equipment directly to PV module is that its electric characteristics keep on changing continuously depending up on a variety of factors including temperature and irradiance. This type of constant fluctuation makes it difficult in order to isolate the variables affecting PV hardware setup. Contrarily, while using the programmable power supply, the voltage and current are usually set to static values which do not change.

The programmable setup of power supply does not react similarly to a real PV module efficiently. A photovoltaic emulator over comes all the backlogs of methods mentioned earlier i.e. a real PV module and a programmable power supply. Photovoltaic cell emulators replicate a PV module more accurately than any programmable power supply. Thus it provides a way to test in controlled environment and obtain efficient outputs from PV hardware when compared to a real PV designed module.

With changing temperature and weather conditions a controlled environment is quite tough to obtain in order to test the photovoltaic equipment. The Photovoltaic panel's characteristics will keep changing based on many varieties of conditions including the temperature variations of PV panel, the entire quantity of irradiance that is received and the PV panel material.

A PV emulator will replicate the current and voltage characteristics of a PV panel under various conditions, but it will also provide more control strategies in order to allow better testing methods of PV equipment. Within the PV emulator the panel design, temperature and irradiance can be as per user specified demands. In order to determine how exactly the PV system will work for a particular value of Sun power at a value of irradiance say 500W/m² at temperature of 20°C, the user can specifically mention these parameters to the microprocessor of PV emulator, Thus user can then individually change to any value of either irradiance or temperature and finally determine how these factors affect the working of a piece of PV hardware being tested. Having consistent output of electrical characteristics will allow the analysis and optimization of Photovoltaic system.

The improved control strategy that is designed for a PV emulator will provide us with more sophisticated and better measurements under various conditions. A number of solar panels are available for purchase, but it would be highly expensive to buy every type of panel and test them individually. A PV emulator would be able to replicate any number of different types of PV panels, under any temperature and weather conditions. By just changing the PV panel data within the designed emulator, any type of PV panel can be simulated without the hassle of getting a new solar panel and connecting it to the PV hardware to be tested.

3.8 Conclusion

Photovoltaic emulators are designed and developed for educational and commercial purposes. A few of these photovoltaic emulators are used as modular so that they can be designed to be connected in series or parallel fashion to implement an entirely new photovoltaic array. Photovoltaic emulators are also used to test the photovoltaic systems mounted on space satellites. Due to the extreme atmospheric conditions in outer space, researchers would like to accurately study the working behaviour of PV system in outer space. Thus Photovoltaic emulators are their best alternative for efficient energy production and in fact most practical option. A special interest on emulator is presented, so that a unique wide range of study can be done in future.

4. CHAPTER 4

DC – DC CONVERTERS

4.1 Introduction

DC-DC voltage conversion can be achieved by through many methods. Every method has its own benefits and also disadvantages, it changes as per a variety of operating conditions and their specifications. Few specifications of converters are voltage conversion capacity, output power, efficiency of power conversion, power handling capability etc. In this chapter we will discuss about various types of converters and their operation.

4.2 DC-DC converters

DC to DC converters can be divided in to two types basically

Converters without isolation

These DC to DC converters do not have any type of isolation transformer component between input and output. Few commonly rigged circuits of DC to DC converters in category of without isolation are as follows:

- Buck converter
- Boost converter
- Buck-boost converter

The buck converter can be described as the step down converter. In this type of converter the input voltage is always greater than the output voltage. Boost converter can be described as the step up converter. In this type of converter the input voltage is always less than output voltage of the converter.

The buck-boost converter is a combination of the buck and boost converters. The buck boost converter gives an advantage to be operated in both conditions based on duty cycle of the switch used in it (duty cycle t_{on}/T_s where t_{on} represents the duration of switch ON condition and T_s represents the total switching time period of the switch). The buck and boost converters are the basic converter design topologies, rest converters are merely the converter derived by combination of these.

Converters with isolation

In this type of converter combination a transformer is used between input and output to create isolation. The electrical isolation created in these is an extra feature. It is mainly helpful in conditions where input (V_{in}) and output (V_{out}) voltages differ entirely. The converters designed with isolation capability are again sub divided into 2 types based upon the polarity of core excitation of the transformer used.

These can be explained as follows:

Unidirectional core excitation, here the core used is excited with forward currents which are of only one direction in nature. In this type of DC to DC converters the designed isolation transformer core works in only the positive subdivision of B-H curve.

Bidirectional core excitation, here the core used is excited with either (both forward and backward) direction current. In this type of converters the designed isolation transformer core can be operated alternatively in both direction i.e. positive as well as negative sub divided portions of the B-H curve.

Few commonly used converters designed with isolation component are:

- Cuk converter (it can be designed to be used in non-isolated condition too)
- Push-pull type of converter
- Forward type of converter
- Half bridge type of converter
- Full bridge type of converter
- Fly back type of converter

4.2.1 Buck converter

The basic designed circuit of buck converter consists an inductor, a diode, a capacitor, a switch and an error amplifier having switch control circuit [Figure 4.1]. The circuit can be operated by varying the entire duration of operation time where inductor receives the input energy supplied from source.

By Figure 4.1, it can be found out that the output voltage of the converter is sensed by the implemented error amplifier thus an error voltage is produced which enables to control the duty cycle of the switch.

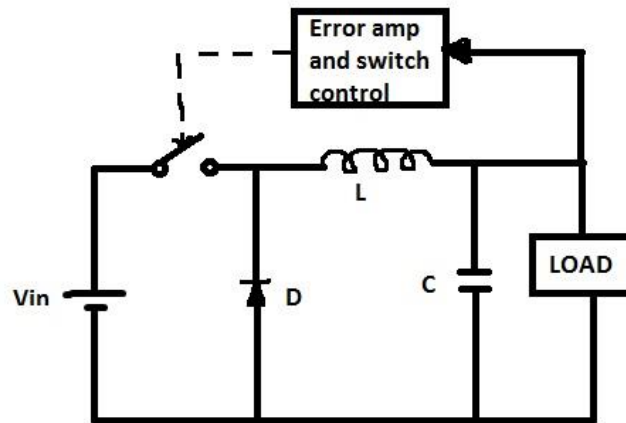


Fig 4.1 Buck converter circuit

The switch can be controlled by using a PWM generator, as long as the switch remains in ON condition the load draws the current for the entire duration and voltage tries to drop. There is requirement of an oscillator with fixed frequency to drive the switch included in the circuit.

Operation of Buck converter

When the switch of the buck converter is in ON condition [Figure 4.2], the voltage that flows through the inductor can be calculated as $V_{in} - V_{out}$. Derived From equations of inductor, the current flowing in the inductor component will rise at certain rate, it can be depicted as:

$$\text{Rate of change of current in inductor} = \frac{(V_{in} - V_{out})}{L}$$

During this operation period the diode D gets reverse biased and hence do not conduct current.

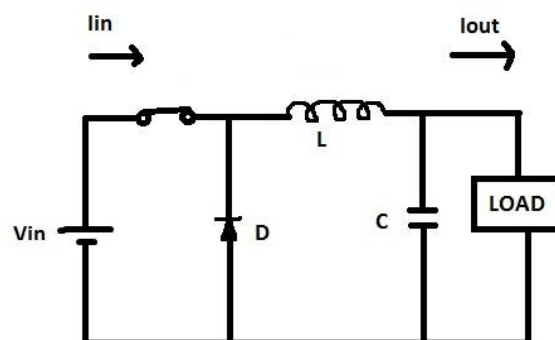


Fig 4.2 Buck converter circuit in ON state

When the switch gets in to open condition, i.e. called as OFF state of the switch as depicted in the in Figure.4.3, the current will still continue to flow as inductor tries to maintain the

operation by continuing the same amount of current flow. Thus as a result, the load continues to receive the current through the supply from inductor. The diode, D during the operation forms a return path having current I_{diode} value equal to I_{out} value flowing through it. While the operating switch is open, due to reversed polarity in inductor, the flow of current through the inductor keeps decreasing with a slope expressed as $\frac{(-V_{out})}{L}$.

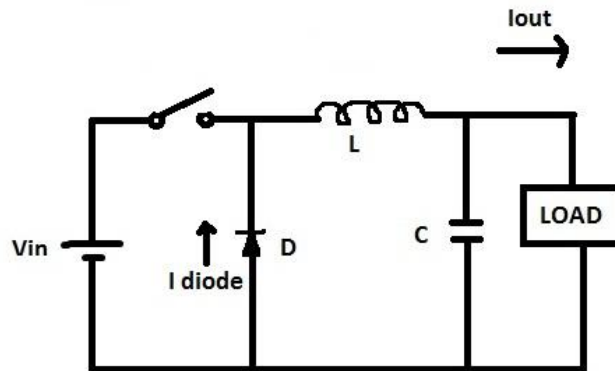


Fig 4.3 Buck converter circuit in OFF state

4.2.2 Boost converter

The designed boost converter circuit when compared to buck converter finds many similarities. Yet the boost converter circuit can be found to be slightly unique. The basic circuit of the boost converter also called as step up converter consists of an inductor, a diode, a capacitor and a switch and an error amplifier having switch control circuit [Figure 4.4].

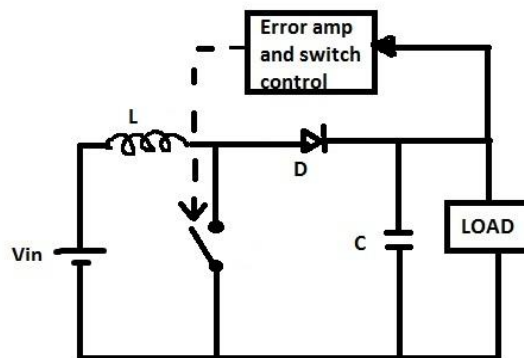


Fig 4.4 Boost converter circuit

The boost converter circuit can be operated by varying the entire duration of operation time where inductor receives the input energy supplied from source. By the circuit diagram, it can

be found out that the output voltage of the converter is sensed by the implemented error amplifier thus an error voltage is produced which enables to control the duty cycle of the switch.

The switch can be controlled by using a PWM generator, as long as the switch remains in ON condition the load draws the current for the entire duration and voltage tries to drop. There is requirement of an oscillator with fixed frequency to drive the switch included in the circuit.

Operation of Boost converter

The operation of mechanism of boost converter is comparatively straightforward. While the switch is in ON condition, the voltage V_{in} flows across inductor. The current flowing across inductor component will rise at certain rate, it can be depicted as:

$$\text{Rate of change of current in inductor} = \frac{(V_{in})}{L}$$

While the switch in is OFF condition as depicted in Figure.4.5, the voltage flowing across the inductor keeps changing and the value would be equal to $V_{out} - V_{in}$. The Current value flowing in the inductor keeps reducing at a rate $= \frac{(V_{out}-V_{in})}{L}$.

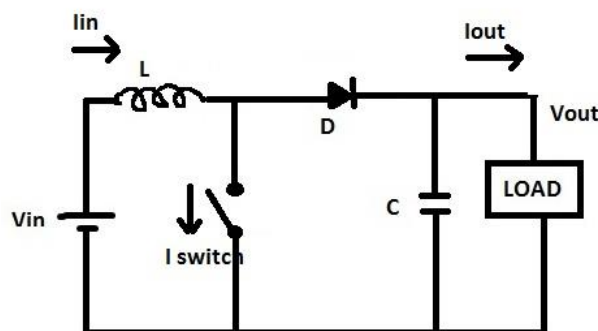


Fig 4.5 Boost converter with switch in OFF condition

4.2.3 Buck-Boost Converter

The buck-boost converter presents a higher level of capacity than that of buck or boost converter respectively. There are many types of circuit combinations those can be used as buck-boost converters:

- Positive V_{in} , Negative V_{out} : This type circuit combination of a buck-boost converter is as depicted in Figure.4.6, it has same components as of the simple buck or boost converters explained earlier. Perhaps this converter will be able to produce a negative output for the given positive input. But this might be required for a finite number of applications, hence it is not usually the most convenient format for use.

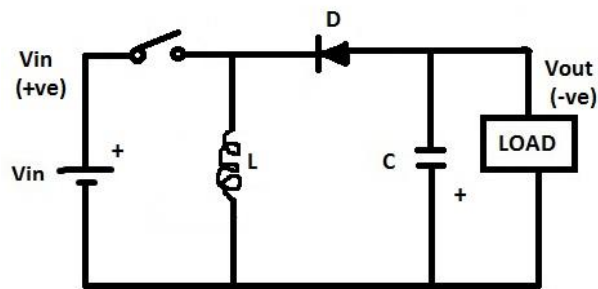


Fig 4.6 Buck-boost converter circuit with negative V_{out}

While the switch is in closed condition, the current is built up through inductor and when the switch is in open condition, inductor feeds current through diode to the connected load. The polarities of the circuit including diode component in buck-boost converter can be reversed in order to produce a positive value of output voltage from supplied negative value input voltage.

- Negative V_{in} , Positive V_{out} : In this type of designed buck-boost converter circuit, it provides input and output to be of similar polarity. In order to achieve this, we require more number of components than usual requirement for regular converter. The circuit for this type circuit combination of a buck-boost converter is as depicted in Figure.4.7.

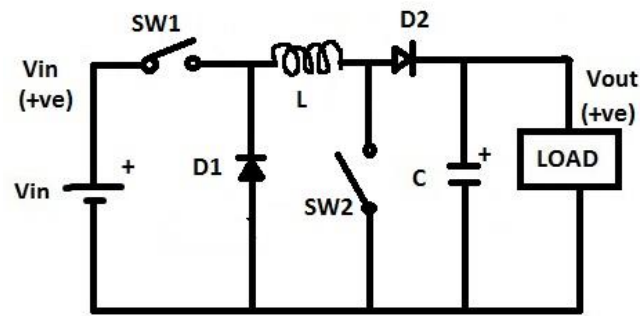


Fig 4.7 Buck-boost converter circuit providing positive V_{out}

In this type of circuit, both the switches are required to be operated simultaneously, i.e. both switches are closed or either open. While the switches are in open condition, the inductor current starts to build up. At certain required instance, both the switches are simultaneously opened. Inductor then supplies the current to connected load through operation of both the diodes.

In the contemporary researches, two new type of converters are developed, they are Cuk and Sepic converter. They are designed to have many advantages over the usual buck-boost type of converters.

The merits and demerits of three non-isolated converters explained earlier can be summarized as follows:

➤ **Buck converter**

- It takes the pulsed input current and it needs input filter.
- The uninterrupted output current amounts in occurrence of lesser output voltage ripple.
- The produced Output voltage is invariably lesser than supplied input voltage.

➤ **Boost converter**

- It takes uninterrupted input current, it also eliminates need of input filter.
- It produces a pulsed output current and it even creates more output voltage ripple.
- The produced Output voltage is invariably greater than supplied input voltage.

➤ **Buck - Boost converter**

- It takes the pulsed input current and needs the input filter in the circuit.
- It produces pulsed output current and it also create more output voltage ripple
- The produced Output voltage is invariably either greater or smaller than supplied input voltage.

4.2.4 Cuk converter

The Buck converter can be called as Voltage to Current converter circuit, the Boost converter can be called as Current to Voltage converter circuit, Buck-Boost converter can be called as Voltage-Current-Voltage converter circuit and finally Cuk converter can be also be called as a Current-Voltage-Current converter as depicted in Figure 4.8. All the types of designed switching converters have to fall under one of the above discussed configurations. Thus by looking into merits and demerits of previously explained converters, it will be quite good to combine advantages of the explained types of converters into one converter. Cuk converter is said to be one such type of dc-dc converter.

It has the following merits:-

- It takes up Continuous input current.
- It takes up Continuous output current.
- The Output voltage magnitude can either be lesser or greater than the input voltage.

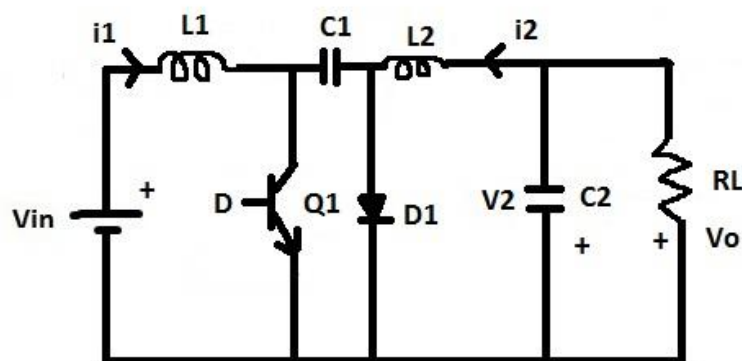


Fig 4.8 Cuk converter circuit

The Cuk converter can be described as the step up/down converter based the designed type of the boost-buck topology. Cuk converter is designed to have two sections .i.e. an input and output stages. The input voltage V_{in} is fed to the circuit by inductor named L_1 and while transistor Q_1 is in switched on condition, the current i_1 forms magnetic field of the inductor. When the diode D_1 gets reverse biased and then the energy starts getting dissipated from storage elements placed in the output stage of the converter. While Q_1 transistor gets turned off, the inductor L_1 tries in order to maintain the same amount of current flowing across it by reversing the polarity and reduces the sourcing current in order to reduce its magnetic field. Hence it provides the energy to output across capacitor C_1 . The inductor currents in the circuit are the currents of input and output. Thus, in case the Conservation of energy principle is implemented:

$$\frac{V_o}{V_{in}} = \frac{D}{1-D}$$

Where $D =$ Duty cycle:

$$D = \frac{T_{on}}{T_{on}+T_{off}}$$

The voltage ratio of the designed Cuk converter circuit is similar as of buck-boost converter, yet its main merit over rest all converters is that inductors in input and output stage produces filtered current at both sides. When all the basic converters have current of pulsating nature on minimum one side of converter circuit it may be on input/output part. By changing the duty cycle of the connected switch, output voltage can be changed and it can also be varied either greater or lesser than input voltage.

The only disadvantage of the cuk converter is that it provides negative voltage at output. This limits the application of cuk converter in many fields, in order to overcome the problem, another type of converter has ben designed, called as sepic converter.

4.2.5 Sepic converter

Sepic converter is a type of DC to DC converter having ability of operating in either in step up/down mode and hence it is extensively made use of in battery operated applications, by varying the duty cycle of gate signal given to connected switch. When the duty cycle is greater

than 0.5 the converter will produce step up and when it is lesser than 0.5, it will produce step down output voltage. Previously discussed converter types .i.e. buck, boost, buck-boost are used to either step up /down voltage have few limitation like pulsating nature of current input or output, inverted type of output voltage, these reasons make it unreliable for different types of battery applications. Hence it's not an easy task for conventional type of power converters to give uninterrupted higher efficiency specifically in case when it has to produce step up/down voltage at output. These type of characteristics can be obtained using sepic converter.

Operation of Circuit

SEPIC can be abbreviated as Single-ended primary inductor converter. It is a DC-DC type of converter, which allows output voltage to be either more or less than, or even equal to the magnitude at its supplied input. The output voltage of converter can be controlled by changing duty cycle of switch. A sepic converter is same as that of a usual buck-boost converter, but it has merits of producing the non-inverted output.

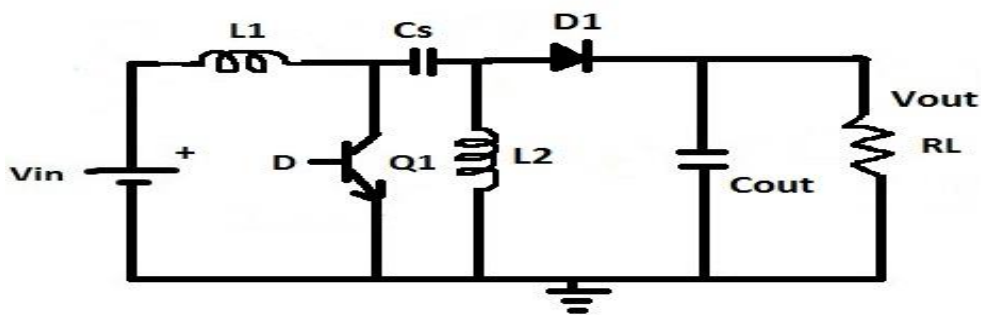


Fig 4.9Sepic converter circuit

A SEPIC converter operates in continuous conduction type mode when the current across inductor L_1 does not decrease to zero [0] value. While the steady-state operation of Sepic converter, average voltage through capacitor C_s is similar to input voltage of the converter. Due to C_s blocking the direct current in the circuit, the average current through it will be zero. This makes inductor L_2 as the only source for load current in the circuit. Thus average current across inductor L_2 is basically average load current. Thus it is unconventional of input voltage. By above discuss we arrive at following conclusion:

$$V_{in} = V_{L1} + V_{Cs} + V_{L2}$$

Since average voltage .i.e. V_{Cs} is equal to the value of V_{in}

$$V_{L1} = -V_{L2}.$$

The average currents in the circuit could be summed as:

$$I_{D1} = I_{L1} - I_{L2}$$

By switching on Q_1 , the current I_{L1} starts increasing in positive direction while at the same time, current I_{L2} starts increasing in negative direction. Thus capacitor .i.e. C_s starts supplying energy in order to increase value of current across I_{L2} hence it increases amount of energy stored at L_2 .

By switching off the switch Q_1 , the current I_{C_s} equals the value of current as of I_{L1} . Current I_{L2} keeps to continue operation in negative direction and never changes its operation direction. We can derive out of the figure that I_{L2} with negative value will sum up with I_{L1} in order to increase amount of total current fed to load.

$$I_{D1} = I_{C_s} - I_{L2}. \text{ [Kirchhoff's Current Law]}$$

Thus during Q_1 's off condition, the supplied power to load by L_1 and L_2 . The inductor L_1 charges the Coupling capacitor (C_s) in this off cycle operation and it recharges L_2 inductor in on cycle. It's only because of these coupling capacitor and inductor that the buck and boost converter abilities are enabled in this converter.

Thus the merits of sepic converter can be concluded as, all though it is similar to buck boost converter, yet it has many merits like producing the output voltage of non-inverted nature, it does not require any filter, coupled inductor can be used and so on.

4.3. Conclusion

Table 4.1 Comparison of DC-DC converter's properties

Buck	Boost	Buck-Boost	Cuk	Sepic
input current of Pulsed nature.	input current of Pulsed nature.	input current of Pulsed nature.	input current of Continuous nature	input current of Continuous nature
Needs input filter	Needs input filter	Needs input filter	Needs more number of components	Does not require input filter
output current of Continuous nature	output current of Continuous nature	output current of pulsed nature	output current of Continuous nature	output current of pulsed nature
No change in output polarity	Change in output polarity	Change in output polarity	Change in output polarity	Change in output polarity
Higher efficiency	Higher efficiency	Higher efficiency	Higher efficiency	Coupled inductor could be used
Can Only be used for step down applications	Can only be used for step up applications	Can be used for both step up / down applications	Can be used for both step up / down applications	Can be used for both step up / down applications

Hence after studying all the topologies of DC-DC converters, we have selected buck converter to work on the implementation of closed loop operation, since buck has few complications and could be studied extensively, we are further taking consideration of a variety of input voltage and detailed analysis is made. In other words it all most acts like a PV emulator.

5. CHAPTER 5

MATHEMATICAL MODELLING

The conversion of fixed DC source voltage into variable voltage source turns out to be the most important aspect in many of the industrial applications around the world, and that's where the DC-DC converter comes in to picture. Like the transformer, DC-DC converters can vary the .i.e. step up /step down the supplied voltage. Marine hoists, trolley vehicles, fork lift vehicles, traction motors and so on the use of DC converter cannot be limited and especially the electric automobile industry.

As discussed in the previous chapter about the various types of DC-DC converters, we intend to present the mathematical modelling of buck converter that is used and worked upon in the project.

5.1 Modelling of Buck converter with negligible values of parasitic resistance

The basic design of buck converter consists of an inductor, a diode, a capacitor, a switch and a switch control circuit. Few elements like inductor and capacitor contain a very small amount of in built resistance and in this analysis we are considering them to be very negligible. The circuit can be operated by varying the entire duration of operation time where inductor receives the input energy supplied from source.

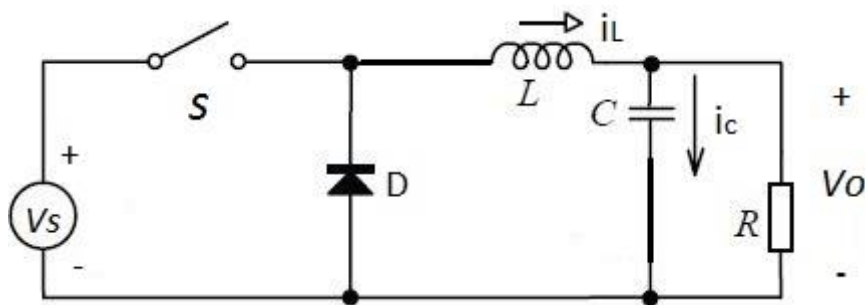


Fig 5.1 Circuit diagram of Buck converter

The voltage flowing through inductor L could be expressed as:

$$e_L = L \frac{di}{dt} \quad (5.1)$$

Supposing that the current across inductor increases linearly during time t_1 from initial value I_1 to I_2 .

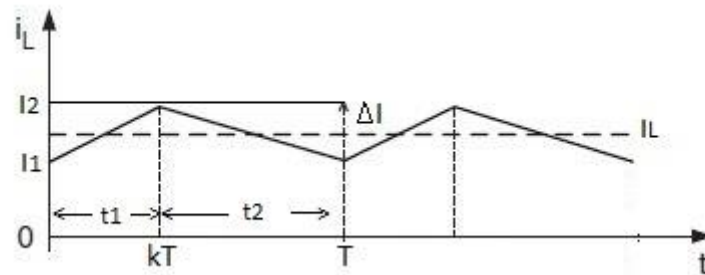


Fig 5.2 Waveform of operation of buck converter

$$V_s - V_o = L \frac{I_2 - I_1}{t_1} = L \frac{\Delta I}{t_1} \quad (5.2)$$

$$t_1 = L \frac{\Delta I}{V_s - V_o} \quad (5.3)$$

and during time t_2 , the current in inductor decreases to I_1 from I_2

$$-V_o = -L \frac{\Delta I}{t_2} \quad (5.4)$$

$$t_2 = \frac{\Delta I L}{V_o} \quad (5.5)$$

The peak to peak ripple current across inductor L can be expressed as : $\Delta I = I_2 - I_1$, this in equations 5.2 and 5.4, we get

$$\Delta I = \frac{(V_s - V_o)t_1}{L} = \frac{V_o \cdot t_2}{L} \quad (5.6)$$

Substituting the values of t_1 and t_2 .i.e. $t_1 = kT$ and $t_2 = (1-k) T$ gives the average output as

$$V_o = V_s \cdot \frac{t_1}{T} = V_s \cdot k$$

$$\text{Thus deriving the gain .i.e. } \frac{V_o}{V_s} = k \quad (5.7)$$

5.2 State space averaging of Buck converter

State space averaging is considered to be the most important and effective tool for modelling and computer simulation applied to the switched circuits with a view of DC – DC converters, it is in both time and frequency domain. Rather than the complicated level switching of the converter, a much easier model is made use off, which eases effects of switching and will replace the complex waveforms by its low frequency envelopes.

The state space averaging can be viewed as the simplified study of the usual equations of the switching converter, it also determines results for all the harmonics in the input signals and this is done in frequency domain. The buck converter considered here is with the negligible values of the parasitic resistances.

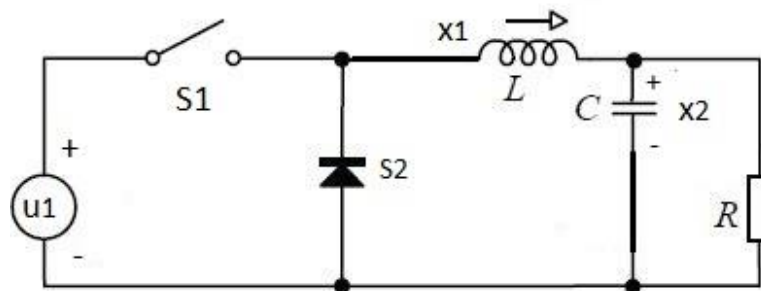


Fig 5.3 Buck converter circuit for state space averaging

The Figure 5.3 is drawn to provide the idea of converter circuit used for the analysis. Here the state variable are considered to be x 's and all the sources are considered to be u 's.

Mode 1: In this mode, it is indicating the initial operation condition of buck converter with switch S_1 in on position and S_2 in off position.

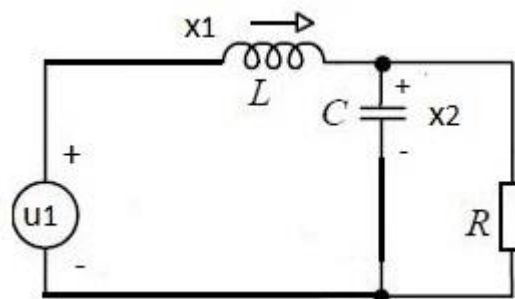


Fig 5.4 Equivalent circuit of converter in mode 1

Applying the Kirchoff's voltage rule [KVL] to the loop, we derive

$$u_1 = L x_1' + x_2 \quad (5.8)$$

$$C x_2' = x_1 - \frac{1}{R} x_2 \quad (5.9)$$

The equations 5.8 and 5.9 can be rewritten as

$$x_1' = -\frac{1}{L} x_2 + \frac{1}{L} u_1 \quad (5.10)$$

$$x_2' = -\frac{1}{C} x_2 + \frac{1}{RC} x_1 \quad (5.11)$$

these equations can then be written in form of $x' = A_1 x + B_1 u_1$

$$x = \text{state vector} = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

$$A_1 = \text{state coefficient matrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix}$$

$u_1 =$ source vector

$$B_1 = \text{source coefficient matrix} = \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix}$$

Mode 2: In this mode, it is indicating the initial operation condition of buck converter with switch S1 in off position and S2 in on position

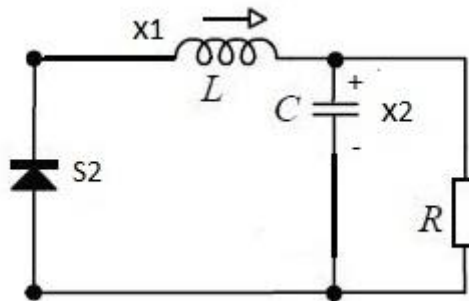


Fig 5.5 Equivalent circuit of converter in mode 2

Applying the Kirchhoff's voltage rule [KVL] to the loop, we derive

$$0 = L x_1' + x_2 \quad (5.12)$$

$$C x_2' = x_1 - \frac{1}{R} x_2 \quad (5.13)$$

The equations 5.12 and 5.13 can be rewritten as

$$x_1' = -\frac{1}{L} x_2 \quad (5.14)$$

$$x_2' = -\frac{1}{C} x_2 + \frac{1}{RC} x_1 \quad (5.15)$$

these equations can then be written in form of $x' = A_2 x + B_2 u_1$

$$x = \text{state vector} = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

$$A_2 = \text{state coefficient matrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix}$$

$u_1 = \text{source vector}$

$$B_2 = \text{source coefficient matrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

the final solution of the state space averaging can be obtained only after the analysis of two modes that we have done, thus we get

$$A = A_1 k + A_2 (1-k) \quad (5.16)$$

$$B = B_1 k + B_2 (1-k) \quad (5.17)$$

Substituting the values of A_1, A_2, B_1, B_2 we get

$$A = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \quad (5.18)$$

$$B = \begin{bmatrix} k \\ \frac{1}{L} \\ 0 \end{bmatrix} \quad (5.19)$$

Thus this state form of the analysis would lead us to equations of the state space averaged model i.e.

$$x_1' = -\frac{1}{L} x_2 + \frac{k}{L} u_1 \quad (5.20)$$

$$x_2' = -\frac{1}{C} x_2 + \frac{1}{RC} x_2 \quad (5.21)$$

5.3 Modelling of Buck converter with finite values of parasitic resistance

The Buck converter circuit elements like inductor and capacitor contain a very small amount of in build resistance and in this analysis we are considering them to be of finite values. All though in usual circuit analysis these resistances are neglected, yet when implemented in the circuit for applications these do have a certain amount of effect on the operation of the converter.

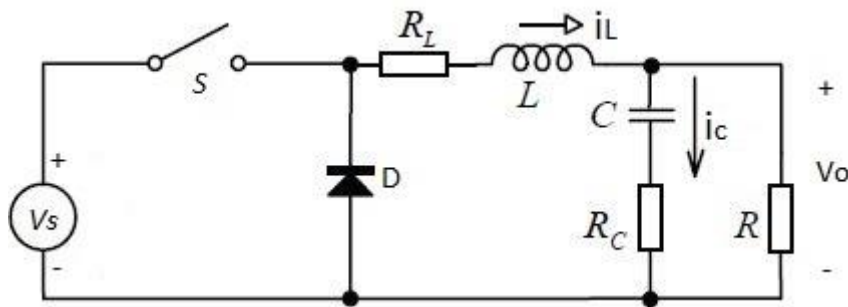


Fig 5.6 Buck converter circuit with parasitic resistance

Considering the V_{in} as input voltage, I_{in} as input current and I_o as the load current

$$V_{in} \cdot I_{in} = I_o^2 R \quad (5.22)$$

$$V_{in} \cdot I_{in} = V_o I_o \quad (5.23)$$

$$\frac{V_o}{V_{in}} = \frac{I_{in}}{I_o} = k \quad (5.24)$$

Writing the equations we get

$$V_{in} \cdot I_{in} = I_o^2 \cdot r_L + I_o^2 R \quad (5.25)$$

Using the equation 5.24 in equation 5.25, we get

$$V_{in} \cdot k \cdot I_o = I_o^2 \cdot r_L + I_o^2 R \quad (5.26)$$

$$V_{in} \cdot k = I_o (r_L + R) \quad (5.27)$$

$$V_{in} \cdot k = \frac{V_o}{R} (r_L + R) \quad (5.28)$$

Thus deriving the value of gain as

$$\frac{V_o}{V_{in}} = k \cdot \frac{R}{r_L + R} \quad (5.29)$$

5.4 State space averaging of Buck converter with parasitic resistance

Mode 1: Considering the buck converter in mode 1 operation

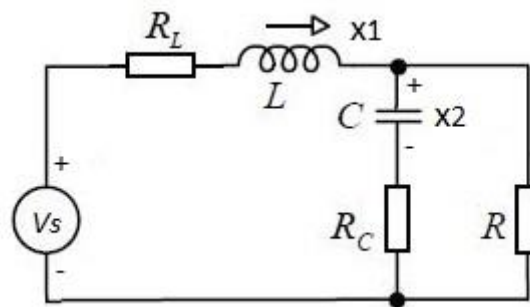


Fig 5.7 Equivalent circuit of converter in mode 1

the equations can then be written in form of $\dot{x}' = A_1 x + B_1 u_1$

$$\dot{x}' = A_1 x + B_1 u_1 \quad (5.30)$$

$$y_1 = C_1 \cdot X \quad (5.31)$$

$$A_1 = \begin{bmatrix} -\frac{R_L + R_c || R}{L} & -\frac{R}{L(R_c + R)} \\ \frac{R}{C(R_c + R)} & -\frac{1}{C(R_c + R)} \end{bmatrix}$$

$$B_1 = \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix}$$

$$C_1 = \begin{bmatrix} 1 & 0 \\ R_c || R & \frac{R}{(R_c + R)} \end{bmatrix}$$

Mode 2: Considering the buck converter in mode 2 operation

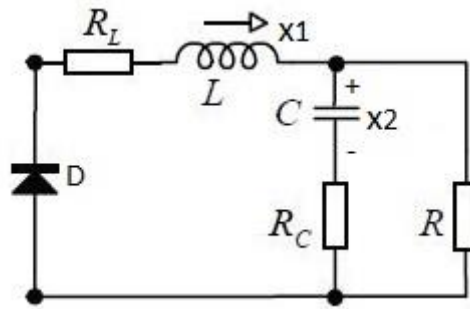


Fig 5.8 Equivalent circuit of converter in mode 1

$$x' = A_2 X + B_2 u_2 \quad (5.32)$$

$$y_2 = C_2 \cdot X \quad (5.33)$$

$$A_2 = \begin{bmatrix} -\frac{R_L + R_C || R}{L} & -\frac{R}{L(R_C + R)} \\ \frac{R}{C(R_C + R)} & -\frac{1}{C(R_C + R)} \end{bmatrix}$$

$$B_2 = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

$$C_2 = \begin{bmatrix} 1 & 0 \\ R_C || R & \frac{R}{(R_C + R)} \end{bmatrix}$$

the final solution of the state space averaging can be obtained only after the analysis of two modes that we have done, thus we get

$$A = A_1 k + A_2 (1-k) \quad (5.34)$$

$$B = B_1 k + B_2 (1-k) \quad (5.35)$$

Substituting the values of $A_1, A_2, B_1, B_2, C_1, C_2$ we get

$$A = \begin{bmatrix} \frac{-(R_L + R || R_C)}{C(R_C + R)} & \frac{-R}{L(R_C + R)} \\ \frac{R}{C(R_C + R)} & \frac{-1}{C(R_C + R)} \end{bmatrix} \quad (5.36)$$

$$B = \begin{bmatrix} k \\ \frac{k}{L} \\ 0 \end{bmatrix} \quad (5.37)$$

$$C = \begin{bmatrix} k & 0 \\ Rc \parallel R & \frac{R}{(Rc+R)} \end{bmatrix} \quad (5.38)$$

5.5 Conclusion

As discussed earlier the State space averaging is the most explicitly effective tool for modelling and conducting the computer simulation applied to the designed switching circuits with a view of DC – DC converters, it is in both time and frequency domain. Rather than the complicated level switching of the converter, a much easier model is made use off, which eases effects of switching and will replace the complex waveforms by its low frequency envelopes.

The state space averaging can be viewed as the simplified rule for studying of the equations of the switching converter, it also determines results for all the harmonics in the input signals and this is done in frequency domain.

6. CHAPTER 6

HARDWARE IMPLEMENTATION OF BUCK CONVERTER

6.1 Introduction

The hardware implementation of closed loop buck converter is made with intention to check the operating strategy, the components used are as per the availability of the components at the time of design. Basically with an intention to design a low cost and light weighted working model.

6.2 Hardware design for implementation

The hardware is implemented to have 12V DC as the unregulated input supply to the buck converter as well as the microcontroller. The output could be measured across the load and in order to check working for different loading condition, we need to go on adding the extra load. The voltage is sensed by the microcontroller input and a control pulse is given out by microcontroller in form of PWM to the gate terminal of the MOSFET in the converter.

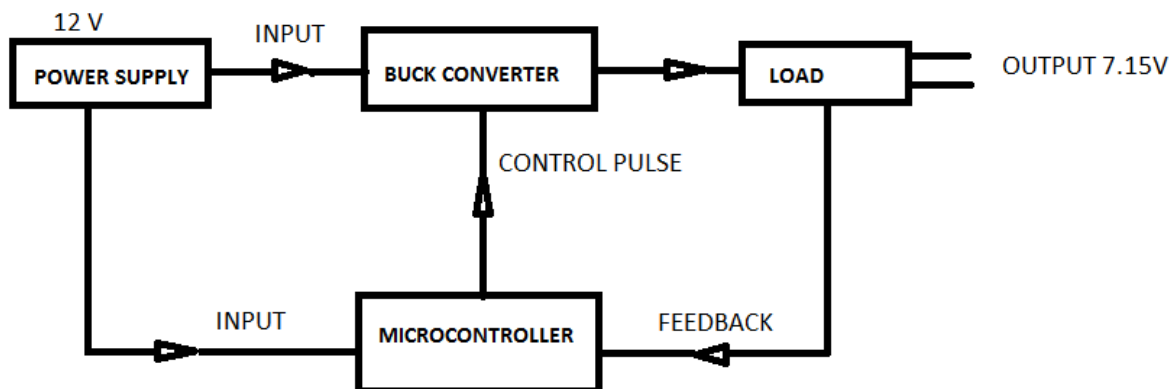


Fig 6.1 Block diagram of the hardware setup

The equally important part of the hardware is microcontroller. The microcontroller ATmega 8 is made use off. The ATmega8 is a low-power CMOS 8-bit microcontroller based on the AVR RISC architecture. By executing powerful instructions in a single clock cycle, the ATmega8

achieves throughputs approaching 1MIPS per MHz, allowing the system designer to optimize power consumption versus processing speed.

The core combines a rich instruction set with 32 general purpose working registers. All the 32 registers are directly connected to the Arithmetic Logic Unit (ALU), allowing two independent registers to be accessed in one single instruction executed in one clock cycle. The resulting architecture is more code efficient while achieving throughputs up to ten times faster than conventional CISC microcontrollers.

The ATmega8 provides the following features: 8 Kbytes of In-System Programmable Flash with Read-While-Write capabilities, 512 bytes of EEPROM, 1 Kbyte of SRAM, 23 general purpose I/O lines, 32 general purpose working registers, three flexible Timer/Counters with compare modes, internal and external interrupts, a serial programmable USART, a byte oriented Two wire Serial Interface, a 6-channel ADC (eight channels in TQFP and QFN/MLF packages) with 10-bit accuracy, a programmable Watchdog Timer with Internal Oscillator, an SPI serial port, and five software selectable power saving modes.

The Idle mode stops the CPU while allowing the SRAM, Timer/Counters, SPI port, and interrupt system to continue functioning. The Power down mode saves the register contents but freezes the Oscillator, disabling all other chip functions until the next Interrupt or Hardware Reset. In Power-save mode, the asynchronous timer continues to run, allowing the user to maintain a timer base while the rest of the device is sleeping.

The ADC Noise Reduction mode stops the CPU and all I/O modules except asynchronous timer and ADC, to minimize switching noise during ADC conversions. In Standby mode, the Crystal/resonator Oscillator is running while the rest of the device is sleeping. This allows very Fast start-up combined with low-power consumption.

By combining an 8-bit RISC CPU with In-System Self-Programmable Flash on a monolithic chip, the ATmega8 is a powerful microcontroller that provides a highly-flexible and cost-effective solution to many embedded control applications.

6.3 Program

```
int main(void)
{
    DDRD = 0xFF;
    PORTD = 0x00;

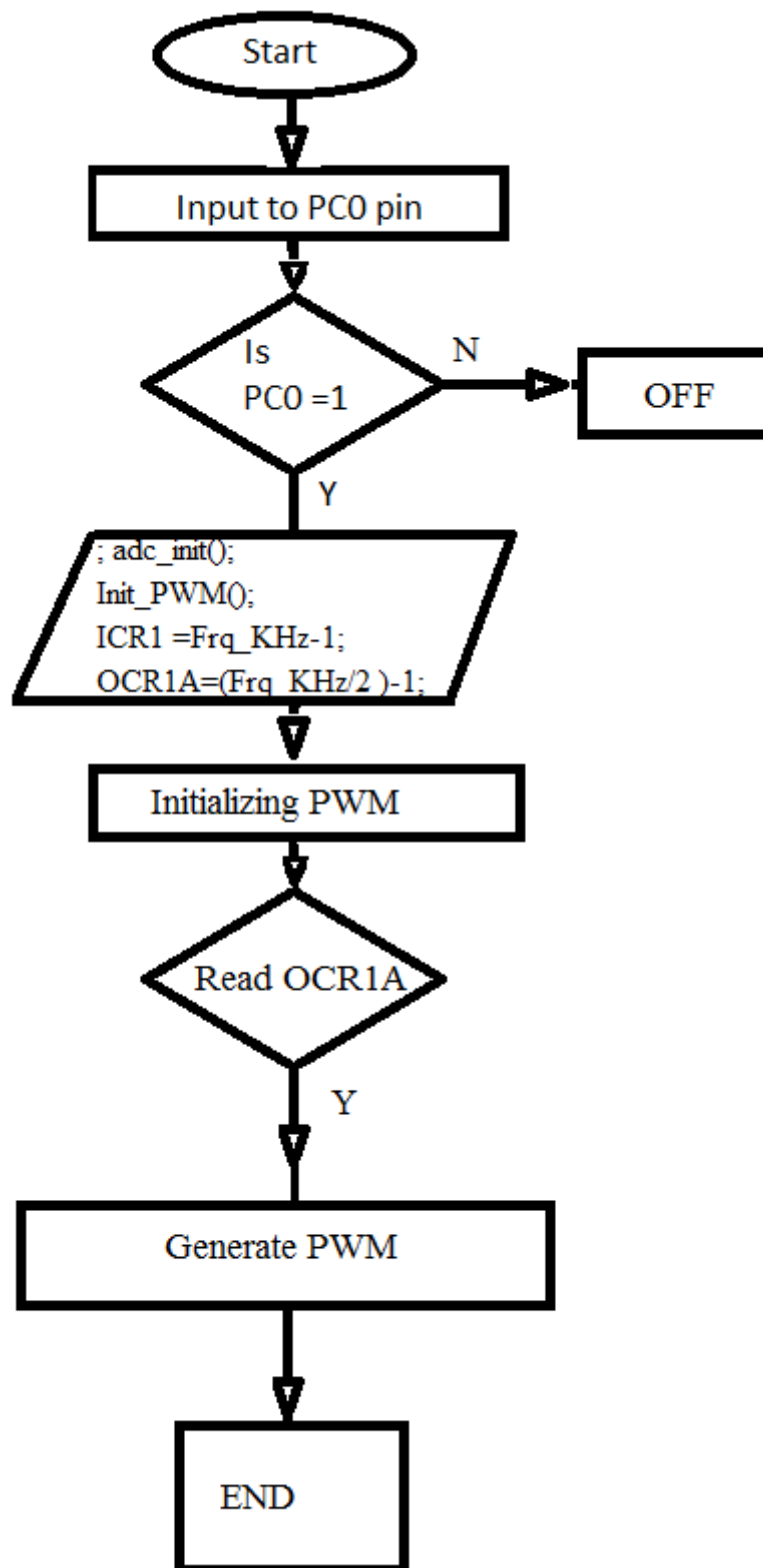
    DDRB = 0xFF;
    PORTB = 0x00;

    DDRC = 0xF0;
    PORTC = 0x00;

    adc_init();
    Init_PWM();
    ICR1 = Frq_KHz-1;
    OCR1A=(Frq_KHz/2)-1;

    while(1)
    {
        _delay_ms(1);
        adcValue=adc_read(0);
        // OCR1A=( ( adcValue/1023 ) *Frq_KHz );
        df=1024/Frq_KHz;
        df++;
        OCR1A=(Frq_KHz - adcValue/df );
        // OCR1A= adcValue/13 ;
    }
}
```

6.4 Flow Chart of the program



6.5 Conclusion

The hardware is implemented with available components, in order to check the model working mechanism of the converter. The output of the hardware is discussed in the results and discussion chapter, further.

7. CHAPTER 7

RESULTS AND DISCUSSIONS

7.1 Introduction

In this chapter we will discuss about the results of the various varieties of simulations carried out in MATLAB/Simulink. The simulation of the circuit is carried out in many various types of conditions of the converter. The Various results are simulated and obtained with conditions of negligible parasitic resistance and also with finite values of the resistances. These conditions are also simulated with P and PI types of controllers.

7.2 Circuit diagram and control strategy of closed loop buck converter

The Solar emulator or closed loop buck converter discussed so far with all the circuit components is designed as shown in Figure 7.1. The entire simulation is carried out in MATLAB/ Simulink software. The circuit with a DC voltage as input voltage, is then stepped down by the buck converter operation. The control circuit can then be employed with various types' controllers and the operation condition can be varied to study and analyse the emulator operation.

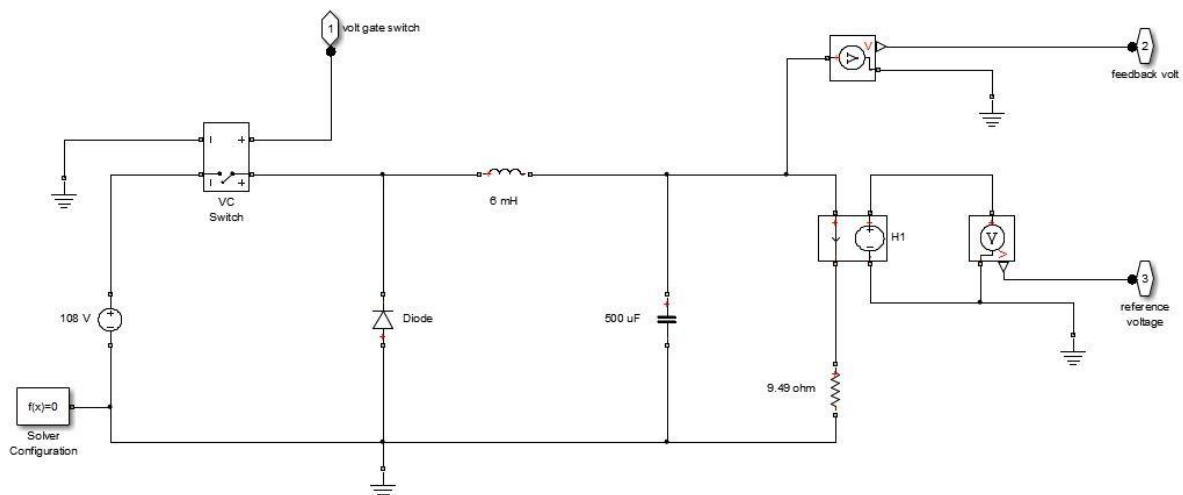


Fig 7.1 Buck converter circuit as implemented

The control circuit employed is with various method, where in the derived output voltage is compared with reference voltage. It is usual that we a certain amount of error when the comparison is done, this error signal is then fed to P/PI controller in order to vary it as per required conditions [Figure 7.2]. The then obtained signal is again compared with a high frequency voltage using a comparator. Thus after going through all these variation the finally obtained signal is fed to the switching device as the gate signal and the output as well as other analysis data to noted to carry out the study.

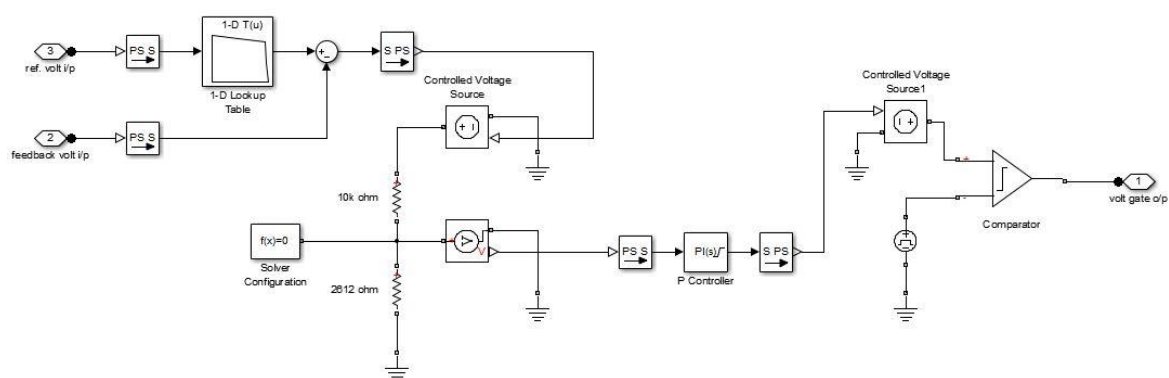


Fig 7.2Control circuit implemented for converter

7.3 Various control methods and strategies for circuit operation and results

The control strategies play an important role in the circuit operation perhaps that is the only major motive behind the designing of closed loop converter. The decision to select a certain type of controller is also equally important as it effects in handling the error and maintaining the gain value of the circuit efficiently.

P Controller:

It is mostly used to stabilize the unstable process of first order, having energy storage device. The P controller is used in order to reduce steady state error occurring in the system. The steady state error of the system reduces as simultaneously the value of proportional gain factor K starts increasing. Although the error gets reduced, the P controller cannot completely manage to eliminate the steady state error completely from the system. When the proportional gain is

increased, it gives smaller amplitude and also phase margin. It also provide the swift dynamics which satisfy the wider frequency band and higher sensitivity to noise.

The proportional controller is expressed as:

$$\mathbf{P} = \mathbf{K}_p \cdot \mathbf{e} (t)$$

where K_p is the gain & $e(t)$ is the error signal.

This type of controller is used only when the system designed is able to tolerate the constant steady state error. Apart from this we can conclude that using the P controller reduces the rise time. After reduction of steady state error to certain value, further increasing the K will lead to overshoot in system response. Oscillations are caused by the P controller when there are lags or any dead time of aggressive nature. Larger the number of higher order lags, larger the problem it leads. It also amplifies the process noise directly.

P-I controller:

PI controller has the element of integrator along with proportional controller. This type of controller is used in order to eliminate steady state error occurring from the P controller. It has a negative impact in terms of speedy response and also on overall stability of the system, hence it is used in the system where the speedy response is not the main issue.

The proportional – integrator controller is expressed as:

$$\mathbf{PI} = \mathbf{K}_p \cdot \mathbf{e} (t) + \mathbf{K}_i \int_t^0 \mathbf{e} (t) dt$$

where K_p and K_i are gains & $e(t)$ is the error signal.

Although the integrator element can reduce the steady state error, it cannot predict the error occurring in the future. Various methods are used to study the circuit operation and are as explained further.

7.3.1 Lookup table method of data expression

The multi-dimensional Lookup table block used in simulation evaluates any representation of given sampled function in any number of variables. This method of look up table is used in MATLAB/Simulink simulation. This block maps any input values to output values by a simple method of interpolating the values in form of table with defined parameters as specified. The block supports all types of interpolation methods like constant, linear and so on.

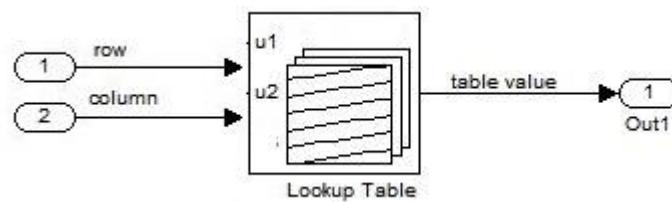


Fig 7.3 Lookup table representation

The simulation is carried out with data mapping by lookup table and using P, PI controllers setting for both the non-parasitic converter as well as for parasitic converter. The derived results are presented in graph and in tabular form.

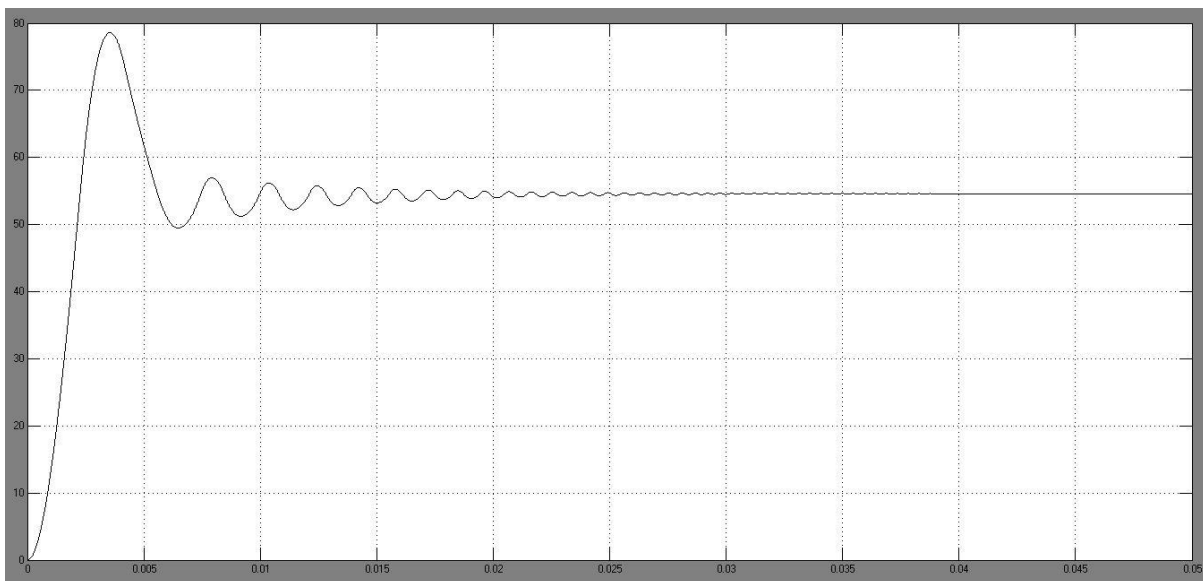


Fig 7.4 Output by lookup table method with non-parasitic resistance and P controller

The output of simulation for P controller value of 100 with negligible values of parasitic resistance is shown in Figure 7.4. The graph obtained has peak over shoot of 78.620, settling time of 0.035 seconds and steady state error of 2.1m. The same configuration of P controller with finite values of parasitic resistance gives the similar graph but with values of peak over

shoot of 73.335, settling time of 0.028 seconds and steady state error of 2.2m as depicted in Figure 7.5.

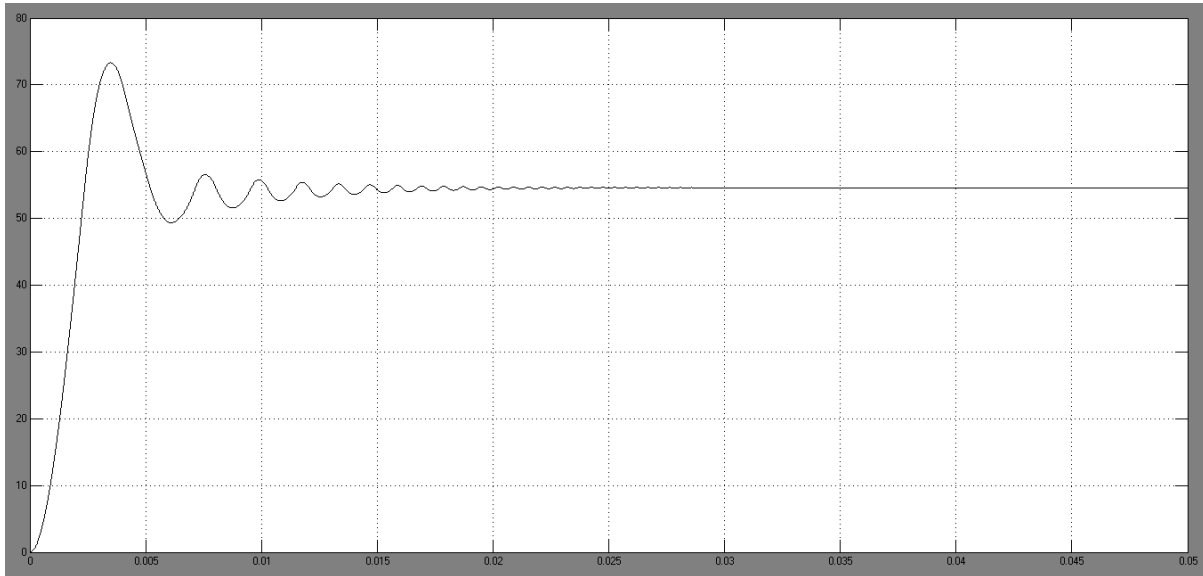


Fig 7.5 Output by lookup table method with parasitic resistance and P controller

This comparison of output by graphical representation gives a better comparative study for considering the parameters of the converter circuit and for future analysis. A detailed simulation and obtained outputs are presented in tabular form in Table 7.1 for different values of proportional controller.

Table 7.1 Output with different values of R_L and R_C and P controller

P controller = 80				
	$R_L=0; R_C=0$	$R_L=0.5; R_C=0$	$R_L=0.5; R_C=1e-6$	$R_L=0; R_C=1e-6$
Settling time	0.032 sec	0.025 sec	0.026 sec	0.030 sec
Peak overshoot	78.612	73.278	73.278	78.597
Steady state error	2.7m	2.6m	2.6m	2.7m
P controller = 100				
Settling time	0.035 sec	0.027 sec	0.028 sec	0.037 sec
Peak overshoot	78.620	73.335	73.335	78.606
Steady state error	2.1m	2.2m	2.2m	2.4m
P controller = 150				
Settling time	0.044 sec	0.030 sec	0.030 sec	0.045 sec
Peak overshoot	78.638	73.335	73.335	78.624

Steady state error	1.4m	2.4m	2.1m	2.1m
--------------------	------	------	------	------

A detailed simulation for PI controller and with converter having parasitic resistances and non-parasitic resistances respectively using same method is carried out further.

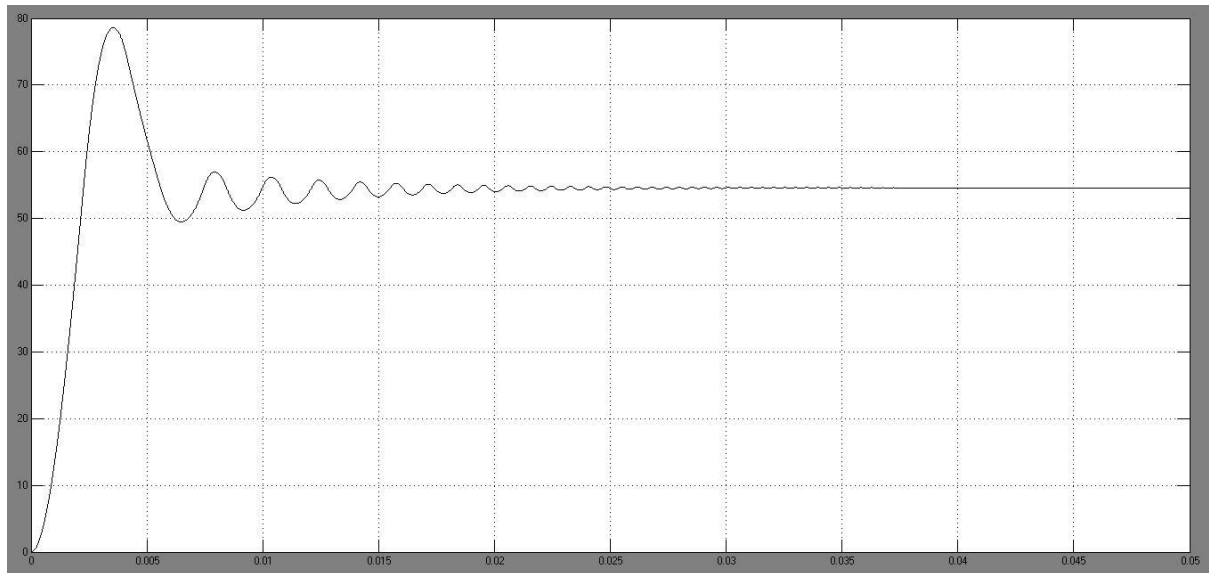


Fig 7.6 Output by lookup table method with non-parasitic resistance and PI controller

The output of simulation for PI controller value of 100 and 1 respectively and with negligible values of parasitic resistance is shown in Figure 7.6. The graph obtained has peak over shoot of 78.622, settling time of 0.035 seconds and steady state error of 2.5m. The same configuration of PI controller with finite values of parasitic resistance gives the similar graph but with values of peak over shoot of 73.334, settling time of 0.028 seconds and steady state error of 2.1m as depicted in Figure 7.7.

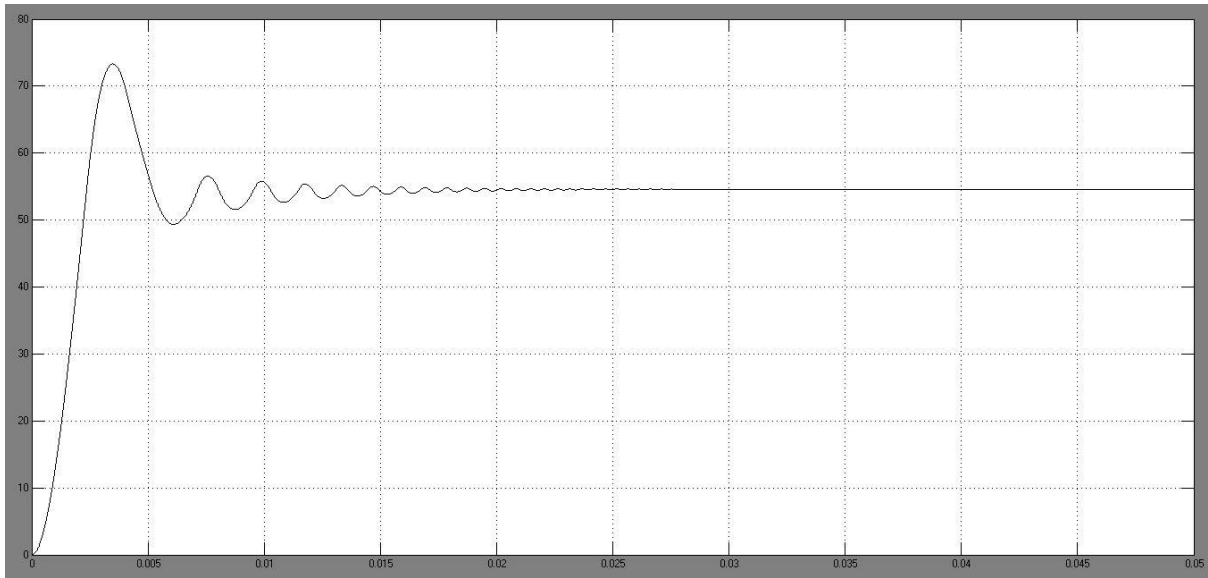


Fig 7.7 Output by lookup table method with parasitic resistance and PI controller

This comparison of output by graphical representation gives a better comparative study for considering the parameters of the converter circuit and for future analysis. A detailed simulation and obtained outputs are presented in tabular form in Table 7.2 for different combination of values of PI controller.

Table 7.2 Output with different values of R_L and R_C and PI controller

P = 80 ; I = 0.5				
	$R_L=0; R_C=0$	$R_L=0.5; R_C=0$	$R_L=0.5; R_C=1e-6$	$R_L=0; R_C=1e-6$
Settling time	0.032 sec	0.025 sec	0.026 sec	0.033 sec
Peak overshoot	78.613	73.280	73.280	78.600
Steady state error	2.5m	2.7m	2.7m	2.7m
P = 80 ; I = 1				
Settling time	0.032 sec	0.026 sec	0.027 sec	0.033 sec
Peak overshoot	78.614	73.282	73.280	78.600
Steady state error	2.7m	2.6m	2.7m	2.6m
P = 80 ; I = 1.5				
Settling time	0.032 sec	0.027 sec	0.028 sec	0.034 sec
Peak overshoot	78.614	73.281	73.282	78.600
Steady state error	2.7m	2.6m	2.6m	2.7m
P = 100 ; I = 0.5				

	$R_L=0; R_C=0$	$R_L=0.5; R_C=0$	$R_L=0.5; R_C=1e-6$	$R_L=0; R_C=1e-6$
Settling time	0.035 sec	0.028 sec	0.028 sec	0.037 sec
Peak overshoot	78.621	73.335	73.335	78.620
Steady state error	2.1m	2.2m	2.1m	2.6m
P = 100 ; I = 1				
Settling time	0.035 sec	0.028 sec	0.028 sec	0.037 sec
Peak overshoot	78.622	73.334	73.334	78.610
Steady state error	2.5m	2.3m	2.1m	2.7m
P = 100 ; I = 1.5				
Settling time	0.034 sec	0.028 sec	0.028 sec	0.036 sec
Peak overshoot	78.622	73.336	73.334	78.620
Steady state error	2.1m	2.4m	2.2m	2.6m
P = 150 ; I = 0.5				
	$R_L=0; R_C=0$	$R_L=0.5; R_C=0$	$R_L=0.5; R_C=1e-6$	$R_L=0; R_C=1e-6$
Settling time	0.048 sec	0.044 sec	0.043 sec	0.048 sec
Peak overshoot	78.637	73.335	73.335	78.634
Steady state error	1.4m	1.2m	1.4m	1.4m
P = 150 ; I = 1				
Settling time	0.045 sec	0.043 sec	0.043 sec	0.044 sec
Peak overshoot	78.630	73.335	73.334	78.632
Steady state error	1.4m	1.4m	1.4m	1.3m
P = 150 ; I = 1.5				
Settling time	0.044 sec	0.039 sec	0.044 sec	0.043 sec
Peak overshoot	78.630	73.335	73.335	78.630
Steady state error	1.6m	1.5m	1.4m	1.3m

7.3.2 User defined function method of data expression

In this method the data expression we make use of curve fitting toolbox in the MATLAB software. This tool enables us to do curve fitting on any type of curve in multi-dimensional form. The user need to choose the dimension as per the requirement. We obtained the curve

fitting equations in two dimensional form. Thus Curve fitting tool enables us to obtain the equation of various degree and parameters.

On the further part, the equations obtained from curve fitting tool are then implemented by making use of user defined function block in simulation, in order to express the equation of the curve. The function block abbreviated as fcn enables the user to apply any specified mathematical expression as the input. The formed equation can have any of the components of mathematical nature. The components like:

- The input to functional block is represented by u.
- Numerical constants
- Arithmetical operators like +, -, *, /, ^.
- Relational operators like ==, !=, =, >, <, >=, <= .
- Logical operators like &&, ||, !.
- Parentheses in expression and also mathematical functions.

Thus the simulation is carried out with implementing user defined functional block and using P, PI controllers setting for both the non-parasitic converter as well as for parasitic converter. The derived results are presented in graph and in tabular form.

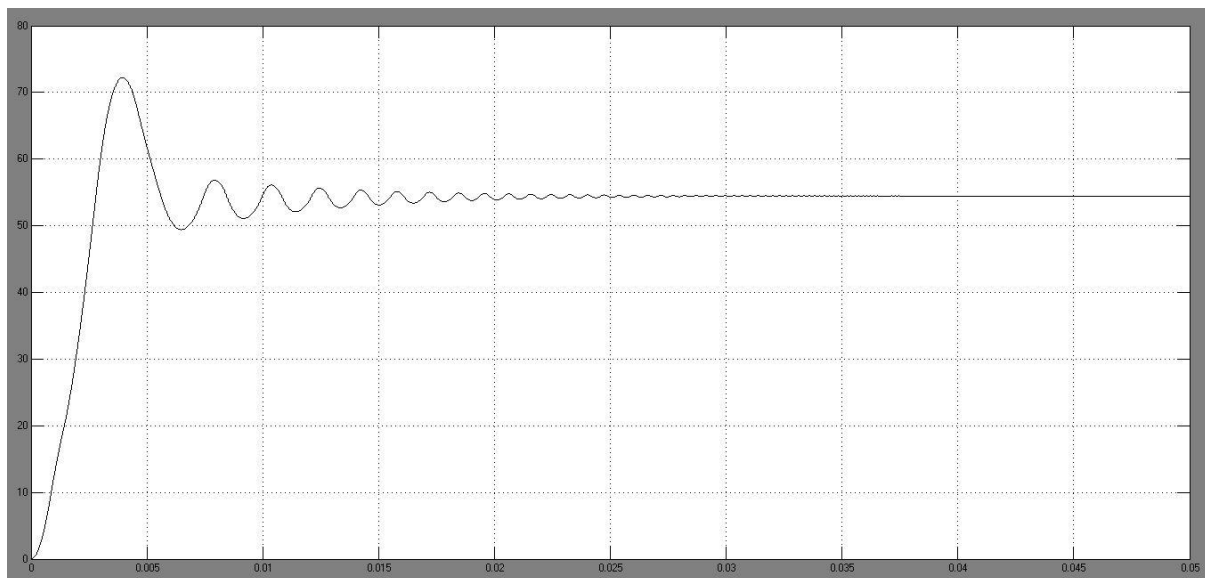


Fig 7.8 Output by User defined function method with non-parasitic resistance and P controller

The output of simulation for P controller value of 100 with negligible values of parasitic resistance is shown in Figure 7.8. The graph obtained has peak over shoot of 72.222, settling time of 0.038 seconds and steady state error of 3.9m. The same configuration of P controller with finite values of parasitic resistance gives the similar graph but with values of peak over shoot of 68.025, settling time of 0.027 seconds and steady state error of 3.6m as depicted in Figure 7.9.

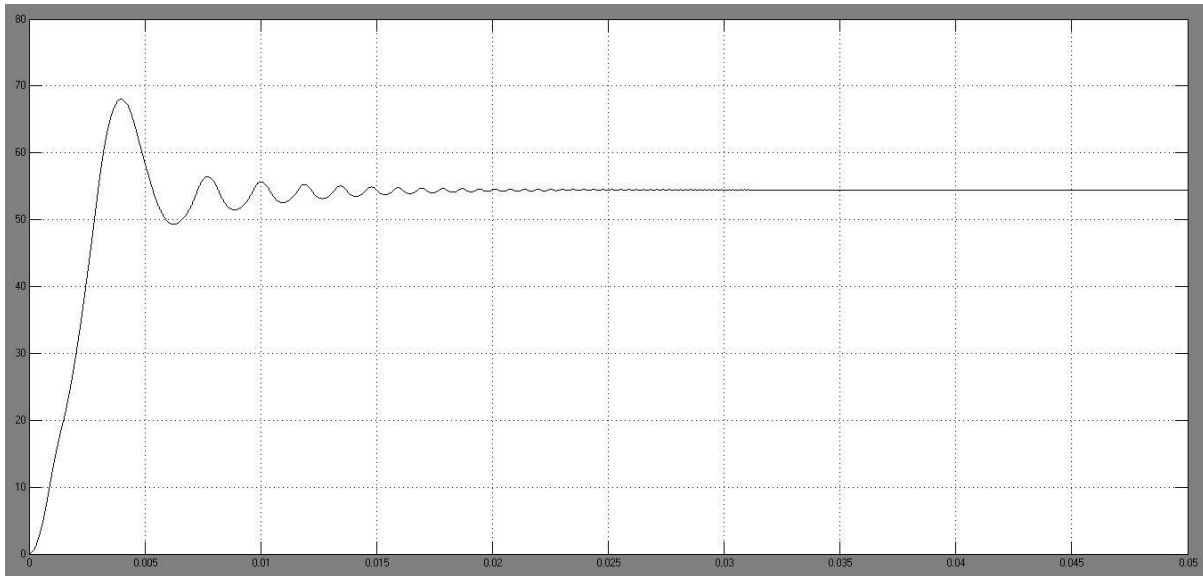


Fig 7.9 Output by User defined function method with parasitic resistance and P controller

This comparison of output by graphical representation gives a better comparative study for considering the parameters of the converter circuit and for future analysis. A detailed simulation and obtained outputs are presented in tabular form in Table 7.3 for different values of proportional controller.

Table 7.3 Output with different values of RL and RC and P controller

P controller = 80				
	$R_L=0; R_C=0$	$R_L=0.5; R_C=0$	$R_L=0.5; R_C=1e-6$	$R_L=0; R_C=1e-6$
Settling time	0.038 sec	0.027 sec	0.028 sec	0.034 sec
Peak overshoot	72.225	67.980	67.980	72.225
Steady state error	4.1m	4.1m	3.2m	3.9m
P controller= 100				
Settling time	0.038 sec	0.027 sec	0.027 sec	0.036 sec

Peak overshoot	72.222	68.025	68.025	72.223
Steady state error	3.9m	4.0m	3.6m	3.9m
P controller= 150				
Settling time	0.040 sec	0.027 sec	0.027 sec	0.038 sec
Peak overshoot	72.294	68.015	68.010	72.293
Steady state error	4.0m	4.1m	3.3m	4.0m

A detailed simulation for PI controller and with converter having parasitic resistances and non-parasitic resistances respectively using same method is carried out further.

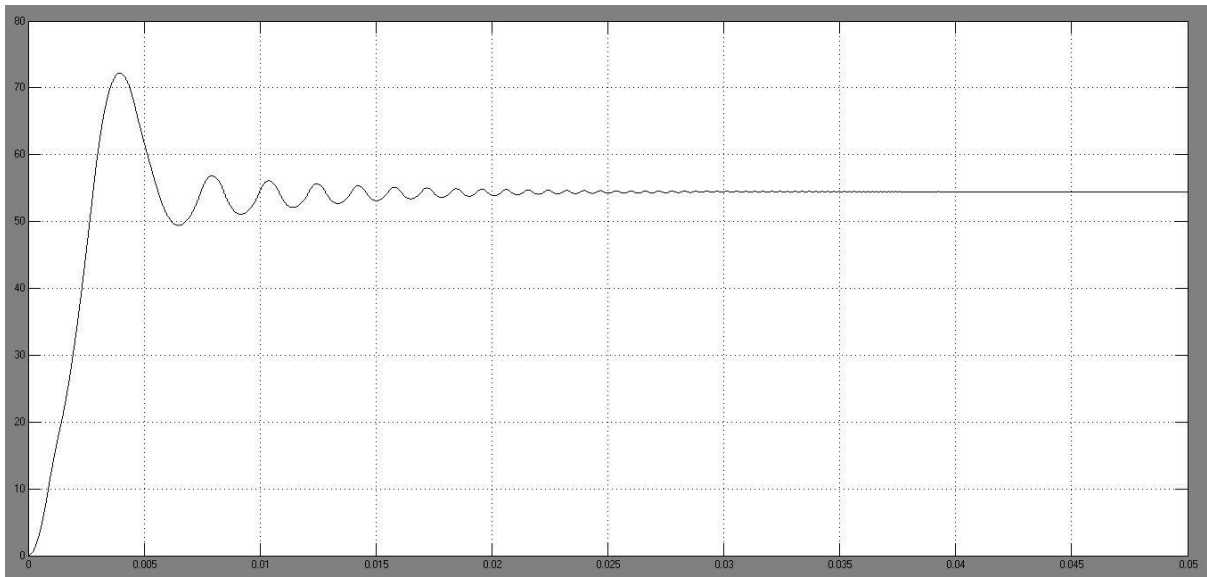


Fig 7.10 Output by User defined function method with non-parasitic resistance and PI controller

The output of simulation for PI controller value of 100 and 1 respectively and with negligible values of parasitic resistance is shown in Figure 7.10. The graph obtained has peak overshoot of 72.224, settling time of 0.038 seconds and steady state error of 3.9m. The same configuration of PI controller with finite values of parasitic resistance gives the similar graph but with values of peak overshoot of 68.025, settling time of 0.027 seconds and steady state error of 3.9m as depicted in Figure 7.11.

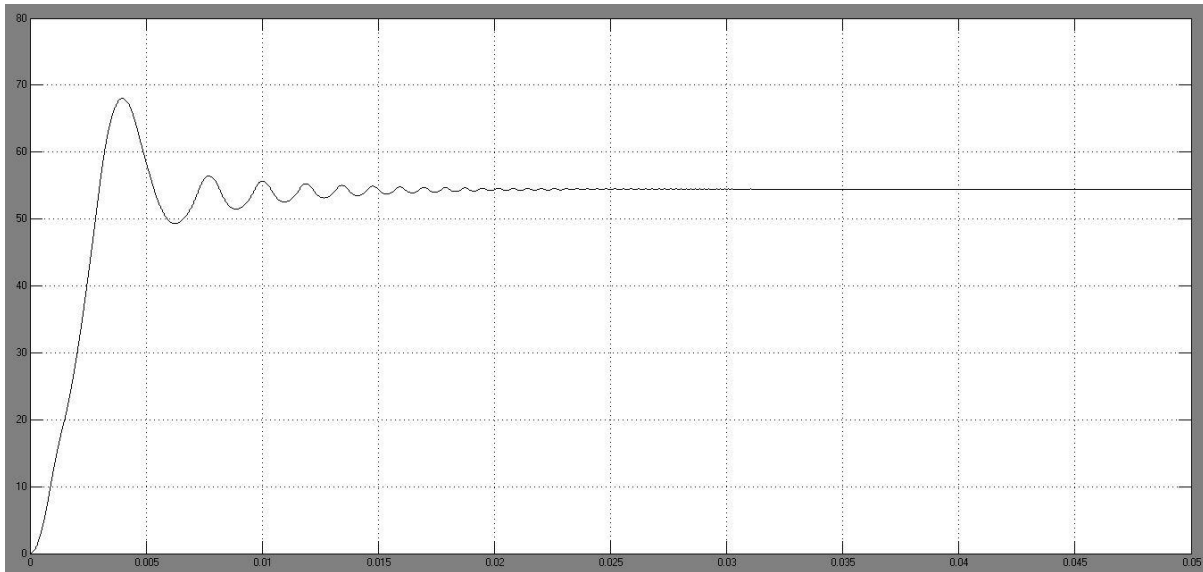


Fig 7.11 Output by User defined function method with parasitic resistance and PI controller

This comparison of output by graphical representation gives a better comparative study for considering the parameters of the converter circuit and for future analysis. A detailed simulation and obtained outputs are presented in tabular form in Table 7.4 for different combination of values of PI controller.

Table 7.4 Output with different values of RL and RC and PI controller

P = 80 ; I = 0.5				
	R _L =0; R _C =0	R _L =0.5; R _C =0	R _L =0.5; R _C =1e-6	R _L =0; R _C =1e-6
Settling time	0.037 sec	0.029 sec	0.027 sec	0.037 sec
Peak overshoot	72.210	68.000	67.980	72.224
Steady state error	3.9m	3.8m	4.0m	3.8m
P = 80 ; I = 1				
Settling time	0.038 sec	0.027 sec	0.027 sec	0.037 sec
Peak overshoot	72.225	67.980	67.978	72.226
Steady state error	3.8m	3.7m	3.9m	3.9m
P = 80 ; I = 1.5				
Settling time	0.038 sec	0.028 sec	0.027 sec	0.036 sec
Peak overshoot	72.223	67.979	67.978	72.225
Steady state error	3.9m	3.8m	4.0m	3.8m
P = 100 ; I = 0.5				

	$R_L=0; R_C=0$	$R_L=0.5; R_C=0$	$R_L=0.5; R_C=1e-6$	$R_L=0; R_C=1e-6$
Settling time	0.037 sec	0.028 sec	0.027 sec	0.037 sec
Peak overshoot	72.220	68.025	68.025	72.222
Steady state error	3.8m	3.9m	4.1m	3.9m
P = 100 ; I = 1				
Settling time	0.038 sec	0.027 sec	0.027 sec	0.037 sec
Peak overshoot	72.224	68.025	68.025	72.220
Steady state error	3.9m	3.8m	3.9m	3.9m
P = 100 ; I = 1.5				
Settling time	0.038 sec	0.028 sec	0.027 sec	0.037 sec
Peak overshoot	72.222	68.025	68.025	72.221
Steady state error	3.8m	3.9m	3.9m	3.9m
P = 150 ; I = 0.5				
	$R_L=0; R_C=0$	$R_L=0.5; R_C=0$	$R_L=0.5; R_C=1e-6$	$R_L=0; R_C=1e-6$
Settling time	0.038 sec	0.027 sec	0.027 sec	0.036 sec
Peak overshoot	72.293	68.015	68.016	72.293
Steady state error	3.7m	3.7m	4.0m	3.8m
P = 150 ; I = 1				
Settling time	0.038 sec	0.027 sec	0.027 sec	0.037 sec
Peak overshoot	72.294	68.015	68.015	72.293
Steady state error	3.8m	3.8m	3.9m	3.9m
P = 150 ; I = 1.5				
Settling time	0.038 sec	0.026 sec	0.027 sec	0.037 sec
Peak overshoot	72.292	68.015	68.016	72.293
Steady state error	3.7m	3.8m	4.1m	3.9m

7.3.3 PLA method of data expression using two linear lines

Piecewise linear approximation method is a type of approximation technique in mathematics. A piecewise linear function of a certain curve is said to be composed of a number of straight-

line sections. The PLA functions are affine functions. If the PLA function is continuous in nature, then the graph is considered be a polygonal curve.

In this type of linear approximation technique, any curve can be approximated into many linear lines so as to get continuous function. We are going to use this method in order to approximate the curve of data in to two linear lines. The two linear lines can be expressed in equations as:

1st linear equation: $f(x) = P1*x+P2$, where $P1= -1.781$ and $P2= 64.78$

2nd linear equation: $f(x) = P1*x+P2$, where $P1= -137.7$ and $P2= 846.4$

These equation are implemented by use of matlab user defined function block. The MATLAB Function block is enabled to generate efficient embeddable code on basis of the equation defined by user.

The user defined function are expressed by generating the C or C++ code. The disadvantage of the block is that we cannot use any other coding language then C or C++. In addition to restrictions on the language, it supports all the functions available like, all the Arithmetical Operators, Matrix and advanced matrix operations, Trigonometric functions.

Thus the simulation is carried out with implementing user defined functional block and using P, PI controllers setting for both the non-parasitic converter as well as for parasitic converter. The derived results are presented in graph and in tabular form.

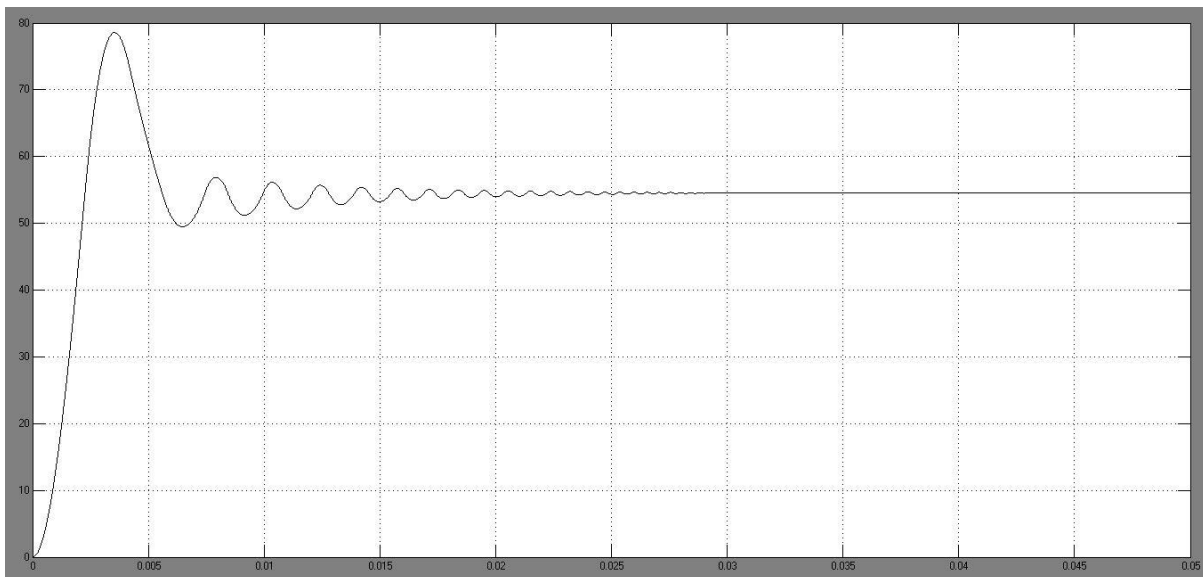


Fig 7.12 Output by Piecewise linear approximation method with non-parasitic resistance and P controller

The output of simulation for P controller value of 100 with negligible values of parasitic resistance is shown in Figure 7.12. The graph obtained has peak over shoot of 78.572, settling time of 0.028 seconds and steady state error of 2.2m. The same configuration of P controller with finite values of parasitic resistance gives the similar graph but with values of peak over shoot of 73.242, settling time of 0.023 seconds and steady state error of 2.4m as depicted in Figure 7.13.

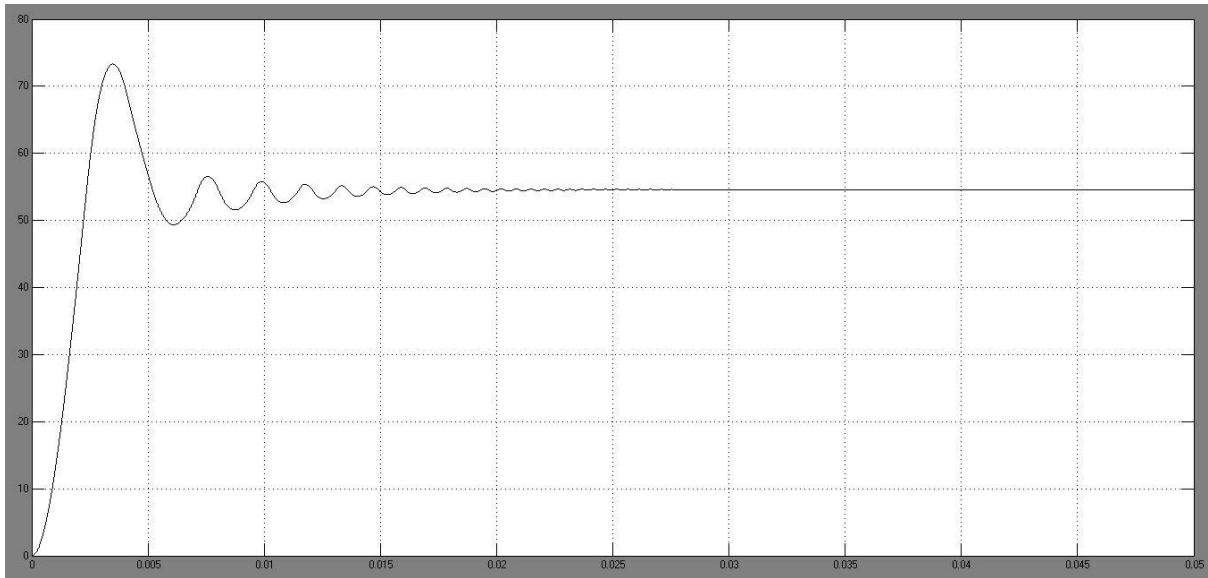


Fig 7.13 Output by Piecewise linear approximation method with parasitic resistance and P controller

This comparison of output by graphical representation gives a better comparative study for considering the parameters of the converter circuit and for future analysis. A detailed simulation and obtained outputs are presented in tabular form in Table 7.5 for different values of proportional controller.

Table 7.5 Output with different values of RL and RC and P controller

P controller = 80				
	$R_L=0; R_C=0$	$R_L=0.5; R_C=0$	$R_L=0.5; R_C=1e-6$	$R_L=0; R_C=1e-6$
Settling time	0.029 sec	0.023 sec	0.023 sec	0.030 sec
Peak overshoot	78.572	73.238	73.236	78.568
Steady state error	2.3m	2.5m	2.4m	2.7m
P controller= 100				
Settling time	0.028 sec	0.024 sec	0.023 sec	0.033 sec

Peak overshoot	78.572	73.240	73.242	78.590
Steady state error	2.2m	2.3m	2.4m	2.6m
P controller= 150				
Settling time	0.030 sec	0.023 sec	0.023 sec	0.031 sec
Peak overshoot	78.573	73.245	73.245	78.576
Steady state error	2.3m	2.5m	2.5m	2.7m

A detailed simulation for PI controller and with converter having parasitic resistances and non-parasitic resistances respectively using same method is carried out further.

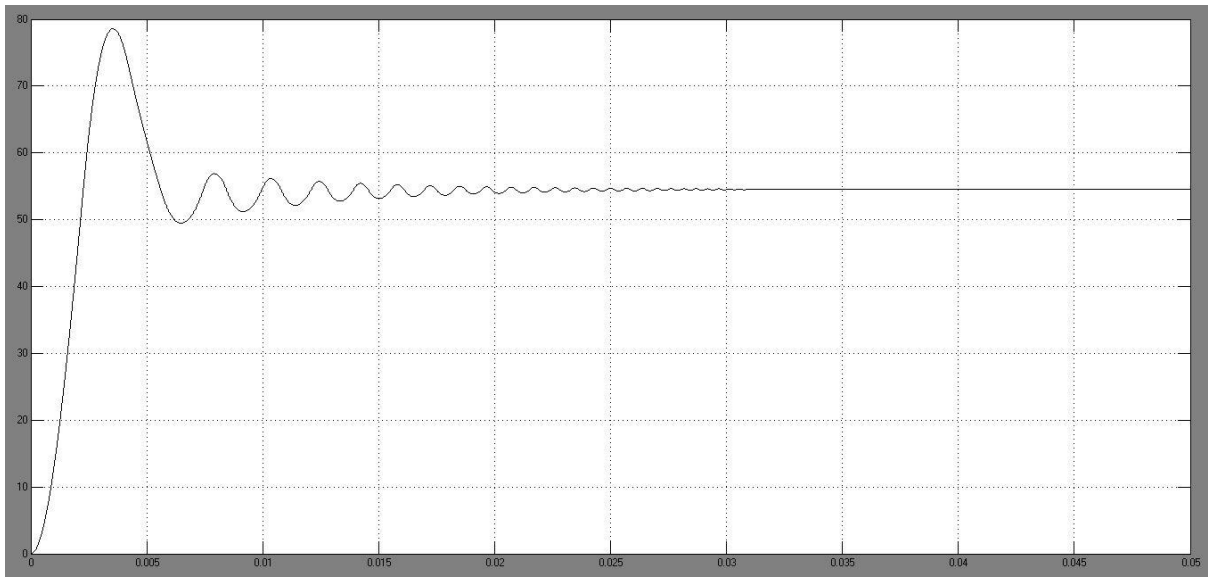


Fig 7.14 Output by Piecewise linear approximation method with non-parasitic resistance and PI controller

The output of simulation for PI controller value of 100 and 1 respectively and with negligible values of parasitic resistance is shown in Figure 7.14. The graph obtained has peak over shoot of 78.573, settling time of 0.032 seconds and steady state error of 2.5m. The same configuration of PI controller with finite values of parasitic resistance gives the similar graph but with values of peak over shoot of 73.239, settling time of 0.025 seconds and steady state error of 2.8m as depicted in Figure 7.15.

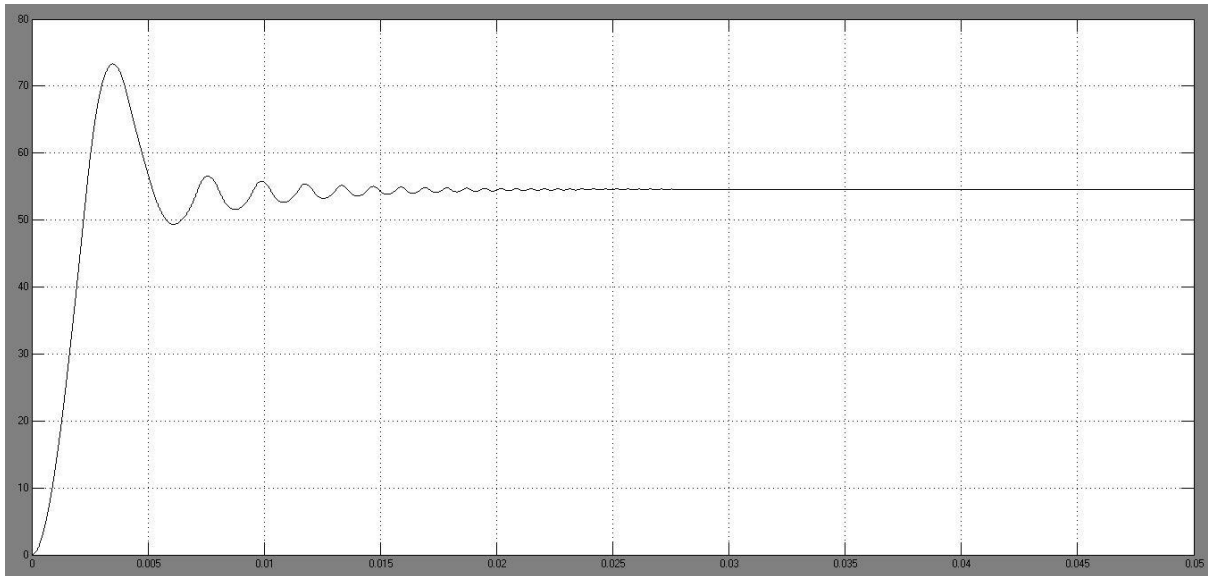


Fig 7.15 Output by Piecewise linear approximation method with parasitic resistance and PI controller

This comparison of output by graphical representation gives a better comparative study for considering the parameters of the converter circuit and for future analysis. A detailed simulation and obtained outputs are presented in tabular form in Table 7.6 for different combination of values of PI controller.

Table 7.6 Output with different values of RL and RC and PI controller

P = 80 ; I = 0.5				
	R _L =0; R _C =0	R _L =0.5; R _C =0	R _L =0.5; R _C =1e-6	R _L =0; R _C =1e-6
Settling time	0.028 sec	0.024 sec	0.024 sec	0.032 sec
Peak overshoot	78.573	73.238	73.240	78.572
Steady state error	2.7m	3.0m	2.9m	2.7m
P = 80 ; I = 1				
Settling time	0.031 sec	0.024 sec	0.024 sec	0.030 sec
Peak overshoot	78.572	73.234	73.238	78.572
Steady state error	2.6m	2.6m	2.8m	2.7m
P = 80 ; I = 1.5				
Settling time	0.031 sec	0.024 sec	0.025 sec	0.030 sec
Peak overshoot	78.573	73.240	73.239	78.572
Steady state error	2.5m	2.6m	2.8m	2.6m
P = 100 ; I = 0.5				

	$R_L=0; R_C=0$	$R_L=0.5; R_C=0$	$R_L=0.5; R_C=1e-6$	$R_L=0; R_C=1e-6$
Settling time	0.032 sec	0.025 sec	0.025 sec	0.031 sec
Peak overshoot	78.573	73.240	73.240	78.572
Steady state error	2.4m	2.4m	2.8m	2.6m
P = 100 ; I = 1				
Settling time	0.032 sec	0.024 sec	0.025 sec	0.031 sec
Peak overshoot	78.573	73.240	73.239	78.572
Steady state error	2.5m	2.4m	2.8m	2.7m
P = 100 ; I = 1.5				
Settling time	0.028 sec	0.025 sec	0.025 sec	0.030 sec
Peak overshoot	78.572	73.242	73.241	78.572
Steady state error	2.6m	2.5m	2.9m	2.6m
P = 150 ; I = 0.5				
	$R_L=0; R_C=0$	$R_L=0.5; R_C=0$	$R_L=0.5; R_C=1e-6$	$R_L=0; R_C=1e-6$
Settling time	0.030 sec	0.025 sec	0.024 sec	0.031 sec
Peak overshoot	78.573	73.240	73.245	78.572
Steady state error	2.4m	2.6m	2.5m	2.7m
P = 150 ; I = 1				
Settling time	0.033 sec	0.025 sec	0.024 sec	0.029 sec
Peak overshoot	78.571	73.250	73.243	78.572
Steady state error	2.5m	2.5m	2.5m	2.6m
P = 150 ; I = 1.5				
Settling time	0.031 sec	0.024 sec	0.024 sec	0.030 sec
Peak overshoot	78.573	73.250	73.245	78.573
Steady state error	2.4m	2.4m	2.6m	2.6m

7.3.4 PLA method of data expression using combination of two linear lines and a curve

In this type of linear approximation technique, any curve can be approximated into many linear line so as to get continuous function, but we are combining the 2 linear lines and curve so as to get a proper mathematical expression for representing the curve. We are going to use this

method in order to approximate the curve of data precisely. The complete equations can be expressed as:

1st linear equation: $f(x) = P1*x+P2$, where $P1= -1.781$ and $P2= 64.78$

2nd curve equation: $f(x) = P1*x^2+P2*x+P3$, where $P1= -43.97$, $P2= 377.7$, $P3=-663.5$

3rd linear equation: $f(x) = P1*x+P2$, where $P1= -137.7$ and $P2= 846.4$

These equation are implemented by use of matlab user defined function block. The MATLAB Function block is enabled to generate efficient embeddable code on basis of the equation defined by user.

Thus the simulation is carried out with implementing user defined functional block and using P, PI controllers setting for both the non-parasitic converter as well as for parasitic converter. The derived results are presented in graph and in tabular form.

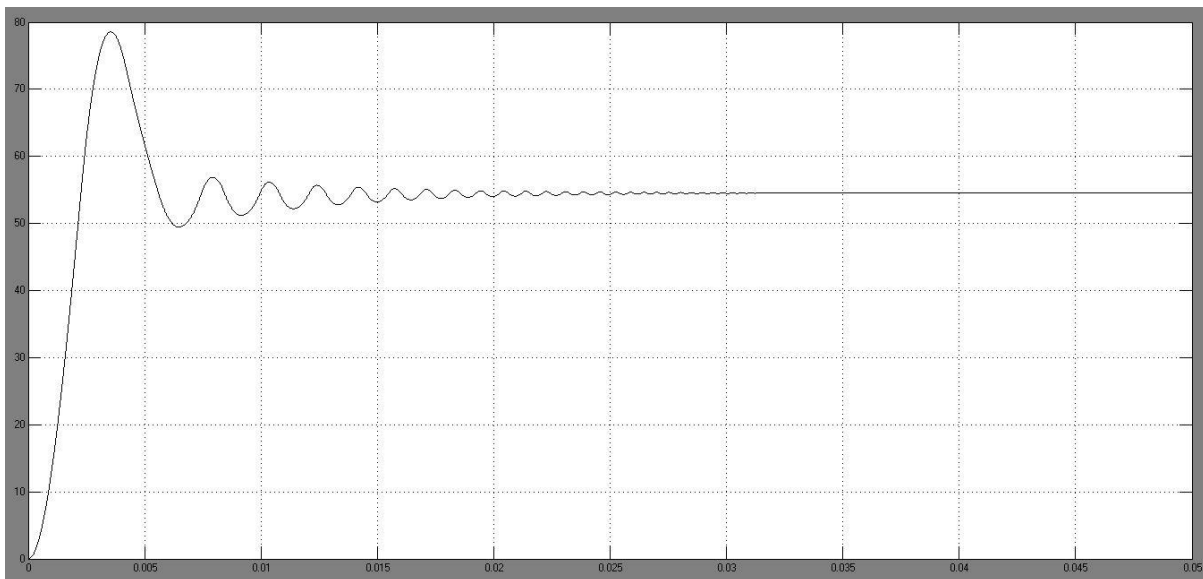


Fig 7.16 Output by PLA method using combination of lines and curve with non-parasitic resistance and P controller

The output of simulation for P controller value of 100 with negligible values of parasitic resistance is shown in Figure 7.16. The graph obtained has peak over shoot of 78.565, settling time of 0.032 seconds and steady state error of 3.0m. The same configuration of P controller with finite values of parasitic resistance gives the similar graph but with values of peak over shoot of 73.232, settling time of 0.025 seconds and steady state error of 2.4m as depicted in Figure 7.17.

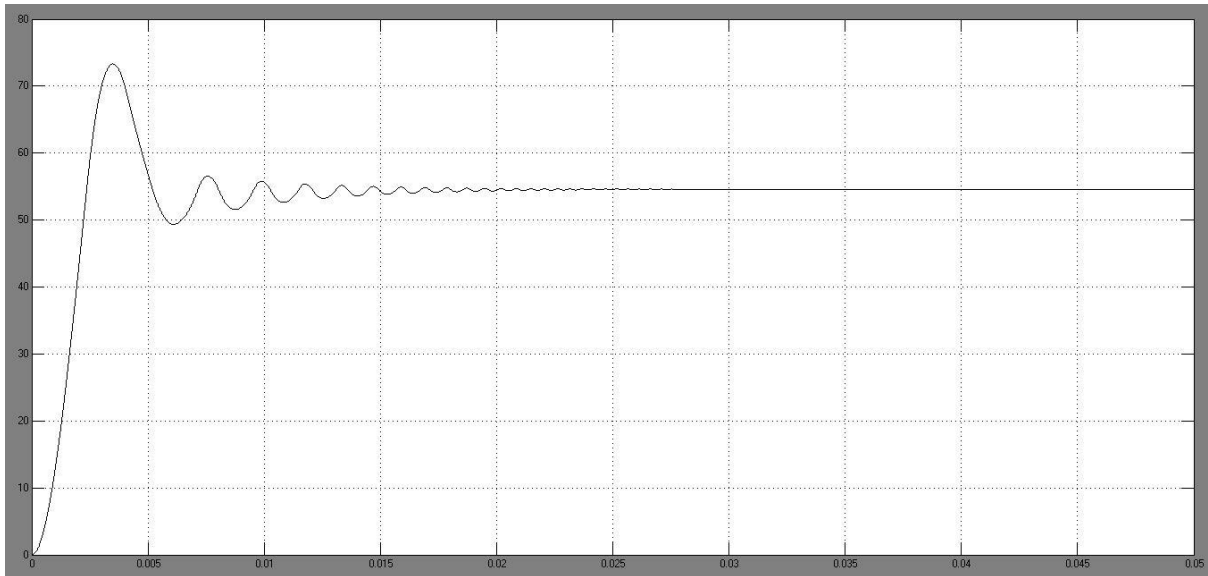


Fig 7.17 Output by PLA method using combination of lines and curve with parasitic resistance and P controller

This comparison of output by graphical representation gives a better comparative study for considering the parameters of the converter circuit and for future analysis. A detailed simulation and obtained outputs are presented in tabular form in Table 7.7 for different values of proportional controller.

Table 7.7 Output with different values of RL and RC and P controller

P controller = 80				
	$R_L=0; R_C=0$	$R_L=0.5; R_C=0$	$R_L=0.5; R_C=1e-6$	$R_L=0; R_C=1e-6$
Settling time	0.031 sec	0.024 sec	0.025 sec	0.031 sec
Peak overshoot	78.565	73.230	73.229	78.565
Steady state error	3.1m	2.6m	2.5m	3.1m
P controller= 100				
Settling time	0.032 sec	0.024 sec	0.025 sec	0.031 sec
Peak overshoot	78.565	73.232	73.232	78.565
Steady state error	3.0m	2.5m	2.4m	3.0m
P controller= 150				
Settling time	0.033 sec	0.025 sec	0.024sec	0.032 sec
Peak overshoot	78.565	73.235	73.236	78.566
Steady state error	3.1m	2.6m	2.5m	3.1m

A detailed simulation for PI controller and with converter having parasitic resistances and non-parasitic resistances respectively using same method is carried out further.

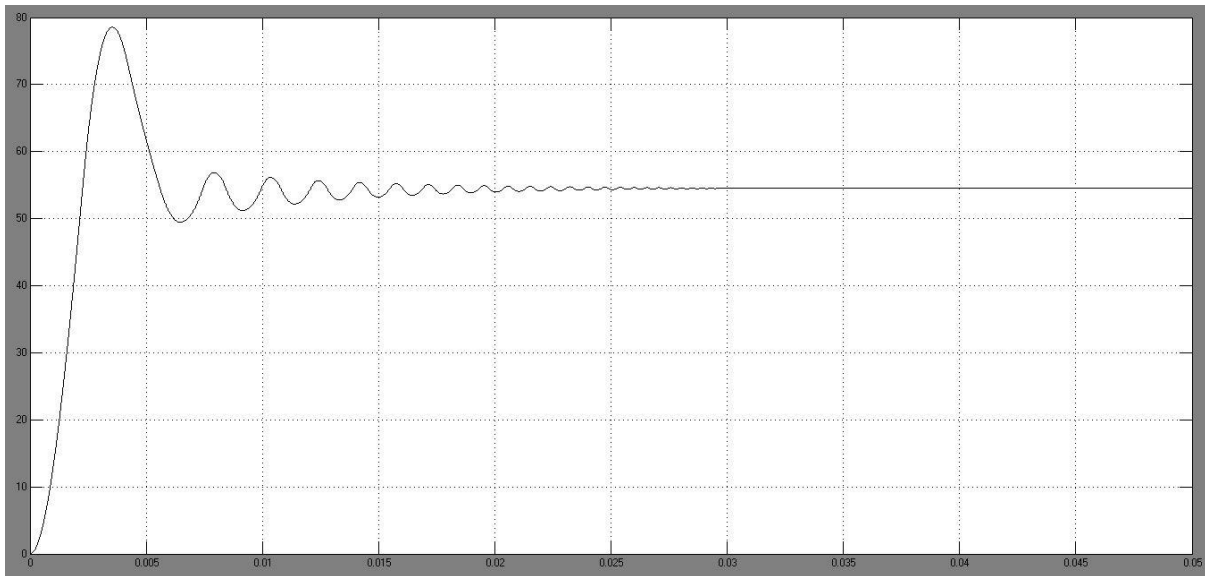


Fig 7.18 Output by PLA method using combination of lines and curve with non-parasitic resistance and PI controller

The output of simulation for PI controller value of 100 and 1 respectively and with negligible values of parasitic resistance is shown in Figure 7.18. The graph obtained has peak over shoot of 78.566, settling time of 0.030 seconds and steady state error of 2.6m. The same configuration of PI controller with finite values of parasitic resistance gives the similar graph but with values of peak over shoot of 73.233, settling time of 0.024 seconds and steady state error of 2.6m as depicted in Figure 7.19.

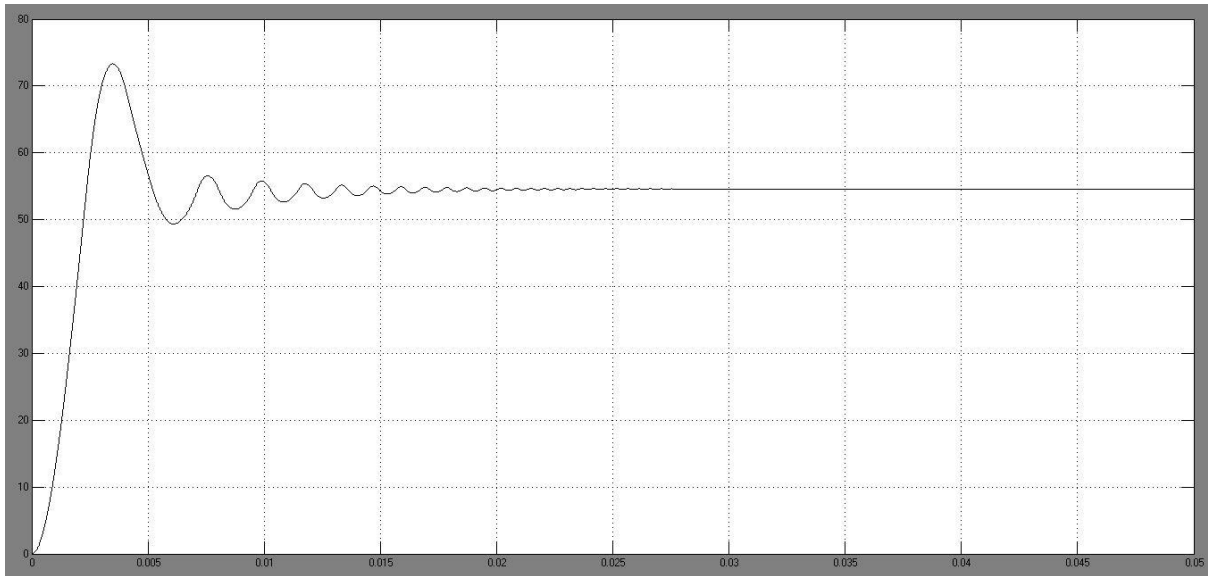


Fig 7.19 Output by PLA method using combination of lines and curve with parasitic resistance and PI controller

This comparison of output by graphical representation gives a better comparative study for considering the parameters of the converter circuit and for future analysis. A detailed simulation and obtained outputs are presented in tabular form in Table 7.8 for different combination of values of PI controller.

Table 7.8 Output with different values of RL and RC and PI controller

P = 80 ; I = 0.5				
	R _L =0; R _C =0	R _L =0.5; R _C =0	R _L =0.5; R _C =1e-6	R _L =0; R _C =1e-6
Settling time	0.030 sec	0.023 sec	0.024 sec	0.029 sec
Peak overshoot	78.565	73.227	73.230	78.565
Steady state error	2.9m	2.5m	2.7m	2.8m
P = 80 ; I = 1				
Settling time	0.028 sec	0.025 sec	0.023 sec	0.030 sec
Peak overshoot	78.565	73.230	73.229	78.565
Steady state error	2.7m	2.4m	2.6m	2.9m
P = 80 ; I = 1.5				
Settling time	0.031 sec	0.025 sec	0.025 sec	0.030 sec
Peak overshoot	78.565	73.230	73.230	78.565
Steady state error	3.0m	2.4m	2.6m	2.7m
P = 100 ; I = 0.5				

	$R_L=0; R_C=0$	$R_L=0.5; R_C=0$	$R_L=0.5; R_C=1e-6$	$R_L=0; R_C=1e-6$
Settling time	0.030 sec	0.025 sec	0.025 sec	0.030 sec
Peak overshoot	78.567	73.232	73.232	78.565
Steady state error	2.6m	2.2m	2.5m	2.8m
P = 100 ; I = 1				
Settling time	0.030 sec	0.026 sec	0.024 sec	0.029 sec
Peak overshoot	78.566	73.233	73.233	78.565
Steady state error	2.6m	2.4m	2.6m	2.8m
P = 100 ; I = 1.5				
Settling time	0.032 sec	0.024 sec	0.026 sec	0.030 sec
Peak overshoot	78.566	73.233	73.233	78.565
Steady state error	2.6m	2.7m	2.6m	2.9m
P = 150 ; I = 0.5				
	$R_L=0; R_C=0$	$R_L=0.5; R_C=0$	$R_L=0.5; R_C=1e-6$	$R_L=0; R_C=1e-6$
Settling time	0.031 sec	0.025 sec	0.024 sec	0.030 sec
Peak overshoot	78.565	73.236	73.235	78.566
Steady state error	2.7m	2.5m	2.4m	2.8m
P = 150 ; I = 1				
Settling time	0.033 sec	0.025 sec	0.024 sec	0.029 sec
Peak overshoot	78.566	73.235	73.236	78.566
Steady state error	2.7m	2.4m	2.4m	2.9m
P = 150 ; I = 1.5				
Settling time	0.033 sec	0.024 sec	0.024 sec	0.030 sec
Peak overshoot	78.565	73.237	73.235	78.566
Steady state error	2.7m	2.4m	2.5m	2.8m

7.4 Hardware results

The implemented hardware is to show as the model of working methodology of the buck converter. The output of the converter is measured for the few varying ranges of the input voltage that is supplied, in order to check the buck converter operation.

Table 7.9: Varying output voltage measured for varying input voltage.

Sl.no	Input (Volt)	Output (Volt)
1	12	7.31
2	10	5.38
3	8	3.53
4	6	1.68
5	4	0.12

The converter output is also checked for various loading conditions and the output graphical representation of the voltage is captured using the oscilloscope [Figure 7.20 and 7.21].

Table 7.10: Varying output voltage measured for varying load with input of 12V DC.

Sl.no	Load (ohms)	Output voltage (volts)
1	100	7.13
2	147	6.78
3	194	6.54
4	241	6.3
5	288	0.12

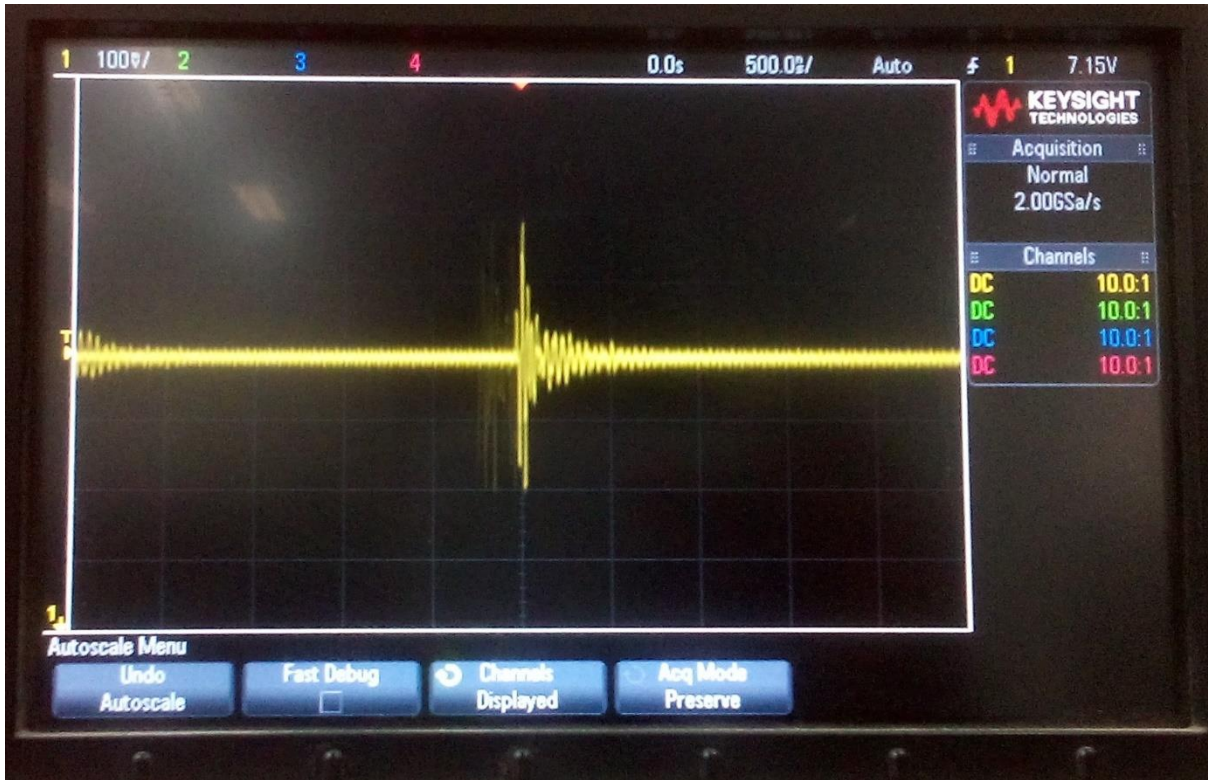


Figure 7.20 Output of hardware obtained for input voltage of 12V DC with load of 145ohms.

The graphs in Figure 7.20 and Figure 7.21 can be compared to note that the output voltage is stepped down after the operation of buck converter.

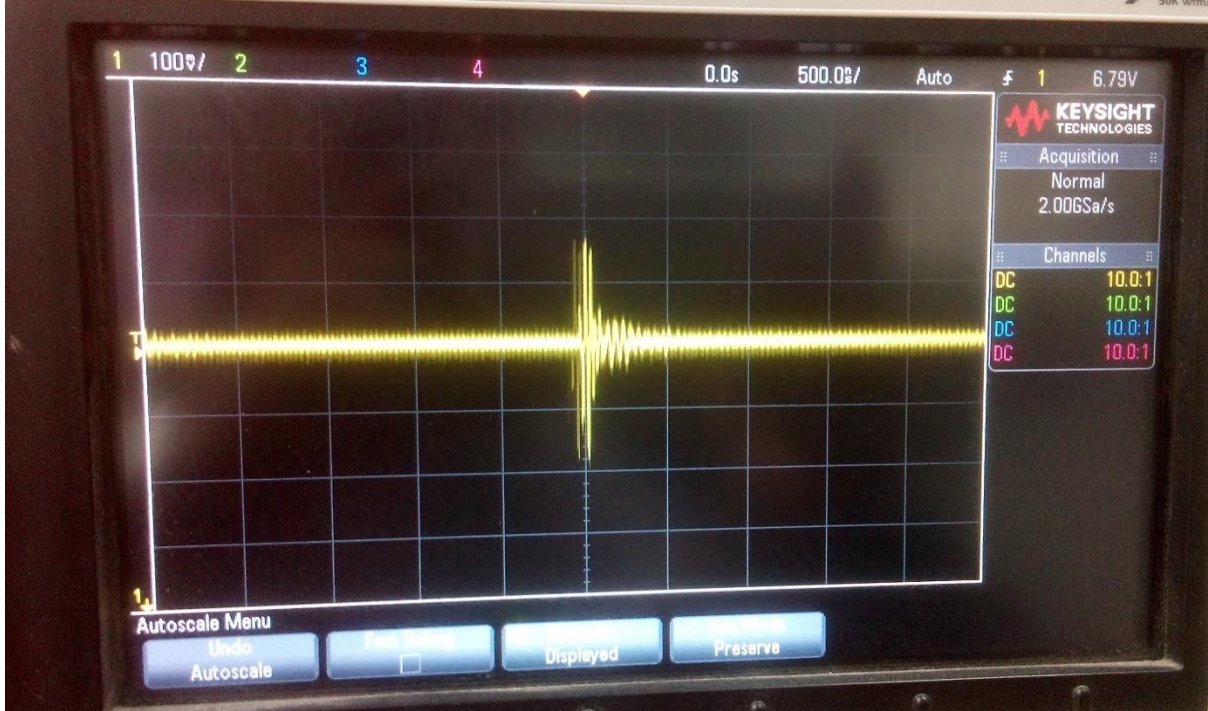


Figure 7.21 Output of hardware obtained for input voltage of 12V DC with load of 145ohms.

7.5 Conclusion

The simulation carried out with various combination of P controller and PI controller, along with parasitic and non-parasitic circuit combination gives out a variety of outputs, which enables us to have a broad analysis of the operation entirely. We can easily make out from the graph as well as the data of tabular column that the system with parasitic resistance comparatively gives the output with less peak overshoot and also has a less settling time. Hence making it more realistic output.

The output of hardware is measured and the graph is captured using oscilloscope and further the improved model can be designed to carry out a detailed analysis.

8. CHAPTER 8

CONCLUSION AND FUTURE SCOPE OF THE WORK

The Proposed Closed loop control of Buck converter gives an opportunity to study converter and also the emulators and is designed, developed for educational and commercial purposes. A few of these emulators are used as modular sets so that they can be designed to be connected in series or parallel fashion to implement an entirely new photovoltaic array. Photovoltaic emulators are nowadays used to test the photovoltaic systems mounted on space satellites. Due to the extreme atmospheric conditions in outer space, researchers would like to accurately study the working behaviour of PV system in outer space. Thus Photovoltaic emulators are their best alternative for efficient energy production and in fact most practical option.

The future scope of this work would be:

- The emulator can be implemented with other converters for getting better results.
- The further modified circuit of the closed loop converters can also be used as emulators.
- It can be implemented with consideration of more non-ideal aspects of components.
- It can be implemented with more improvised control circuit.

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Appendix 1

Features

- High-performance, Low-power Atmel® AVR® 8-bit Microcontroller
 - Advanced RISC Architecture
 - 130 Powerful Instructions – Most Single-clock Cycle Execution
 - 32 × 8 General Purpose Working Registers
 - Fully Static Operation
 - Up to 16MIPS Throughput at 16MHz
 - On-chip 2-cycle Multiplier
 - High Endurance Non-volatile Memory segments
 - 8Kbytes of In-System Self-programmable Flash program memory
 - 512Bytes EEPROM
 - 1Kbyte Internal SRAM
 - Write/Erase Cycles: 10,000 Flash/100,000 EEPROM
 - Data retention: 20 years at 85°C/100 years at 25°C⁽¹⁾
 - Optional Boot Code Section with Independent Lock Bits
 - In-System Programming by On-chip Boot Program
 - True Read-While-Write Operation
 - Programming Lock for Software Security
 - Peripheral Features
 - Two 8-bit Timer/Counters with Separate Prescaler, one Compare Mode
 - One 16-bit Timer/Counter with Separate Prescaler, Compare Mode, and Capture Mode
 - Real Time Counter with Separate Oscillator
 - Three PWM Channels
 - 8-channel ADC in TQFP and QFN/MLF package
 - Eight Channels 10-bit Accuracy
 - 6-channel ADC in PDIP package
 - Six Channels 10-bit Accuracy
 - Byte-oriented Two-wire Serial Interface
 - Programmable Serial USART
 - Master/Slave SPI Serial Interface
 - Programmable Watchdog Timer with Separate On-chip Oscillator
 - On-chip Analog Comparator
 - Special Microcontroller Features
 - Power-on Reset and Programmable Brown-out Detection
 - Internal Calibrated RC Oscillator
 - External and Internal Interrupt Sources
 - Five Sleep Modes: Idle, ADC Noise Reduction, Power-save, Power-down, and Standby
 - I/O and Packages
 - 23 Programmable I/O Lines
 - 28-lead PDIP, 32-lead TQFP, and 32-pad QFN/MLF
 - Operating Voltages
 - 2.7V - 5.5V (ATmega8L)
 - 4.5V - 5.5V (ATmega8)
 - Speed Grades
 - 0 - 8MHz (ATmega8L)
 - 0 - 16MHz (ATmega8)
 - Power Consumption at 4Mhz, 3V, 25°C
 - Active: 3.6mA
 - Idle Mode: 1.0mA
 - Power-down Mode: 0.5µA
-

Pin Descriptions

VCC Digital supply voltage.

GND Ground.

Port B (PB7..PB0)
XTAL1/XTAL2/TOSC1/
TOSC2 Port B is an 8-bit bi-directional I/O port with internal pull-up resistors (selected for each bit). The Port B output buffers have symmetrical drive characteristics with both high sink and source capability. As inputs, Port B pins that are externally pulled low will source current if the pull-up resistors are activated. The Port B pins are tri-stated when a reset condition becomes active, even if the clock is not running.

Depending on the clock selection fuse settings, PB6 can be used as input to the inverting Oscillator amplifier and input to the internal clock operating circuit.

Depending on the clock selection fuse settings, PB7 can be used as output from the inverting Oscillator amplifier.

If the Internal Calibrated RC Oscillator is used as chip clock source, PB7..6 is used as TOSC2..1 input for the Asynchronous Timer/Counter2 if the AS2 bit in ASSR is set.

Port C (PC5..PC0) Port C is a 7-bit bi-directional I/O port with internal pull-up resistors (selected for each bit). The Port C output buffers have symmetrical drive characteristics with both high sink and source capability. As inputs, Port C pins that are externally pulled low will source current if the pull-up resistors are activated. The Port C pins are tri-stated when a reset condition becomes active, even if the clock is not running.

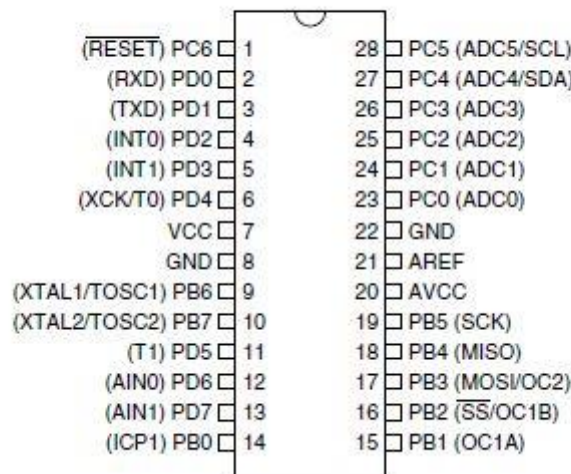
PC6/RESET If the RSTDISBL Fuse is programmed, PC6 is used as an I/O pin. Note that the electrical characteristics of PC6 differ from those of the other pins of Port C.

If the RSTDISBL Fuse is unprogrammed, PC6 is used as a Reset input. A low level on this pin for longer than the minimum pulse length will generate a Reset, even if the clock is not running.

Port D (PD7..PD0) Port D is an 8-bit bi-directional I/O port with internal pull-up resistors (selected for each bit). The Port D output buffers have symmetrical drive characteristics with both high sink and source capability. As inputs, Port D pins that are externally pulled low will source current if the pull-up resistors are activated. The Port D pins are tri-stated when a reset condition becomes active, even if the clock is not running.

RESET Reset input. A low level on this pin for longer than the minimum pulse length will generate a reset, even if the clock is not running.

PDIP



Appendix 2

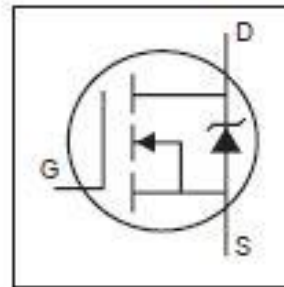
International
IOR Rectifier

PD - 94053

IRFZ44N

HEXFET® Power MOSFET

- Advanced Process Technology
- Ultra Low On-Resistance
- Dynamic dv/dt Rating
- 175°C Operating Temperature
- Fast Switching
- Fully Avalanche Rated



$V_{DS} = 55V$
$R_{DS(on)} = 17.5m\Omega$
$I_D = 49A$

Description

Advanced HEXFET® Power MOSFETs from International Rectifier utilize advanced processing techniques to achieve extremely low on-resistance per silicon area. This benefit, combined with the fast switching speed and ruggedized device design that HEXFET power MOSFETs are well known for, provides the designer with an extremely efficient and reliable device for use in a wide variety of applications.

The TO-220 package is universally preferred for all commercial-industrial applications at power dissipation levels to approximately 50 watts. The low thermal resistance and low package cost of the TO-220 contribute to its wide acceptance throughout the industry.



Absolute Maximum Ratings

	Parameter	Max.	Units
$I_D @ T_C = 25^\circ C$	Continuous Drain Current, $V_{GS} @ 10V$	49	A
$I_D @ T_C = 100^\circ C$	Continuous Drain Current, $V_{GS} @ 10V$	35	
I_{DM}	Pulsed Drain Current ①	160	
$P_D @ T_C = 25^\circ C$	Power Dissipation	94	W
	Linear Derating Factor	0.63	W/°C
V_{GS}	Gate-to-Source Voltage	± 20	V
I_{AR}	Avalanche Current ①	25	A
E_{AR}	Repetitive Avalanche Energy ①	9.4	mJ
dv/dt	Peak Diode Recovery dv/dt ②	5.0	V/ns
T_J	Operating Junction and	-55 to + 175	°C
T_{STG}	Storage Temperature Range		
	Soldering Temperature, for 10 seconds		
	Mounting torque, 6-32 or M3 screw	10 lbf-in (1.1N-m)	


Thermal Resistance

	Parameter	Typ.	Max.	Units
$R_{\theta JC}$	Junction-to-Case	—	1.5	°C/W
$R_{\theta CS}$	Case-to-Sink, Flat, Greased Surface	0.50	—	
$R_{\theta JA}$	Junction-to-Ambient	—	62	

IRFZ44N

International
IGR Rectifier

Electrical Characteristics @ $T_J = 25^\circ\text{C}$ (unless otherwise specified)

	Parameter	Min.	Typ.	Max.	Units	Conditions
$V_{(BR)DSS}$	Drain-to-Source Breakdown Voltage	55	—	—	V	$V_{GS} = 0V, I_D = 250\mu A$
$\Delta V_{(BR)DSS}/\Delta T_J$	Breakdown Voltage Temp. Coefficient	—	0.058	—	V/ $^\circ\text{C}$	Reference to $25^\circ\text{C}, I_D = 1\text{mA}$
$R_{DS(on)}$	Static Drain-to-Source On-Resistance	—	—	17.5	m Ω	$V_{GS} = 10V, I_D = 25A$ ①
$V_{GS(th)}$	Gate Threshold Voltage	2.0	—	4.0	V	$V_{DS} = V_{GS}, I_D = 250\mu A$
g_m	Forward Transconductance	19	—	—	S	$V_{DS} = 25V, I_D = 25A$ ②
I_{DSS}	Drain-to-Source Leakage Current	—	—	25	μA	$V_{DS} = 55V, V_{GS} = 0V$
		—	—	250		$V_{DS} = 44V, V_{GS} = 0V, T_J = 150^\circ\text{C}$
I_{OSS}	Gate-to-Source Forward Leakage	—	—	100	nA	$V_{GS} = 20V$
	Gate-to-Source Reverse Leakage	—	—	-100		$V_{GS} = -20V$
Q_{gd}	Total Gate Charge	—	—	63	nC	$I_D = 25A$
Q_{gs}	Gate-to-Source Charge	—	—	14		$V_{DS} = 44V$
Q_{gd}	Gate-to-Drain ("Miller") Charge	—	—	23		$V_{GS} = 10V$, See Fig. 6 and 13
$t_{d(on)}$	Turn-On Delay Time	—	12	—	ns	$V_{DD} = 28V$
t_r	Rise Time	—	60	—		$I_D = 25A$
$t_{d(off)}$	Turn-Off Delay Time	—	44	—		$R_G = 12\Omega$
t_f	Fall Time	—	45	—		$V_{GS} = 10V$, See Fig. 10 ③
L_D	Internal Drain Inductance	—	4.5	—	nH	Between lead, 6mm (0.25in.) from package and center of die contact
L_S	Internal Source Inductance	—	7.5	—		
C_{iss}	Input Capacitance	—	1470	—	pF	$V_{GS} = 0V$
C_{oss}	Output Capacitance	—	360	—		$V_{DS} = 25V$
C_{riss}	Reverse Transfer Capacitance	—	88	—		$f = 1.0\text{MHz}$, See Fig. 5
E_{AS}	Single Pulse Avalanche Energy ④	—	5300	1500	mJ	$I_{AS} = 25A, L = 0.47\text{mH}$

Source-Drain Ratings and Characteristics

	Parameter	Min.	Typ.	Max.	Units	Conditions
I_S	Continuous Source Current (Body Diode)	—	—	49	A	MOSFET symbol showing the integral reverse p-n junction diode.
I_{SM}	Pulsed Source Current (Body Diode) ①	—	—	160		
V_{SD}	Diode Forward Voltage	—	—	1.3	V	$T_J = 25^\circ\text{C}, I_S = 25A, V_{GS} = 0V$ ②
t_{rr}	Reverse Recovery Time	—	63	95	ns	$T_J = 25^\circ\text{C}, I_F = 25A$
Q_{rr}	Reverse Recovery Charge	—	170	260	nC	$di/dt = 100A/\mu s$ ③
t_{on}	Forward Turn-On Time	Intrinsic turn-on time is negligible (turn-on is dominated by $L_S + L_D$)				

Notes:

① Repetitive rating; pulse width limited by max. junction temperature. (See fig. 11)

② Starting $T_J = 25^\circ\text{C}$, $L = 0.48\text{mH}$
 $R_G = 25\Omega, I_{AS} = 25A$. (See Figure 12)

③ $I_{SD} \leq 25A, di/dt \leq 230A/\mu s, V_{DD} \leq V_{(BR)DSS}$,
 $T_J \leq 175^\circ\text{C}$

④ Pulse width $\leq 400\mu s$; duty cycle $\leq 2\%$.

⑤ This is a typical value at device destruction and represents operation outside rated limits.

⑥ This is a calculated value limited to $T_J = 175^\circ\text{C}$.

Appendix 3

Inductors

Surface Mount for Power Applications

Features

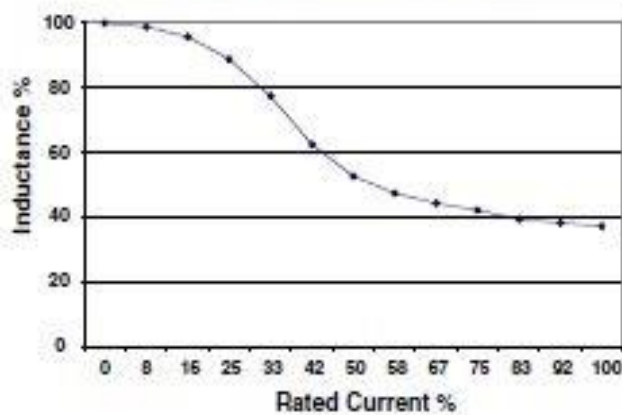
- Low profile 8.46mm in height
- Current ratings up to 100A



Inductance Values at 20°C

Part Number	-----Inductance (uH +/- 20%)-----			Rated DC Current (Amps)	DC Resistance	
	I = 0	1/2 (I max)	I max		m Ohm Typ	m Ohm Max.
31499-01	332.10	167.38	117.56	3.33	220.70	260.43
31499-02	243.09	122.52	86.05	3.90	132.50	156.35
31499-03	133.21	67.14	47.16	5.26	68.84	81.23
31499-04	79.38	40.01	28.10	6.82	40.97	48.34
31499-05	47.40	23.89	16.78	8.82	24.90	29.38
31499-06	29.89	15.06	10.58	11.11	13.67	16.13
31499-07	19.84	10.00	7.02	13.64	9.33	11.01
31499-08	13.28	6.70	4.70	16.67	6.41	7.56
31499-09	8.04	4.05	2.84	21.43	3.90	4.49
31499-10	5.90	2.98	2.09	25.00	2.81	3.23
31499-11	4.10	2.07	1.45	30.00	1.75	2.01
31499-12	2.62	1.32	0.93	37.50	1.24	1.43
31499-13	1.48	0.74	0.52	50.00	0.71	0.82
31499-14	1.03	0.52	0.36	60.00	0.50	0.58
31499-15	0.66	0.33	0.23	75.00	0.36	0.419
31499-16	0.37	0.19	0.13	100.00	0.22	0.23

Inductance vs. Current



Temperature Maximum Values

Operating Temperature: -55C to +125C

Storage Temperature: -65C to +125C

Approximate Weight \leq 8 grams