Use of Bidirectional DC-DC Buck Boost Converter in Distributed Energy Resources (DER)

This Thesis is submitted to the
Dept. of Electrical & Electronic Engineering, BRAC University in partial
fulfillment of the requirements for the Bachelor of Science degree in Electrical &
Electronic Engineering

FAHIM TAJWAR

SHAHRIAR USMAN KHAN

ATIQUR RAHMAN SARDAR

TASNEEM NAWREEN LETHE

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Declaration

We do hereby declare that the thesis titled “Use of Bidirectional DC-DC Buck Boost Converter in Distributed Energy Resources (DER)” is submitted to the Department of Electrical and Electronics Engineering of BRAC University in partial fulfillment of the Bachelor of Science in Electrical and Electronics Engineering. This is our original work and was not submitted elsewhere for the award of any other degree or any other publication.

Date:

Prof. Amina Hasan Abedin

Thesis Supervisor

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____
Fahim Tajwar
Student ID: 13121159

____
Tasneem Nawreen Lethe
ID: 13321027

____
Shahriar Usman Khan
Student ID: 13321057

____
Atiqur Rahman Sardar
Student ID: 13321016

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Thank you

Abstract

Dc-dc converter is widely used in power electronics. It is used in different kind of Distributed energy sources such as solar cell, hybrid electric vehicle. For interfacing current of Micro-gird with main power grid we widely use dc-dc converters. The main task of the Converter is to step up or step down the input voltage depending on duty cycle. It ensures safety and power requirement. In our thesis we worked on Dc-dc bidirectional converter. It is mainly used to buck or boost input voltage. When battery is Lack of charge it will be charging from grid and when grid id off current will supply to the load and additional current to the grid with the help of bidirectional buck boost converter. For Smart grid technology, innovation in Bidirectional Dc-dc converter is one of the most essential parts.

Contents

CHAPTER 1

Distributed Energy Resources DER

1.1 Introduction to DER

Distributed Energy Resources or DER are electric power generation or storage systems which are typically located at or near the end user. The electricity that we receive in our buildings through electric grids, are generated from centralized power plants, which are located far from cities. Distributed energy resource (DER) systems are small-scale power generation technologies located at or near the end user (typically in the range of 3–10,000 kW) used to provide an alternative to or an enhancement of the traditional electric power system. [1]

To discuss about Der some of the terms are needed to be familiar with,

Distributed Generation— Any technology that produces power outside of the utility grid (e.g., fuel cells, microturbines, and photovoltaics)

Distributed Power— Any technology that produces power or stores power (e.g., batteries and flywheels)

Distributed Energy Resources—Any technology that is included in DG and DP as well as demand-side measures. Under this configuration, power can be sold back to the grid where permitted by regulation. [2]

Der is like how it was during Thomas Alva Edison's DC current, when DC power plants used to be situated near the end users. But DC currents could not transfer higher voltages too far. That is why AC currents are used. Because of AC currents power plants got centralized, meaning one power plant could transmit electricity from far to the whole city.

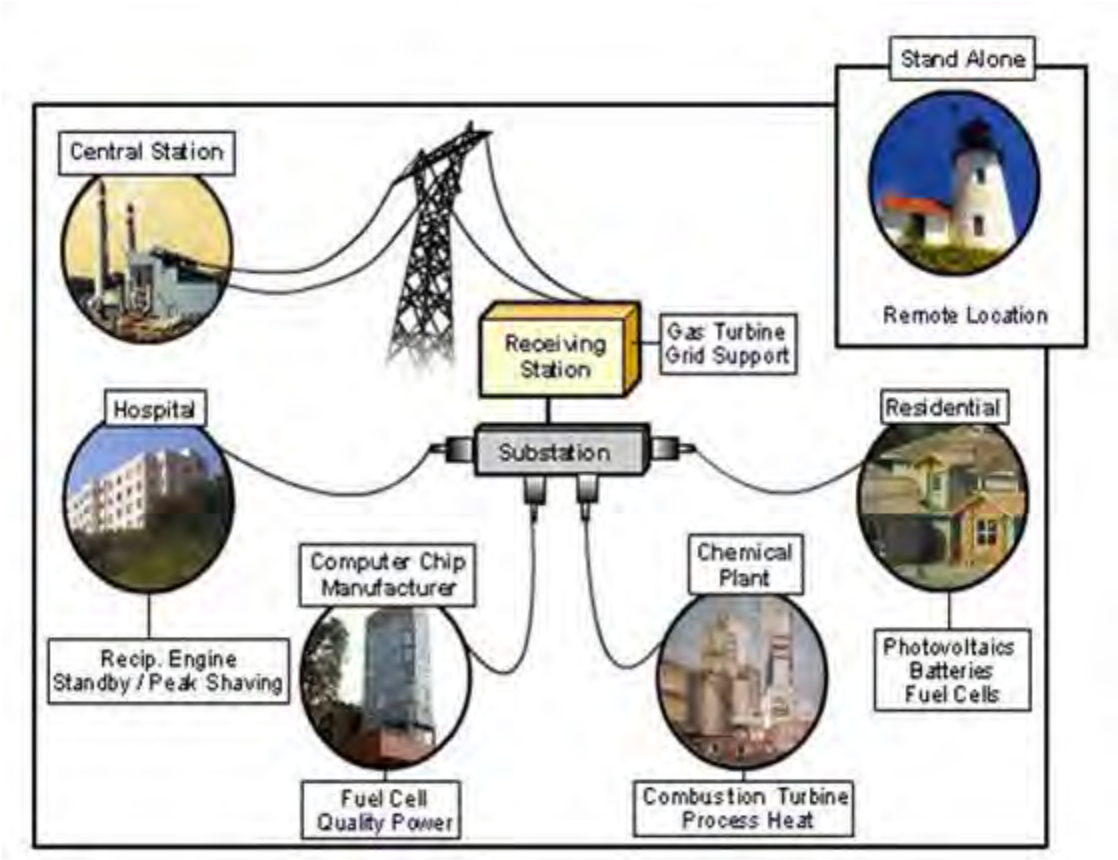

Figure: 1.1 Types of distributed energy resources and technologies

(Image courtesy of the California Energy Commission)

1.2 Why use DER?

All around the world electric grids transmit AC currents from a centralized power plant. These power plants are typically situated far from cities and mainly use fossil fuels, coals, natural gas or hydroelectric power, nuclear power.

As the demand of energy is rising day by day Distributed Energy Resources can be used to supplement the power supplies. More people are moving towards urban areas but the already existing centralized power plants of those areas which mainly supply electricity there, may not meet the increased demand of electricity. Increasing the production of those power plants is also not easy and cannot be done quickly. That is why Distributed Energy Resources can be used to lower the scarcity of power.

We can also use DER during ongoing crisis for example natural calamities, war, where people take refuge far from cities in remote areas where there are no access to electricity.

1.3 Benefits of DER

Through distributed energy resources we can get electricity during outages. We can reduce the cost of electric bills. We can use renewable energies to produce electricity and reduce carbon emissions. We can have less transmission loss and more efficiency by using distributed energy resources.

1.4 Challenges of DER

One of the biggest challenges of using der technologies is its cost and efficiency. Renewable energy sources like PV and Wind-turbines rely very much on weather, so we may not get power the time we need it. Maintenance is another factor considering the challenges different Der users face. Sometimes even when there is no scarcity of current for a long time, DG sources remain unused and thus can become unusable because of technical difficulties.

1.5 Future Role of DER

Distributed Energy Resources (DER) consists of Distributed Generation (DG) units, Distributed **S**torage (DS) units and integrated distributed generation/storage units.
Here technologies used for Distributed Generation and Distributed Storage Energy are mentioned.

1.5.1 For Distributed Generation

a) Fuel Cells,
b) Micro- and mini-gas-turbines,
c) Wind turbines,
d) Combustion Engines,
e) Solar photovoltaic systems,
f) Low-head hydro units,
g) Geothermal systems

1.5.2 For Storage Energy:

a) Battery storage,
b)Ultra-capacitor storage,
c) Low- and high-speed flywheel systems,
d) Superconducting Magnetic Energy Storage (SMES) systems.

DER technologies are still in their early days. Rapid productions and developments of DER has become a necessity as the environmental issues are rising and the demand of energies is also rising. For emergency situations DER technologies can help by providing electricity supplies like in hospitals or to other essential infrastructures or sites. Since DER technologies can provide power during outages and can also provide clean energies and since it can also save money for the users it is obvious that DER technologies will play a pivotal role in the future.

DER technologies can also be integrated to Microgrids and Smartgrids. These new technologies have the possibilities to promise more reliable, efficient and smart ways of managing power systems. These emerging technologies can reduce waste of power and can also be useful to reduce carbon emissions. DER technologies can also save money, and can even allow users to sell electricity by supplying power to the utility grids.

1.6 Organization

Firstly, we research on some DER technology and observe different kinds of converter used in them. Then we have discussed about the electronic interfaces used in DER technology. Then we mentioned Power electronic converter topologies such as DC/DC Converter, DC/AC converter, AC/DC converter, AC/AC converter. later we discussed about categories of DER. After that we introduced Buck Boost Converter. We simulate bidirectional buck boost converter on PSPICE and found our desired output.

Finally, we have talked about the prospect of buck-boost converter in future power electronics.

CHAPTER 2

Power Electronics Interfaces Used in DER Technologies

2.1 DER technology types

The classification of different DER technologies is shown below.

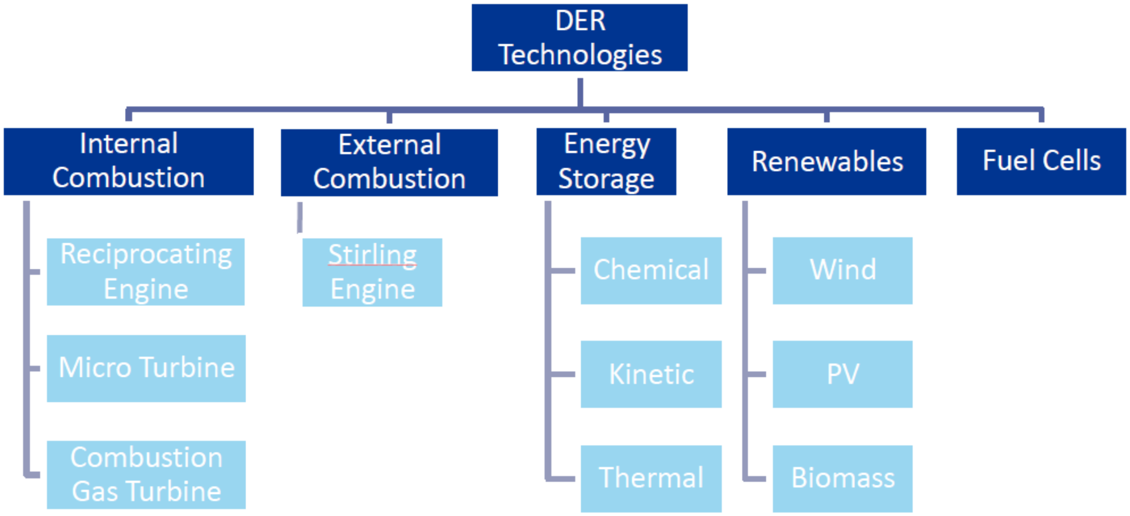

Figure: 2.1 Types of Der technologies

2.2 Power Electronic Topology Used in DER Technologies

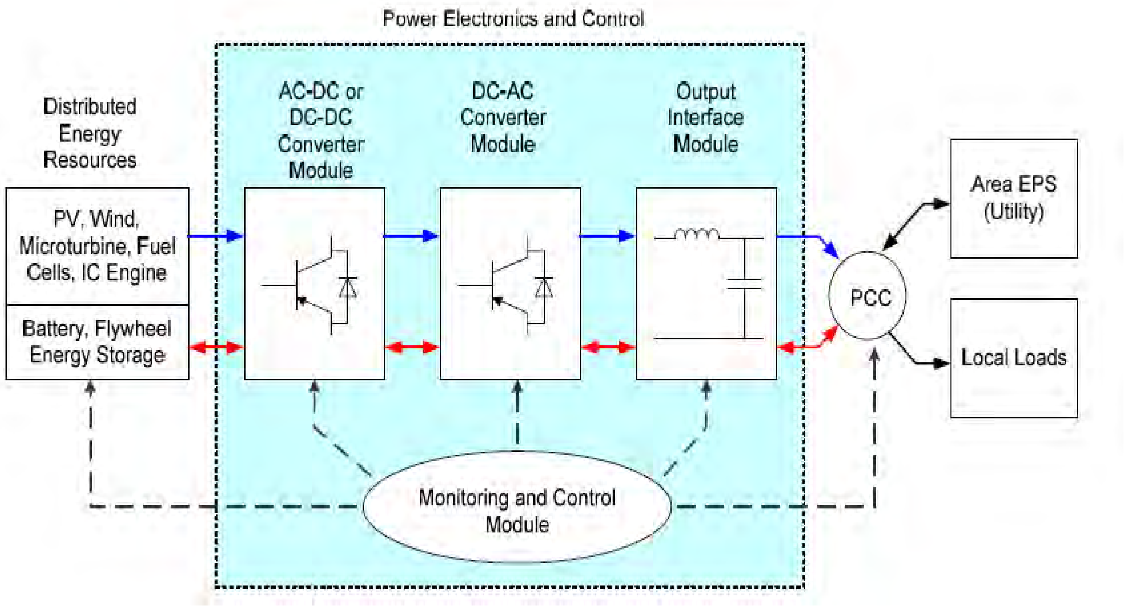

Figure: 2.2 General Topology of DER [4]

Block diagram representation of power electronics interface associated with DER systems is shown in Figure 2.2. Different types of electronic interfaces accept power from the distributed energy source and convert it to power at the required voltage and frequency. For the storage systems, bidirectional flow of power between the storages and the utility is required.

In our thesis we have shown **DC-DC Bidirectional Buck-Boost** controller simulation.

Figure 2.2 illustrates a design approach to organize the interface into modules, each of which can be designed to accommodate a range of DE systems and/or storages. [4]

In figure 2.2 four types of modules for power electronics interface are depicted. These include the source **input converter module**, **an inverter module**, **the output interface module** and **the controller module.** The power flow for the DE sources are shown by the blue arrows and the bidirectional power flow path is shown by the red arrows in the Figure 2.2.

The input converters are designed based on the specific energy source or storage application.

AC-DC converters are used for the DE systems that generate AC output, often they have variable frequencies, such as wind, microturbine, IC engine, or flywheel storage.

DC-DC converter is needed for DC output systems like fuel cells, PV or batteries, where there are needed to change the DC voltage level.

The DC-AC inverter module is the most generic of the modules and converts a DC source to grid-compatible AC power.

The output interface module filters the AC output from the inverter and the interface is operated by the monitoring and control module, which contain the protection for the DE and utility point-of-common-coupling (PCC).

Protective functions for the DE system is controlled by the monitoring and control module and the local electric power system that allows paralleling and disconnection from the electric power system.

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Monitoring functions mainly include real-power, reactive power, and voltage monitoring at the point of the DE connection with the utility at the PCC. It is necessary to synchronize the DE systems since its output must have the same voltage magnitude, phase rotation, phase angle and frequency as the utility. ***Synchronization*** is the act of checking that these four variables are within an acceptable range before paralleling two energy sources.

2.3 Power Electronic Converter Topologies

Power Conversion	**Common Module Names**
AC – DC	Rectifier
DC – AC	Inverter
DC – DC	Boost, Buck, Buck-Boost, Chopper
AC – AC	Cyclo-converter, Matrix Converter
AC – DC – AC	Back-to-Back Converter, Rectifier Inverter

Table 2.1: Power Electronics for different Power Conversions.

There are mainly four possible types of converters; which are DC/DC, DC/AC, AC/DC, and AC/AC. The four converter types are described below:

2.3.1. DC/DC Converter: DC/DC converters are also known as ‘‘Switching Regulator’’. From DC sources such as a battery, fuel cell, solar panels, Electric Vehicles voltage levels requires to be changed to another level, either to supply a DC load or to be used as an intermediate voltage for an adjacent power electronic conversion such as a DC/AC converter. DC/DC converters coupled together with AC/DC converters enable us the use of High Voltage DC (HVDC) transmission which can send power through grids with much more efficiency than the AC grid.

2.3.2. DC/AC Converter: Also known as ‘‘Inverter’’ is a circuit that converts a DC voltage into a sinusoidal AC voltage. DC/AC converters or inverters are used to supply AC loads, control AC motors, or to connect DC devices that are to be connected to the grid. Similar to a DC/DC converter, the input to an inverter can come from sources such as battery, solar cell, or fuel cell or can be from an intermediate DC link that can be supplied from an AC source.

2.3.3 AC/DC Converter: Mainly known as ‘‘Rectifier’’. Usually the AC input to the circuit is a sinusoidal voltage source that operates at 120 V, 60 Hz in U.S.A or a 230 V, 50 Hz elsewhere that converts sinusoidal AC voltages to unidirectional DC voltages.

In some cases the DC voltage is required to further conversion by using a DC/DC or DC/AC converter. As a front-end circuit rectifiers are generally used in many power systems. Rectifiers can cause low power factor and harmonics when connected to power grid.

2.3.4. AC/AC Converter: Out of all converters AC/AC converters are more complex and complicate as they require change of voltages, frequencies, and bipolar voltages, blocking capabilities, which usually require complex device topologies. AC controllers have same fundamental input and output frequencies. The conversion is from a fixed voltage fixed frequency (FVFF) to a variable voltage fixed frequency (VVFF). [4]

Applications include: light dimmers and control of single-phase AC motors that are typically used in home appliances. [4] When both voltage and frequency are changed, the circuits are called ‘‘Cycloconverters’’, which convert a FVFF to variable voltage variable frequency (VVVF) and when fully controlled switches are used, this class of circuit is called ‘‘Matrix Converter’’. [4]

Another way of achieving AC/AC conversion is by using AC/DC and DC/AC through an intermediate DC link, this type of combined converter approach can be complex as the correct control approach must be implemented including simultaneous regulation of the DC link, injection of power with a prescribed power factor and bidirectional control of energy flow. [4]

Chapter 3

DER Technologies

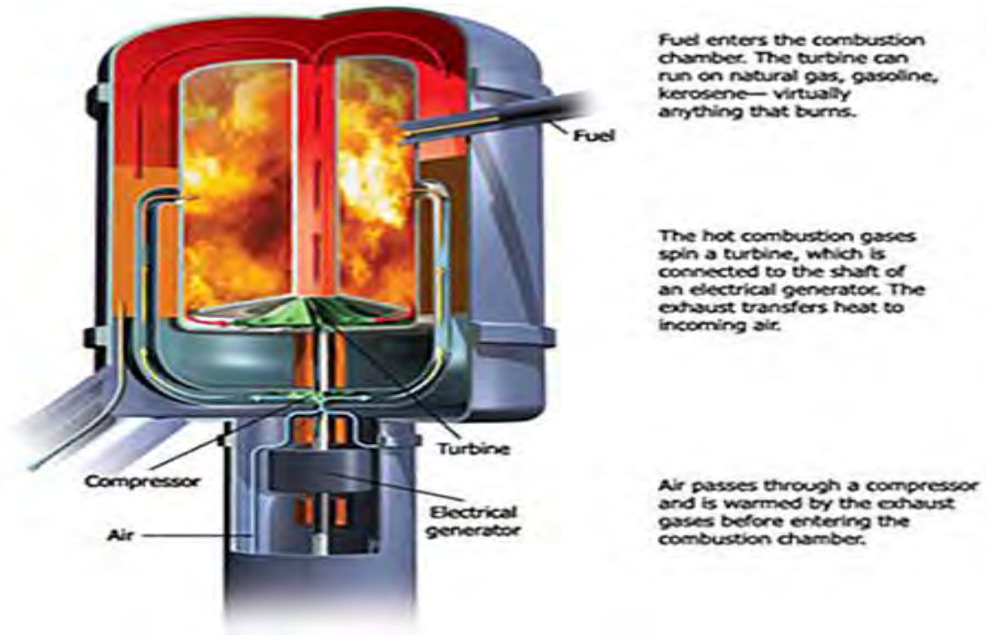
3.1 DER Technologies

In this chapter we are going to familiarize with different types of DER technologies used world wide. In the following sections descriptions of different DER technologies and applications are explained.

3.2 Microturbine

A relatively new distributed generation technology is Microturbine which is being used for stationary energy generation applications. There are types of turbines that produce both heat and electricity on a relatively small scale.

Microturbines are small combustion turbines approximately the size of a refrigerator with outputs of 25 kW to 500 kW. They evolved from automotive and truck turbochargers, auxiliary power units (APUs) for airplanes, and small jet engines. Most microturbines are comprised of a compressor, combustor, turbine, alternator and generator. The figure below illustrates how a microturbine works:



Fuel enters the combustion chamber. The turbine can run on natural gas, gasoline, kerosene— virtually anything that burns.

The hot combustion gases spin a turbine, which is connected to the shaft of an electrical generator. The exhaust transfers heat to incoming air.

Air passes through a compressor and is warmed by the exhaust gases before entering the combustion chamber.

Figure: 3.1 Microturbine’s working Procedure.

3.2.1 Primary applications for Microturbines include:

- Distributed generation—stand-alone, on-site applications remote from power grids
- Quality power and reliability—reduced frequency variations, voltage transients, surges, dips, or other disruptions
- Stand-by power—used in the event of an outage, as a back-up to the electric grid
- Peak shaving—the use of microturbines during times when electric use and demand charges are high
- Boost power—boost localized generation capacity and on more remote grids
- Low-cost energy—the use of microturbines as base load or primary power that is less expensive to produce locally than it is to purchase from the electric utility

- Combined heat and power (cogeneration)—increases the efficiency of on-site power generation by using the waste heat for existing thermal process.

Microturbines have significant share of the distributed generation market. In addition, microturbines offer an efficient power supply and also several potential advantages compared to other technologies for small-scale power generation, including: a small number of moving parts, compact size, lightweight, greater efficiency, lower emissions, lower electricity costs, and opportunities to utilize waste fuels. Waste heat recovery can also be used with these systems to achieve efficiencies greater than 80%. Because of their small size, relatively low capital costs, expected low operations and maintenance costs, and automatic electronic control, microturbines are expected to capture a and clean solution to direct mechanical drive markets such as compression and air-conditioning.

Beside the strengths Microturbines also have some weaknesses. Selected strengths and weaknesses of microturbine technology are listed in the following table from the California Distributed Energy Resources Guide on Microturbines.

Strengths	**Weaknesses**
Small number of moving parts	Low fuel to electricity efficiencies
Compact size	Loss of power output and efficiency with higher ambient temperatures and elevation
Lightweight	
Good efficiencies in cogeneration	
Low emissions	
Can utilize waste fuels	
Long maintenance intervals	
No vibrations	
Less noise than reciprocating engines	
Strengthens energy security	

Table: 3.1 Strengths and Weaknesses of

Microturbines.

Moreover, Microturbines are emerged with variety of technologies for their flexibility in applications. Since microturbines are being developed to utilize a variety of fuels, they are being used for resource recovery and landfill gas applications. These are also well suited for small commercial building establishments. The microturbine is referred as cost effective since it enables cost savings by reducing the peak demand at a facility and lowering demand charges. In DER technology Microturbines are also functional, productive and sustainable.

MICROTURBINE OVERVIEW	
Size Range	25-500 kW
Fuel	Natural gas, hydrogen, propane, diesel
Efficiency	20-30% (Recuperated)
Environmental	Low (<9–50 ppm) NOx
Other Features	Cogeneration (50–80°C water)
Commercial Status	Small volume production, commercial prototypes now.

Table: 3.2 Microturbine Overview

3.3 Combustion Turbines

A combustion turbine, also called a gas turbine, is a type of internal combustion engine. Unlike microturbines, these are larger turbines. It has an upstream rotating compressor coupled to a downstream turbine, and a combustion chamber or area, called a combustor, in between. They are fueled by natural gas, oil or a combination of fuels ("dual fuel").

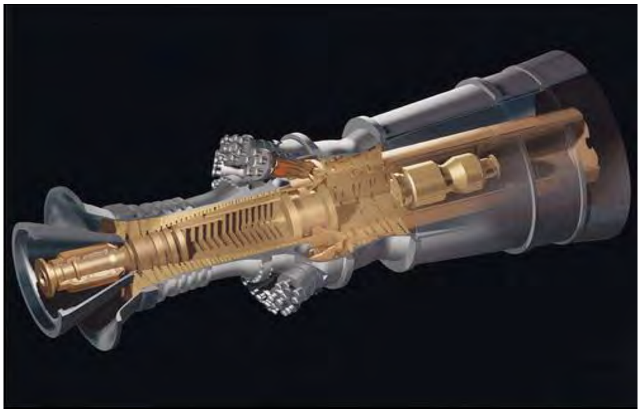


Figure 3.2: Combustion Turbine

The basic operation of the gas turbine is similar to that of the steam power plant except that the working fluid is air instead of water. Fresh atmospheric air flows through a compressor that brings it to higher pressure. Energy is then added by spraying fuel into the air and igniting it so the combustion generates a high-temperature flow. This high-temperature high-pressure gas enters a turbine, where it expands down to the exhaust pressure, producing a shaft work output in the process. The turbine shaft work is used to drive the compressor and other devices such as an electric generator that may be coupled to the shaft. The energy that is not used for shaft work comes out in the exhaust gases, so these have either a high temperature or a high velocity. The purpose of the gas turbine determines the design so that the most desirable energy form is maximized.

Gas turbines are used to power aircraft, trains, ships, electrical generators, pumps, gas compressors and tanks.[5]

Industrial gas turbines differ from aeronautical designs in that the frames, bearings, and blading are of heavier construction. They are also much more closely integrated with the devices they power— often an electric generator—and the secondary-energy equipment that is used to recover residual energy (largely heat).

They range in size from portable mobile plants to large, complex systems weighing more than a hundred tonnes housed in purpose-built buildings. When the gas turbine is used solely for shaft power, its thermal efficiency is about 30%. However, it may be cheaper to buy electricity than to generate it. Therefore, many engines are used in CHP (Combined Heat and Power) configurations that can be small enough to be integrated into portable container configurations.

Gas turbines can be particularly efficient when waste heat from the turbine is recovered by a heat recovery steam generator to power a conventional steam turbine in a combined cycle configuration.

3.3.1 Advantages of Combustion turbines:

- Very high power-to-weight ratio compared to reciprocating engines.
- Smaller than most reciprocating engines of the same power rating.
- Smooth rotation of the main shaft produces far less vibration than a reciprocating engine.

- Fewer moving parts than reciprocating engines results in lower maintenance cost and higher reliability/availability over its service life.
- Greater reliability, particularly in applications where sustained high power output is required.
- Waste heat is dissipated almost entirely in the exhaust. This results in a high-temperature exhaust stream that is very usable for boiling water in a combined cycle, or for cogeneration.
- Lower peak combustion pressures than reciprocating engines in general.
- High shaft speeds in smaller "free turbine units", although larger gas turbines employed in power generation operate at synchronous speeds.
- Low lubricating oil cost and consumption.
- Can run on a wide variety of fuels.
- Very low toxic emissions of CO and HC due to excess air, complete combustion and no "quench" of the flame on cold surfaces.

3.3.2 Disadvantages of Combustion turbine:

- Core engine costs can be high due to use of exotic materials.
- Less efficient than reciprocating engines at idle speed.
- Longer startup than reciprocating engines.
- Less responsive to changes in power demand compared with reciprocating engines.
- Characteristic whine can be hard to suppress.

Gas turbine technology has steadily advanced since its inception and continues to evolve. Development is actively producing both smaller gas turbines and more powerful and efficient engines. Aiding in these advances are computer based design (specifically CFD and finite element analysis) and the development of advanced materials: Base materials with superior high temperature strength (e.g., single-crystal super alloys that exhibit yield strength anomaly) or thermal barrier coatings that protect the structural material from ever-higher temperatures. These advances allow higher compression ratios and turbine inlet temperatures, more efficient combustion and better cooling of engine parts.

To achieve this target, emphasis will be placed on advanced turbine concepts that are fueled with natural gas and coal derived fuels, including hydrogen and syngas, and higher firing temperatures.

Combustion Turbine OVERVIEW	
Size Range	3,000–15,000 kW
Fuel	Natural gas, distillate, methane
Efficiency	25% - 60%
Environmental	Low
Other Features	Can operate base load, back-up, or peaking
Commercial Status	Technology commercially available today—most likely candidate for on-site needs >3 MW in DG application

Table 3.3: Combustion Turbine Overview

3.4 Stirling Engine

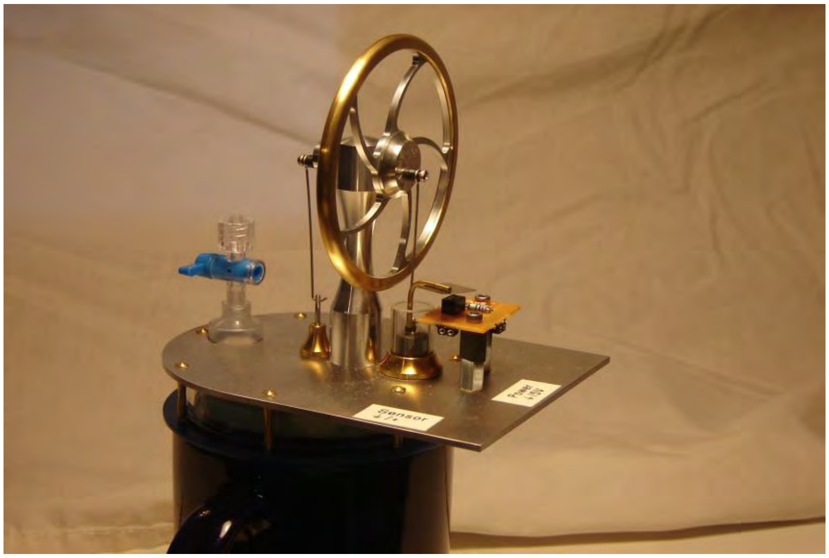


Figure 3.3: Stirling Engine

A Stirling engine is a heat engine that operates by cyclic compression and expansion of air or other gas at different temperatures in such a way that there is a net conversion of heat energy to mechanical work. More specifically, the Stirling engine is a closed-cycle regenerative heat engine with a permanently gaseous working fluid. [5]. Here closed-cycle is a thermodynamic system in which the working fluid is permanently contained within the system and regenerative describes the use of a specific type of internal heat exchanger and thermal store, known as the regenerator. The inclusion of a regenerator differentiates the Stirling engine from other closed cycle hot air engines.

The figure below illustrates the operation of Stirling Engine:

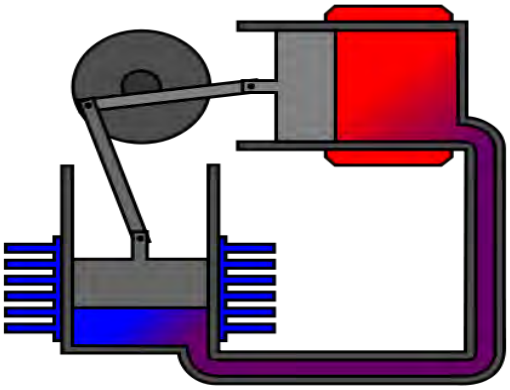


Figure 3.4: Stirling Engine Operation

Stirling engines have a high efficiency compared to steam engines. It is able to reach 50% efficiency. They are capable of noise free operation and can use almost any heat source. The heat energy source is generated external to the Stirling engine rather than by internal combustion with the Otto cycle or Diesel cycle engines. Because the Stirling engine is compatible with alternative and renewable energy sources it could become increasingly significant as the price of conventional fuels rises, and also in light of concerns such as depletion of oil supplies and climate change. This type of engine is currently generating interest as the core component of micro combined heat and power (CHP) units, in which it is more efficient and safer than a comparable steam engine.

There are huge applications of Stirling engine. They can be a part of Hybrid Electric Drive system, can be widely used in aircraft and marine engines. Not only in mechanical field they are also used in Electrical field such as in electrical power generation, solar power generation and so on.

Thermal power stations on the electric grid use fuel to produce electricity. According to the second law of thermodynamics, a heat engine can generate power from the temperature difference. In a CHP system, with the primary heat of high temperature to the Stirling engine electrical power is produced. [6] Some of the energy there is converted to mechanical power in the engine, and the rest passes through to the cooler, where it exits at a low temperature. The power produced by the engine can be used to run an industrial or agricultural process, which in turn creates biomass waste refuse that can be used as free fuel for the engine, thus reducing waste removal costs. This overall process is efficient and cost effective.

Generation of solar power can also be done by the Stirling engine. A Stirling engine can convert solar energy to electricity with an efficiency better than non-concentrated photovoltaic cells, and comparable to concentrated photovoltaics. Solar farms use mirrors to direct and concentrate sunlight onto the engines which in turn drive generators.

Figure 3.5: Stirling Engine

The advantages of Stirling engines are- the silence of operation, high efficiency, the multitude of possible hot sources, the ecological aptitude to respond to the environmental requirements on air pollution, reliability and easy maintenance, expanded lifetime and its characteristic of well adaptability.

On the other hand, the disadvantages are high price, problems due to sealing, delicacy in heat transformation and lack of flexibility.

STIRLING ENGINE OVERVIEW	
Size Range	~120 kW
Fuel	Methanol, Ethanol or the mixture of both
Efficiency	15-30% (Recuperated)
Environmental	High
Other Features	High reliability, low noise and vibration
Commercial Status	Used less

Table 3.4: Striling Engine Overview

3.5 FUEL Cell

Fuel cells are the most demanding technology among DER technologies. A fuel cell is a device that uses a source of fuel, such as hydrogen and an oxidant to create electricity from an electrochemical process. More elaborately, a fuel cell combines hydrogen with oxygen (from air) in a chemical reaction producing water, electricity and heat. Fuel cells do not burn the fuel rather the conversion takes place electrochemically without combustion. Fuel cell converts chemical energy to electrical energy. Their operation is much like a battery but found under the hoods of automobiles or in flashlights.[8]

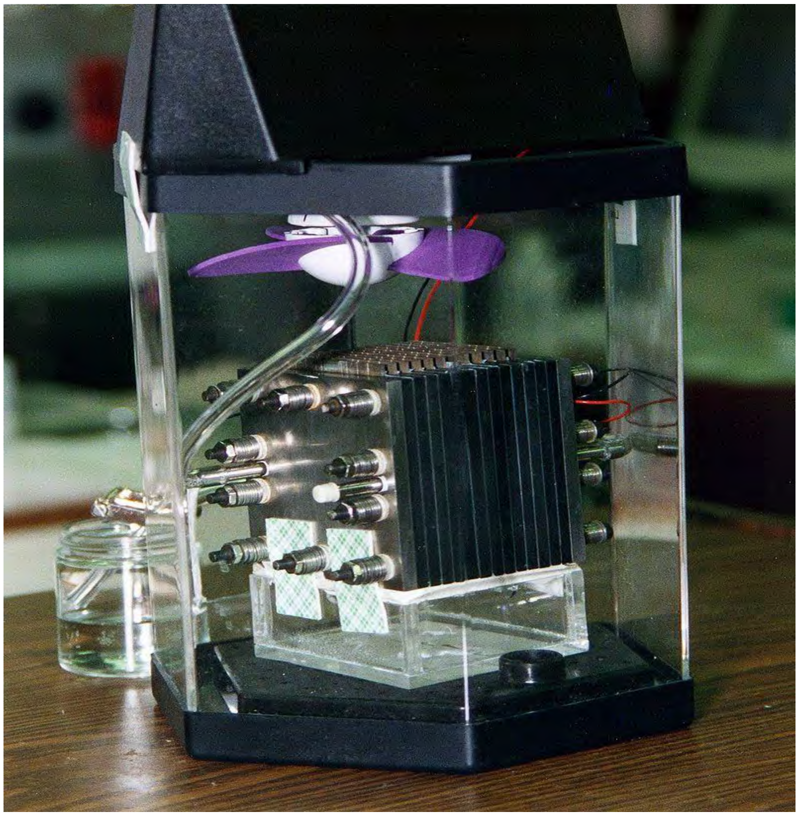


Figure 3.6: Fuel cell

All fuel cells have almost the same basic configuration that is an electrolyte with two electrodes but there might be different types of fuel cells based mainly on what kind of electrolyte they use. Many combinations of fuel and oxidant are also possible. The fuel could be diesel or methanol, while air, chlorine, or chlorine dioxide may serve as oxidants. Most widely used fuel cells nowadays use hydrogen and oxygen as chemicals.

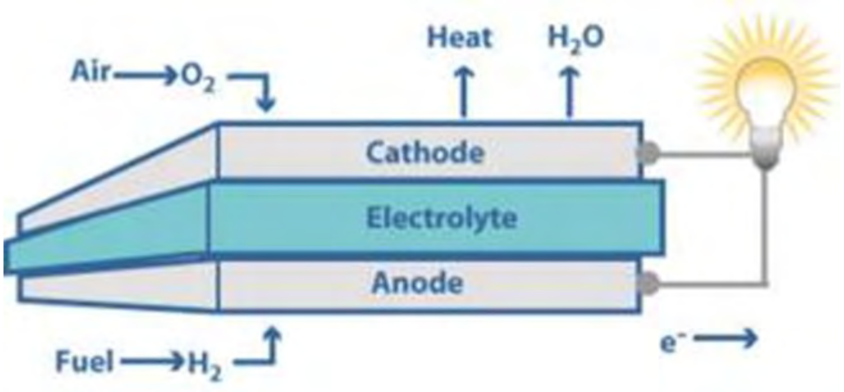


Figure 3.7: Fuel Cell General Mechanism Diagram

Fuel cells have three main applications: transportation, portable uses and stationary installations.

Fuel cell technology is used in automobiles. Almost all major car manufacturers have demonstrated prototype fuel cell vehicles and have announced plans for production and commercialization in the near to midterm future for 5-10 years. [9] The power range for light-duty vehicles are 50-80 kW, for buses 250 kW and in case of niche transport applications it is 1-10 kW.

Since Fuel cells have a higher energy density than batteries, in the portable sector industrial interest for fuel cells in the W power range is great. All electronic devices like mobile phones, laptop computers, personal digital assistants, cameras, and music or multimedia players use this consuming approximate power range (0.1 – 100) W.

Among fuel cell applications, stationary applications are the most diversified category. For this sector power is needed of 1 kW – 5 MW.

Most significantly fuel cells are used in localized Stationary Power Plants and in Distributed Generation.

CHP fuel cells are currently developed in sizes appropriate for use in single or multi-family residential applications (3-50 kW) in order to provide clean, quiet and efficient primary or backup power. [9] Small stationary CHP fuel cell power plants (0.1-5 MW) are a good alternative in such remote locations where grid lines are expensive and/or difficult to install. They offer a competitive energy solution to many communities that are currently not connected to the electric grid without the need to build a heavy infrastructure. The low maintenance and fuel-transport associated costs, and a very limited environmental footprint make fuel cell remote power plants close-to-ideal for this application. Larger stationary CHP fuel cell units (250-400 kW) can also be installed on the premises of an institutional building.

Fuel cell power plants in the MW range are well suited for the distributed generation of electricity at locations near demand. The energy produced by this is of high quality and there are fewer transport losses which results in fewer distribution lines and low environmental impact.

Fuel cells have strong benefits over conventional combustion-based technologies for being used in many power plants and transports. If pure hydrogen is used as a fuel, fuel cells emit only heat and water as a byproduct which is also environment friendly. Hydrogen-powered fuel cells are also far more energy efficient than traditional combustion technologies.

On the other hand, the biggest hurdle for fuel cells today is cost. Fuel cells cannot yet compete economically with more traditional energy technologies, though rapid technical advances are being made. Although hydrogen is the most abundant element in the universe, it is difficult to store and distribute.

If we think about the mitigation of its drawbacks then we may think it somewhat like since many people do have access to natural gas or propane tanks at their houses, so it is likely that these fuels will be used to power future home fuel cells. In addition, the incessant research and development might lead us to the fully developed fuel-cell based infrastructure for power generation and distribution with less cost.

Lastly, it is to be mentioned that Fuel-cells are a potentially important option among others that may contribute to increased economic efficiency and environmental performance. The crucial part is that fuel cell policies need to be integrated into an overall guiding strategy for sustainable development of whole energy system which aims for efficient use of energy and the expansion of renewable energy sources.

Ongoing developments are focused toward larger units. In the near future, however, fuel cell power plants are not intended to replace conventional power plants for primary power generation, but will more likely be used in parallel with the electric grid to increase reliability by getting rid of power blackouts during outages. Utility companies may also utilize them as additional power to relieve grid congestion during peak hours, thereby reducing overall energy costs for end-users. Finally, they could reduce the need for new central power generation, transmission and distribution, and its related high investment costs.

FUEL CELLs OVERVIEW	
Size range	▪ MCFC (molten carbonate fuel cells): 250–2,850 ▪ PAFC (Phosphoric acid fuel cells): 200 ▪ SOFC (solid oxide fuel cells): 225–2,240
No. of cells	400 or more
Fuel	Direct by hydrogen; natural gas, propane, methanol, or other hydrogen-rich source through reformer
Efficiency	65%
Environmental	Low ; not zero emission technology
Other Features	Cogeneration, conversion of fossil fuel etc.
Commercial Status	Has greatest commercial interest

Table 3.5: Fuel Cell Overview

3.6 Photovoltaic Systems

A photovoltaic system or PV system commonly known as solar power system, is a power system designed to supply usable solar power by means of photovoltaics. PV solar cells convert sunlight directly into electricity.

Figure 3.8: Solar Panel

It consists of an arrangement of several components, including solar panels to absorb and convert sunlight into electricity, a solar inverter to change the electric current from DC to AC, as well as mounting, cabling and other electrical accessories to set up a working system. It may also use a solar tracking system to improve the system's overall performance and include an integrated battery solution, as prices for storage devices are expected to decline.

A photovoltaic system uses the sun's radiation to produce usable electricity. It comprises the solar array and the balance of system components. PV systems can be categorized by various aspects, such as, grid-connected vs. stand-alone systems, building-integrated vs. rack-mounted systems, residential vs. utility systems, distributed vs. centralized systems, rooftop vs. ground-mounted systems, tracking vs. fixed-tilt systems, and new constructed vs. retrofitted systems. Other distinctions may include, systems with microinverters vs. central inverter, systems using crystalline silicon vs. thin-film technology, and systems with modules from Chinese vs. European and U.S.-manufacturers.

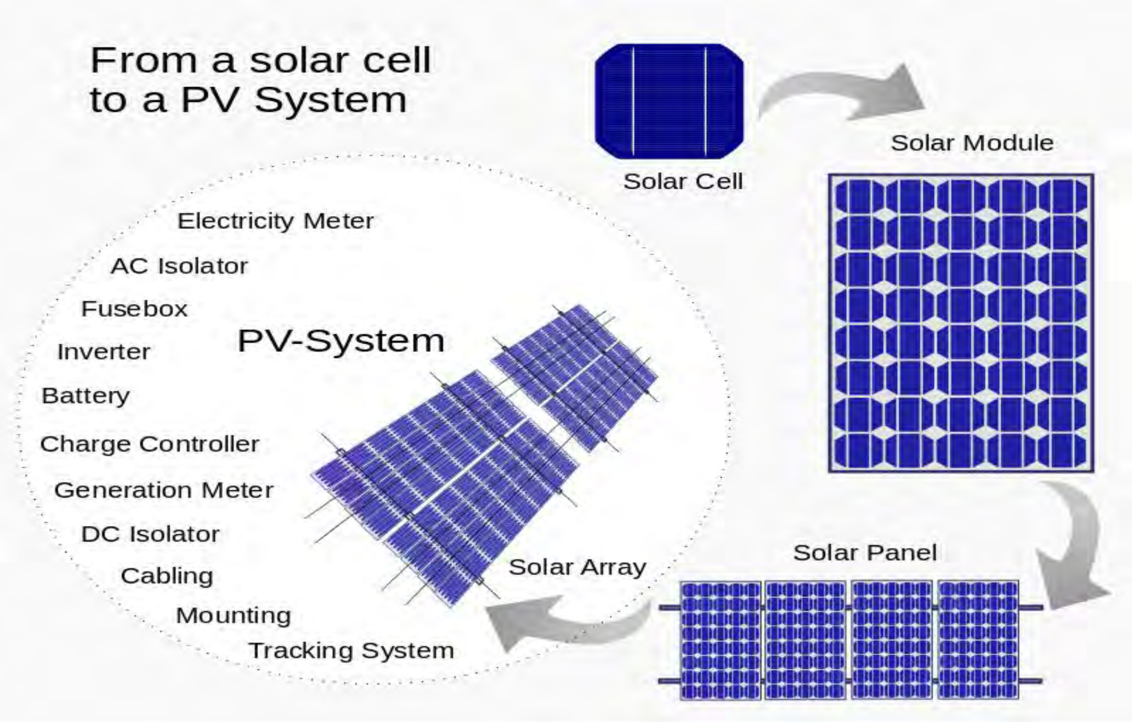


Figure 3.9: Solar Panel Concept

PV systems range from small, rooftop-mounted or building-integrated systems with capacities from a few to several tens of kilowatts, to large utility-scale power stations of hundreds of megawatts. Nowadays, most PV systems are grid-connected, while off-grid or stand-alone systems only account for a small portion of the market. [5]

A grid connected system is connected to a larger independent grid (typically the public electricity grid) and feeds energy directly into the grid. This energy may be shared by a residential or commercial building before or after the revenue measurement point. The difference being whether the credited energy production is calculated independently of the customer's energy consumption (feed-in tariff) or only on the difference of energy (net metering). Grid connected systems vary in size from residential (2–10 kWp) to solar power stations (up to 10s of MWp). This is a form of decentralized electricity generation. The feeding of electricity into the grid requires the transformation of DC into AC by a special, synchronizing grid-tie inverter. In kilowatt-sized installations the DC side system voltage is as high as permitted (typically 1000V except US residential 600 V) to limit ohmic losses. Most modules (60 or 72 crystalline silicon cells) generate 160 W to 300 W at 36 volts. It is sometimes necessary or desirable to connect the modules partially in parallel rather than all in series. One set of modules connected in series is known as a 'string'.[5]

Fundamentally, an inverter changes the DC input voltage from the PV to AC voltage for the grid. This inverter sits between the solar array and the grid, draws energy from each, and may be a large stand-alone unit or may be a collection of small inverters, each physically attached to individual solar panels. The inverter must monitor grid voltage, waveform, and frequency. One reason for monitoring is if the grid is dead or strays too far out of its nominal specifications, the inverter must not pass along any solar energy. An inverter connected to a malfunctioning power line will automatically disconnect in accordance with safety rules. Another reason for the inverter monitoring the grid is because for normal operation the inverter must synchronize with the grid waveform, and produce a voltage slightly higher than the grid itself, in order for energy to smoothly flow outward from the solar array. [11]

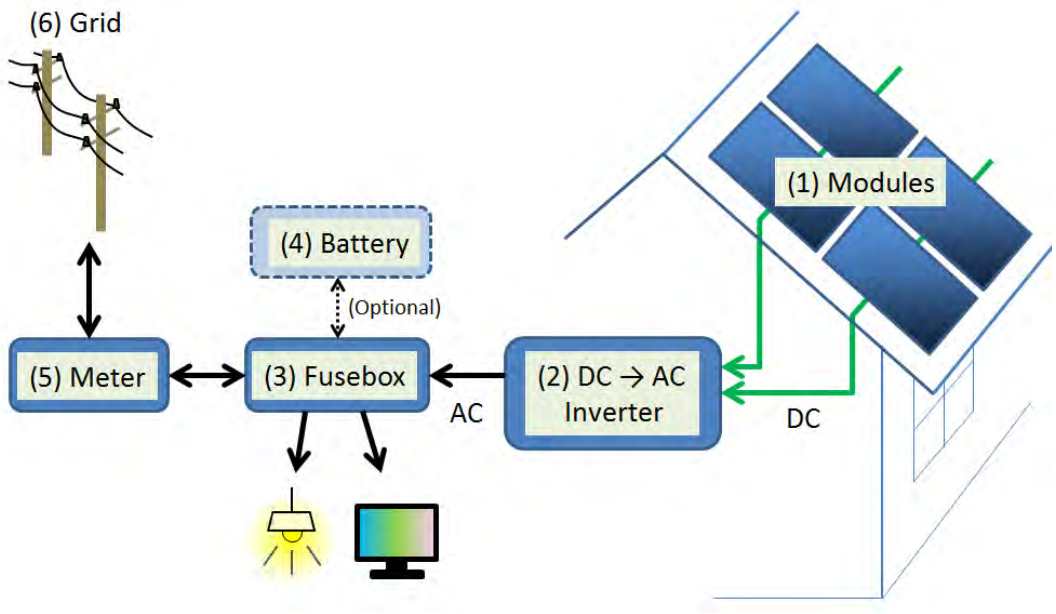


Figure 3.10: Solar Panel Integrated Architecture

A small PV system is capable of providing enough AC electricity to power a single home, or even an isolated device in the form of AC or DC electric. For example, military and civilian Earth observation satellites, street lights, construction and traffic signs, electric cars, solar-powered tents etc. In urban and suburban areas, photovoltaic arrays are commonly used on rooftops to supplement power use; often the building will have a connection to the power grid.

Large utility-scale solar parks or farms are power stations and capable of providing an energy supply to large numbers of consumers. Generated electricity is fed into the transmission grid powered by central generation plants (grid-connected or grid-tied plant), or combined with one, or many, domestic electricity generators to feed into a small electrical grid (hybrid plant). In rare cases generated electricity is stored or used directly by island/standalone plant. PV systems are generally designed in order to ensure the highest energy yield for a given investment. Some large photovoltaic power stations such as Solar

Star, Waldpolenz Solar Park and Topaz Solar Farm cover tens or hundreds of hectares and have power outputs up to hundreds of megawatts. [5]

Grid interconnection of photovoltaic (PV) power generation systems has the advantage of effective utilization of generated power because there are no storage losses involved. [11] Again, grid-connected PV systems are comparatively easier to install as they do not require a battery system.

But the PV power system has some demerits too. First of all, it is very costly. The maintenance charge is huge and without proper maintenance the PV cells will gradually become inactive. Another main concern is, Photovoltaic cell electrical output is extremely sensitive to shading. When even a small portion of a cell, module, or array is shaded, while the remainder is in sunlight, the output falls dramatically due to internal 'short-circuiting'. It not always possible to fall the sunrays upon all over the PV cells in a balanced way; sometimes the sky remains cloudy or sometimes it is shaded. In such cases, instead of adding to the power produced by the panel, the shaded cell absorbs power, turning it into heat.

Researches are still going on regarding mitigation of system drawbacks and making more feasible. Its efficiency is also tried to be increased. A typical "150 watt" PV module of about a square meter in size may be expected to produce 0.75 kilowatt-hour (kWh) every day, on average, after taking into account the weather and the latitude, for an insolation of 5 sun hours/day. In the last 10 years, the efficiency of average commercial wafer-based crystalline silicon modules increased from about 12% to 16% and CdTe module efficiency increased from 9% to 13% during same period. [5] Commercially available panels can go as far as 27%. It has been recorded that a group from The Fraunhofer Institute for Solar Energy Systems have created a cell that can reach 44.7% efficiency, which makes scientists' hopes of reaching the 50% efficiency threshold a lot more feasible. [5]

PV SYSTEM OVERVIEW	
Size Range	Watts to megawatts
Fuel	Silicon (polycrystalline), boron
Efficiency	(16 – 27)%
Environmental	High
Other Features	Operate quietly, no emission
Commercial Status	Moderate; also has further commercial interest

Table 3.6: PV System Overview

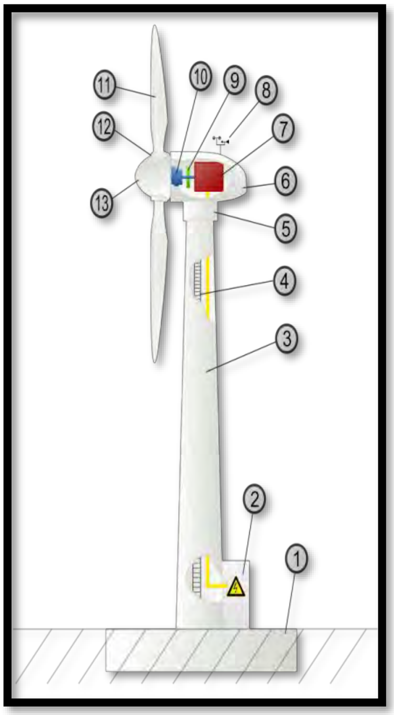
3.7 WIND POWER SYSTEMS

Wind systems work on the basis of wind power which generates electricity with the help of of air flow through Wind Turbines to mechanically power generators for electric power. Wind turbines can be distributed energy resources or they can be built at utility scale. In addition, distributed generation from wind hybrid power systems combines wind power with other DER systems.

Figure 3.11 Wind Mills

Wind turbines are devices that convert the wind's kinetic energy into electrical power. The result of over a millennium of windmill development and modern engineering, today's wind turbines are manufactured in a wide range of horizontal axis and vertical axis types. The smallest turbines are used for applications such as battery charging for auxiliary power. Slightly larger turbines can be used for making small contributions to a domestic power supply while selling unused power back to the utility supplier via the electrical grid. Arrays of large turbines, known as wind farms, have become an increasingly important source of renewable energy and are used in many countries as part of a strategy to reduce their reliance on fossil fuels. [13]

Wind turbine design is the process of defining the form and specifications of a wind turbine to extract energy from the wind. [14] A wind turbine installation consists of the necessary systems needed to capture the wind's energy, point the turbine into the wind, convert mechanical rotation into electrical power, and other systems to start, stop, and control the turbine. [5] The aerodynamics of a wind turbine are not straightforward. The shape and dimensions of the blades of the wind turbine are determined by the aerodynamic performance required to efficiently extract energy from the wind, and by the strength required to resist the forces on the blade.[15] In addition to the aerodynamic design of the blades, the design of a complete wind power system must also address the design of the installation's rotor hub, nacelle, tower structure, generator, controls, and foundation.[16] Turbine design makes extensive use of computer modelling and simulation tools. These are becoming increasingly sophisticated as highlighted by a recent state-of-the-art review by Hewitt et al. [17] Further design factors must also be considered when integrating wind turbines into electrical power grids.



Typical wind turbine components:

1. Foundation
2. Connection to the electric grid
3. Tower
4. Access ladder
5. Wind orientation control
6. Nacelle
7. Generator
8. Anemometer
9. Electric or Mechanical Brake
10. Gearbox
11. Rotor blade

Figure 3.12: Wind turbine architecture

There are different types of wind power system based on the size or production rate of electric power. Small-scale wind power system is one of them. Small-scale wind power is the name given to wind generation systems with the capacity to produce up to 50 kW of electrical power. Isolated communities, that may otherwise rely on diesel generators, may use wind turbines as an alternative. Individuals may purchase these systems to reduce or eliminate their dependence on grid electric power for economic reasons, or to reduce their carbon footprint. Wind turbines have been used for household electric power generation in conjunction with battery storage over many decades in remote areas.

Grid-connected domestic wind turbines may use grid energy storage, thus replacing purchased electric power with locally produced power when available. The surplus power produced by domestic microgenerators can, in some jurisdictions, be fed into the network and sold to the utility company, producing a retail credit for the microgenerators' owners to offset their energy costs.

Another significant factor for wind turbines are its location. Offshore wind power refers to the construction of wind farms in large bodies of water to generate electric power. These installations can utilize the more frequent and powerful winds that are available in these locations and have less aesthetic impact on the landscape than land based projects. However, the construction and the maintenance costs are considerably higher. Whereas the onshore wind is much less expensive than this.

3.7.1 The benefits of Wind Turbines:

· No variable costs for fuel
· In utility implementation, zero emissions may allow green power price premium
· Mature technology
· Multiple manufacturers

3.7.2 Drawbacks of this system are:

· Need to meet siting requirements
· Generation is intermittent with wind, and energy output can vary with wind speed squared or cubed over operation range. Not appropriate as backup or off-grid applications
· Needs utility source for energy purchases and sales
· might require footprint up to 100ft^2/kW

Wind farms consist of many individual wind turbines which are connected to the electric power transmission network. Onshore wind is an inexpensive source of electric power, competitive with or in many places cheaper than coal or gas plants. Offshore wind is steadier and stronger than on land, and offshore farms have less visual impact, but construction and maintenance costs are considerably higher. Small onshore wind farms can feed some energy into the grid or provide electric power to isolated off-grid locations.[18]

Moreover, Wind power gives variable power which is very consistent from year to year but which has significant variation over shorter time scales. It is therefore used in conjunction with other electric power sources to give a reliable supply.

WIND POWER System OVERVIEW	
Size Range	1-1000 kW
Fuel	None—need winds of >12 mph or sometimes higher
Efficiency	Varies depending on location and weather/ climate
Environmental	Moderate; zero-emission technology
Other Features	Safest installment and maintenance
Commercial Status	Successful commercial large designs are available, more contracts on a higher scale are made among manufacturers and global market

Table 3.7: Wind Power System Overview

3.8 Internal Combustion Engine

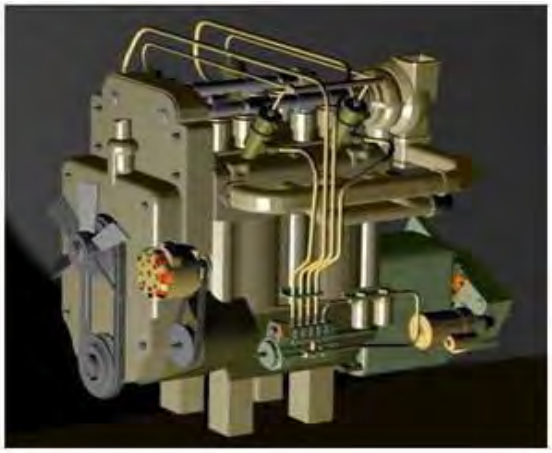


Figure 3.11: Internal Combustion Engine

An internal combustion engine (ICE) is a heat engine where the combustion of a fuel occurs with an oxidizer (usually air) in a combustion chamber that is an integral part of the working fluid flow circuit. In an internal combustion engine, the expansion of the high-temperature and high-pressure gases produced by combustion applies direct force to some component of the engine. The force is applied typically to pistons, turbine blades, rotor or a nozzle. This force moves the component over a distance, transforming chemical energy into useful mechanical energy.

The first commercially successful internal combustion engine was created by Étienne Lenoir around 1859[5] and the first modern internal combustion engine was created in 1876 by Nikolaus Otto.

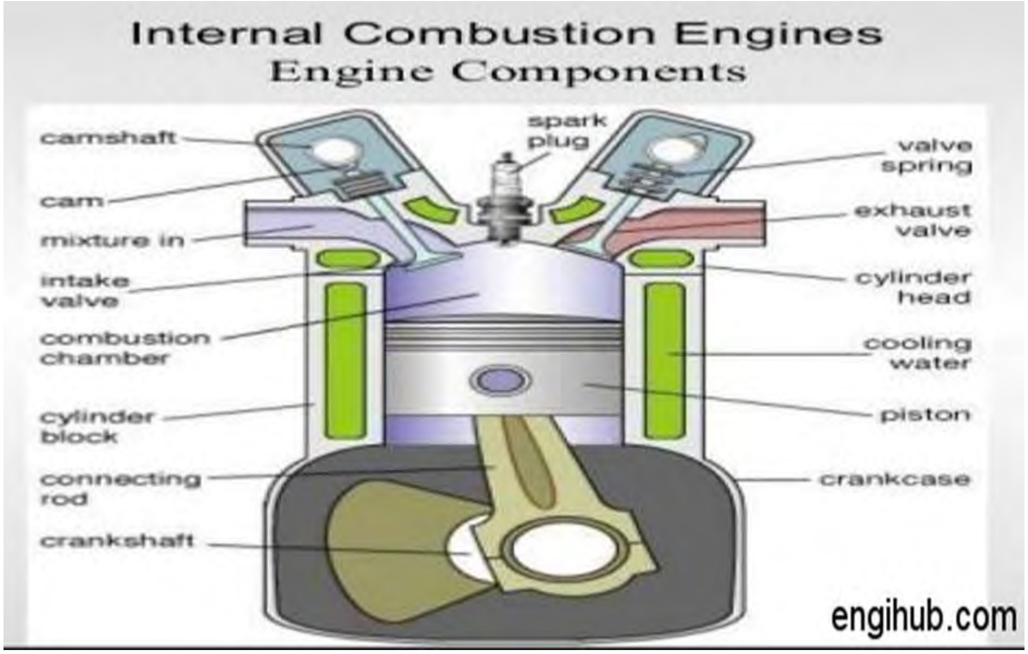


Figure 3.12: Internal Combustion Engine Component

There are different types of IC Engines based on the applications.

3.8.1 Application based IC Engines:

Four-Stroke: The four-stroke internal combustion engine is the type most commonly used for automotive and industrial purposes today (cars and trucks, generators, etc). The steps involved in the operation are:

I. INTAKE stroke: On the intake or induction stroke of the piston, the piston descends from the top of the cylinder to the bottom of the cylinder, reducing the pressure inside the cylinder. A mixture of fuel and air is forced by atmospheric (or greater) pressure into the cylinder through the intake port. The intake valve(s) then close.

II. COMPRESSION stroke: With both intake and exhaust valves closed, the piston returns to the top of the cylinder compressing the fuel-air mixture. This is known as the compression stroke.

III. POWER stroke: While the piston is close to Top Dead Center, the compressed air–fuel mixture is ignited, usually by a spark plug (for a gasoline or Otto cycle engine) or by the heat and pressure of compression (for a diesel cycle or compression ignition engine). A spark plug is an electrical device that fits into the cylinder head of some internal combustion engines and ignites compressed fuels such as aerosol, gasoline, ethanol, and liquefied petroleum gas by means of an electric spark. The resulting massive pressure from the combustion of the compressed fuel-air mixture drives the piston back down toward bottom dead center with tremendous force. This is known as the power stroke, which is the main source of the engine's torque (tendency of a force to rotate an object about an axis) and power.

IV. EXHAUST stroke: During the exhaust stroke, the piston once again returns to top dead center while the exhaust valve is open. This action evacuates the products of combustion from the cylinder by pushing the spent fuel-air mixture through the exhaust valve(s).

- Two-Stroke: The two-stroke type of internal combustion engine is typically used in utility or recreational applications which require relatively small, inexpensive, and mechanically simple motors (chainsaws, jet skis, small motorcycles, etc. A two-stroke engine is an internal combustion engine that completes the process cycle one revolution of the crankshaft (an up stroke and a down stroke of the piston, compared to twice that number for a four-stroke engine). This is accomplished by using the beginning of the compression stroke and the end of the combustion stroke to perform simultaneously the intake and exhaust (or scavenging) functions. In this way, two-stroke engines often provide strikingly high specific power, at least in a narrow range of rotational speeds. The functions of some or all of the valves required by a four-stroke engine are usually served in a two-stroke engine by ports that are opened and closed by the motion of the pistons, greatly reducing the number of moving parts.

- **Wankel**: The Wankel engine (rotary engine) does not have piston strokes. It operates with the same separation of phases as the four-stroke engine with the phases taking place in separate locations in the engine.

- **Wave disk engine**: It is an internal combustion engine which does away with pistons, crankshafts and valves, and replaces them with a disc-shaped shock wave generator. Compression is achieved through the generation of shock waves in a spinning air fuel mixture.

- **Gas turbine**: It is a rotary machine similar in principle to a steam turbine and it consists of three main components: a compressor, a combustion chamber, and a turbine. The air after being compressed in the compressor is heated by burning fuel in it.

- **Jet engines**: This take a large volume of hot gas from a combustion process and feed it through a nozzle which accelerates the jet to high speed. As the jet accelerates through the nozzle, this creates thrust and in turn does useful work.

3.8.2 IC Engines applications:

- Road vehicles such as scooter, motorcycle, buses etc.
- Aircrafts
- Motor boat
- Small machines such as lawn mowers, chainsaws and portable engine generators

3.8.3 Advantages of using IC Engines are:

I. An internal combustion engine is compact and lighter
II. An internal combustion engine can be started immediately
III. These type of engines are quite safe to use

IV. An internal combustion engine has higher efficiency than external combustion engine

3.8.4 Disadvantages of IC Engines:

- Air pollution: Internal combustion engines produce air pollution emissions, due to incomplete combustion of carbonaceous fuel. The main derivatives of the process are carbon dioxide CO2, water and some soot, impure carbon particles resulting from the incomplete combustion of a hydrocarbon. The effects of inhaling this soot have been studied in humans and animals and include asthma, lung cancer, cardiovascular issues, and premature death.

- Noise pollution: Significant contributions to noise pollution are made by internal combustion engines. Automobile and truck traffic operating on highways and street systems produce noise, as do aircraft flights due to jet noise, particularly supersonic-capable aircraft. Rocket engines create the most intense noise.

- One of the problems with internal combustion engines is that it generates high temperature, high pressure exhaust fumes which must be vented away from the engine. These fumes commonly contain pollutants generated by the burning of the fuel in the cylinder

INTERNAL COMBUSTION ENGINE OVERVIEW	
Size Range	(1 – 6000) kW
Fuel	Diesel, natural gas, propane, bio-gas, other petroleum distillates
Efficiency	28% – 37%
Environmental	Very low; there are emissions and noise
Other Features	Stable technology; can be paralleled to grid or other generators with controls package
Commercial Status	Commercially not flourished

Table 3.8: Internal Combustion Engine Overview

3.9 HYBRID Systems

Developers and manufacturers of DER are looking for ways to combine technologies to improve performance and efficiency of distributed generation equipment. Thus, these technologies are not commercially available but has huge commercial interest. Several examples of hybrid systems include:

- Solid oxide fuel cell combined with a gas turbine or microturbine
- Stirling engine combined with a solar dish
- Wind turbines with battery storage and diesel backup generators
- Engines (and other prime movers) combined with energy storage devices such as flywheels.

Chapter 4

Intoduction to Converters

4.1 Buck converter

Buck converter is a converter that steps down the input voltage to the output. it is a switch mode power supply kind consist of at least two semiconductors diode and transistor and at least one energy storage element capacitor, inductor. Capacitor is used to reduce voltage ripple of the input and output.

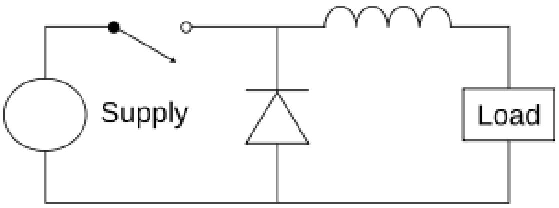


Fig 4: Buck converter circuit diagram.

Theory of operation

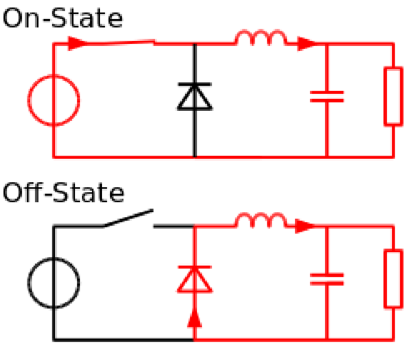


Fig: 4.1 Two circuit configuration of buck converter switch ON and OFF state respectively.

At the beginning when the switch is open the current in the circuit is zero, when the switch is close inductor current start to increase, and the inductor will produce opposing voltage in response to the increasing current. This voltage encounters the input voltage Therefore net voltage will drop across the load. Over time the current changing rate decreases therefore voltage drop across load increases. Meanwhile the inductor will store charge in the form of magnetic field. When the switch is open current will flow through the circuit apart from the input voltage and there will be a voltage drop across inductor. so the net voltage will be always below input voltage.net current flows through the load is greater than the input current makes up for the reduction in voltage and ideally it preserves the power provided to the load. during open stage when inductor will discharge if we close it before fully discharge the voltage at the load will always be greater than the zero.

Continuous mode

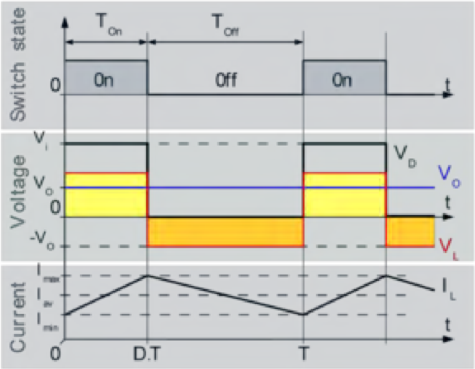


Fig: 4.2 Current and Voltage evolution of continuous ideal buck conveter.

If the current flowing through the inductor never falls to zero in the commutation cycle we can call it continues mode.

When the switch is closed current across the inductor rises linearly since diode is in reverse bias.

VL=Vi- V°

When the switch is open the diode is in forward bias and disconnected from input so the output voltage is V°=-VL and current is IL.

Energy stored in the inductor is

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

Inductor is using for transferring energy from input to the output. The rate of change of IL can be calculated from

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

Where VL equals to vi-v° during the on state and – v° during off state

So, the increase in current during on state

$$\Delta I_{L_{on}=\int_0^{t_{on}}\frac{V_L}{L}dt=\frac{(V_i-V_0}{L})t_{on,t_{on}}=DT}$$

So, the decrease in current during off state

$$\Delta I_{L_{off}} = \int_{t_{on}}^{T=t_{on}+t_{off}}\frac{V_L}{L}dt = -\frac{V_0}{L}t_{off}, t_{off} = (1-D)T$$

If we consider as steady state condition IL is same at t=0 and t=T

So, from above equations we can write

$$\Delta I_{L_{on}} + \Delta I_{L_{off}} = 0$$

$$\frac{V_i - V_0}{L}t_{on} - \frac{V_0}{L}t_{off} = 0$$

In figure 4.2 ΔIon is proportional to the yellow surface and ΔI off is proportional to the orange surface. From above graph we found rectangle that is (Vi- V◦) ton in the on state and -V◦ off for the off state.

In the steady state

$$(V_i - V_0)DT - V_0(1-D)T = 0$$
$$V_0 - DV_i = 0$$

$$D = \frac{V_0}{V_i}$$

We can see that v° is linearly varying with the duty cycle for given input.

Discontinuous mode

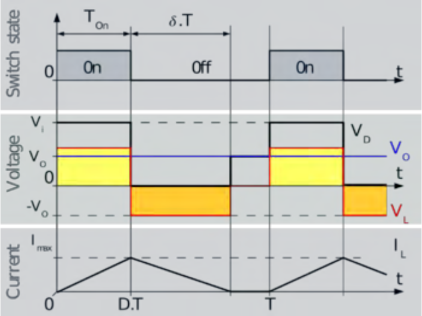


Fig: 4.3 Current and Voltage evolution of discontinuous ideal buck conveter.

In this part current flowing through the inductor falls to zero. The inductor is completely discharged at the end of the commutation cycle. it has some effect on the previous equations.

Inductor current is below zero when capacitor starts to discharge during each cycle and leads to higher switching loss.

We still consider the converter in steady state. So, the voltage across the inductor is zero.

$$(V_i - V_0)DT - V_0\delta T = 0$$

The output current through the load is Io

IL is the average value of the inductor current.

Since IL is in triangular shape.

$$I_L = (\frac{1}{1} I_{L_{max}} DT + \frac{1}{2} I_{L_{max}} \delta T) \frac{1}{T}$$
$$= \frac{I_{L_{max}}(D + \delta)}{2}$$
$$= I_0$$

The inductor current is zero at beginning. That rises to I_{Lmax} at ton. so I_{Lmax}

$$I_{L_{max}} \frac{V_i - V_0}{L} DT$$

Substituting I_{Lmax} to previous value

$$I_0 = \frac{(V_i - V_0)DT(D + \delta)}{2L}$$

the expression can be written as

$$V_0 = V_i \frac{1}{\frac{2LI_0}{D^2 V_i T} + 1}$$

We can see that load voltage is much more complicated in discontinuous mode than the Continuous mode.

4.2 Boost converter

Boost converter is a dc-dc power converter that steps up the input voltage to its output. It is a kind of switched-mode power supply (SMPS) that contain at least two semiconductors (a diode and a transistor) and one energy storage device (capacitor). Capacitor made filter is used to reduce voltage ripple for this kind of circuits both for input and output.

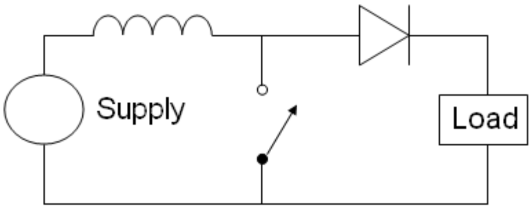


Fig 4.4: Basic schematics of a boost converter.

4.2.1 Overview:

For boosting power, it can be any dc source like battery, solar cell. The process of converting one dc voltage to another dc voltage is called dc-dc power conversion. In boost converter output voltage is always greater than the input voltage that’s why it is called step-up converter also. Since power is constant so output current gets larger than the source current.

4.2.1 Operation:

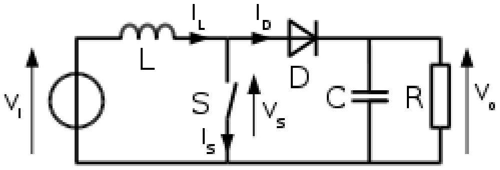


Fig 4.6: boost converter schematics

Continuous mode:

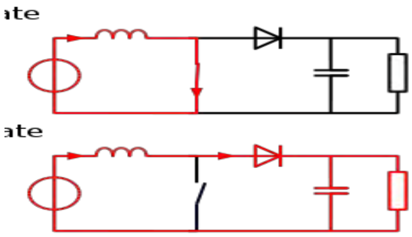


Fig 4.7: On state and off state respectively depending on switch condition.

When the circuit is in continuous mode the current through the inductor never falls to zero.

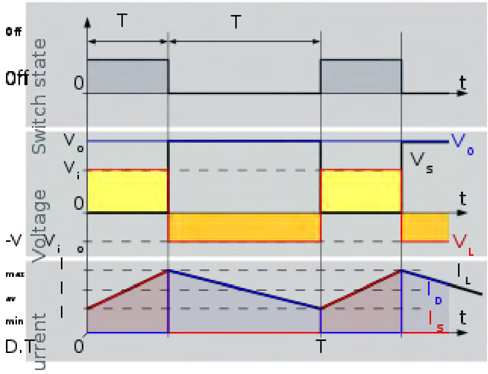


Fig 4.8 Waveforms of current and voltage in a boost converter in continuous mode.

Fig 4.8 Waveforms of current and voltage in a boost converter operating in continuous mode.

The output voltage can be calculated as follows, in the case of an ideal converter operating in steady state conditions.

When the switch S is closed the input voltage across the inductor is Vi and current flowing through the inductor is (IL) during a time period (t) by the formula:

$$\frac{\Delta I_L}{\Delta t} = \frac{V_i}{L}$$

L is the value of inductor.

At the end of the on state, the value of IL is:

$$\Delta_{L_{on}} = \frac{1}{L}\int_0^{DT} V_i dt = \frac{DT}{L} V_i$$

D is the duty cycle. It is the ON time of the total commutation period. Therefore, D ranges between 0 and 1 when the switch is open inductor current flow through the load if we consider l

During the off state when the switch is seen open. So the inductor current is flowing through the load. if we consider voltage drop across diode us zero and capacitor is large enough to keep load voltage constant so equation of IL is

$$V_i - V_0 = L\frac{dI_L}{dt}$$

Therefore, the changing if IL during the of state is

$$\Delta I_{L_{off}} = \int_{DT}^{T} \frac{(V_i - V_0)dt}{L} = \frac{(V_i - V_0)(1-D)T}{L}$$

If the circuit is in steady state condition the energy stored in the inductor is

$$E = \frac{1}{1} L_L^2$$

So, inductor current needs to be same at the starting point and ending point

$$\Delta I_{L_{on}} + \Delta I_{L_{off}} = 0$$

Substituting the value of delta ILon and delta ILoff

$$\Delta I_{L_{on}} + \Delta I_{L_{off}} = \frac{V_i DT}{L} + \frac{(V_i - V_o)(1-D)T}{L} = 0$$

The equation can be written as

$$\frac{V_o}{V_i} = \frac{1}{1-D}$$

The above shows that output voltage is always higher than the input voltage.

Discontinuous mode:

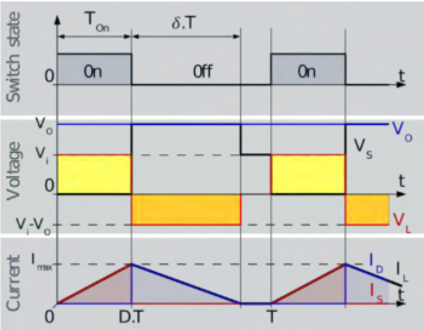


Fig 4.9: waveforms of current and voltage of boost converter in discontinuous mode.

Inductor can be discharge fully before the end of commutation cycle if ripple amplitude of current is too high. it may happen due to lower value of load. so current through the inductor falls to zero during this part and it has strong effect on the output voltage equation. Since in the beginning inductor current is zero I_{Lmax} is

$$I_{L_{max}} = \frac{V_i DT}{L}$$

During the off-period, IL falls to zero after ΔT:

$$I_{L_{max}} + \frac{(V_i - V_0)\delta T}{L} = 0$$

From previous two equations

$$\delta = \frac{V_i D}{V_0 - V_i}$$

I° is equal to the average diode current. During the off-state diode current is equal to the output current. So, the output current can be written as

$$I_0 = I_D = \frac{I_{L_{max}}}{2}\delta$$

Substituting I_{Lmax} and by their values

$$I_0 = \frac{V_i DT}{2L}\frac{V_i}{V_0 - V_i}. = \frac{V_i^2 D^2 T}{2L(V_0 - V_i)}$$

so the output voltage can be written as

$$\frac{V_0}{V_i} = 1 + \frac{V_i D^2 T}{2LI_0}$$

Compare to the continuous mode this discontinuous expression is much more complicated. Output gain is also influenced by inductor value, input voltage, output current and the commutation period

Replacing I°=V°/R into the precious equation, the output voltage gain can be

$$\frac{v_o}{v_i} = \frac{1 + \sqrt{1 + \frac{4D^2}{K}}}{2}$$

4.3 Buck boost converter

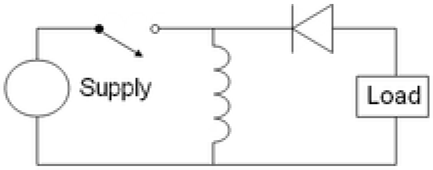


Fig 4.10 Basic schematic of an inverting buck boost converter

Buck boost converter is a dc-dc converter that levels up or down the input voltage to the load voltage. it is more similar or equivalent to fly back converter that has single inductor instead of transistor.

4.3.1 Inverting topology:

Load voltage is always inverse polarity of the input. by controlling the switching we can adjust the output voltage based on duty cycle. One drawback of this switching is that the switch does not have terminal at the ground.

A buck converter combined with a boost converter:

Output has the same polarity as the input and it can be lower or higher than the input. such non-inverting buck boost converter may use single inductor for buck and boost caused by switches instead of diodes that's why it is called four switch buck-boost converter.

Principle of operation of 4 switch topology:

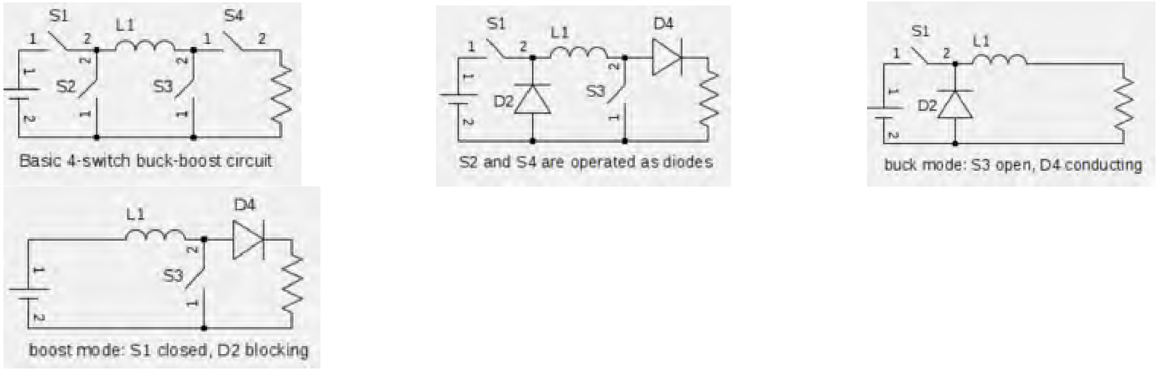


Figure 4.11: basic of 4 switch topologies

4 switches combine the buck and boost operations which make it buck boost converter.it can operate in buck mode or boost mode. in either mode. one switch controls the duty cycle and another is for communication and must be operated in inverse mode to the previous one and other two switches ate remain fixed.

Principle of operation of the inverting topology:

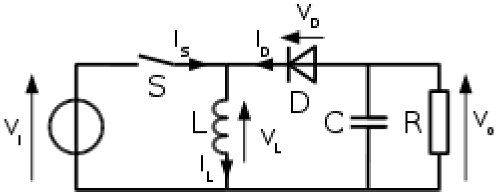


Figure 4.12: Basic schematic of buck boost converter.

Basic principle of inverting buck boost is very simple.
When the switch is closed source is connected to inductor and inductor is accumulating energy. Capacitor supply voltage to the load at same time. When the switch is open the inductor is connected to capacitor and load. So, energy transfers from inductor to load and capacitor**.**

Compared to the 4-switch buck boost the characteristics of the inverting buck boost converter are mainly:

Polarity of the output voltage is opposite to the input voltage output voltage ranges from 0 to -infinity for ideal converter. For buck it is Vi to 0 and for boost converter Vi to infinity.

Continuous mode

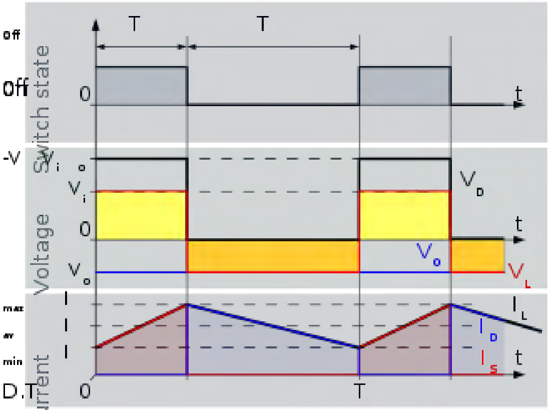


Fig 4.13: waveforms of voltage and current in a buck boost converter operating in continuous mode

If the current flowing through the inductor never stops it is called continuous mode. From t=0 to t=DT, the converter is in on state. So, the rate of change or IL is

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

At end of the on-state increase of current is

$$\Delta I_{L_{on}} = \int_0^{DT} d\, I_l = \int_0^{DT} \frac{V_i}{L} dt = \frac{V_i DT}{L}$$

At the end of the on cycle which represent the on time of total commutating state. During the off state stored energy in inductor transfer to the load and capacitor. if there is no voltage drop across diode and the capacitor is large enough to keep load voltage constant. Then IL is

$$\frac{dI_L}{dt} = \frac{V_0}{L}$$

Therefore, the changing of IL during the off-period is

$$\Delta I_{L_{off}} = \int_{0}^{(1-D)T} d\,I_L = \int_{0}^{(1-D)T} \frac{V_0 dT}{L} = \frac{V_0(1-D)T}{L}$$

if we consider the converter in steady-state condition. The amount of energy stored at each component is always same so the energy in inductor will be

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

So, IL needs to be same always so the changing of IL during on and off state must be zero.

$$\Delta I_{L_{on}} + \Delta I_{L_{off}} = 0$$

Substituting ΔILon and ΔILoff by their expression yields

$$\Delta I_{L_{on}} + \Delta I_{L_{off}} = \frac{V_i DT}{L} + \frac{V_0(1-D)T}{L} = 0$$

This can be written as

$$\frac{V_0}{V_i} = \frac{-D}{1-D}$$

From the above equation we can say that polarity of the output is always negative.

Discontinuous mode

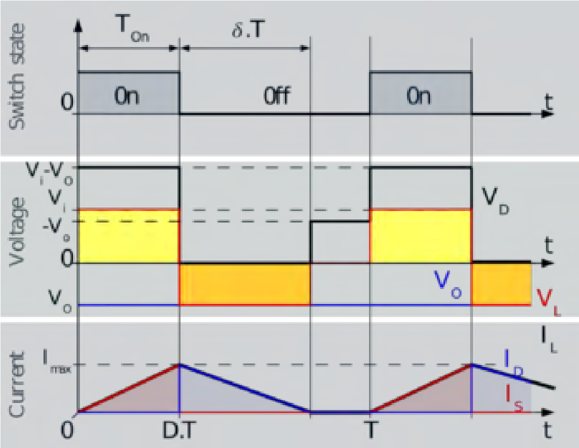


Fig 4.14: waveforms of voltage and current in a buck boost converter operating in discontinuous mode.

Inductor can be discharge fully before the end of commutation cycle if ripple amplitude of current is too high. it may happen due to lower value of load. so current through the inductor falls to zero during this part and it has strong effect on the output voltage equation. since in the beginning inductor current is zero I_{Lmax} is

$$I_{L_{Max}} = \frac{V_i DT}{L}$$

During the off-period, IL falls to zero after ΔT:

$$I_{L_{max}} + \frac{V_0 \delta T}{L} = 0$$

From previous two equations

$$\delta = -\frac{V_i D}{V_0}$$

I° is equal to the average diode current. During the off-state diode current is equal to the output current. So, the output current can be written as

$$I_0 = I_D = \frac{I_{L_{max}}}{2}\delta$$

Substituting ILmax and by their values

$$I_0 = \frac{V_i DT}{2L}\frac{V_i D}{V_0} = -\frac{V_i^2 D^2 T}{2LV_0}$$

so the output voltage can be written as

$$\frac{V_0}{V_i} = -\frac{V_i D^2 T}{I_0 2L}$$

Compare to the continuous mode this discontinuous expression is much more complicated.

Limit between continuous and discontinuous mode:

When low current is drawn by the load that time it is discontinuous. When load draws high current that time it is continuous. The limit between continuous mode and discontinuous mode is reached when inductor current falls it exactly zero.

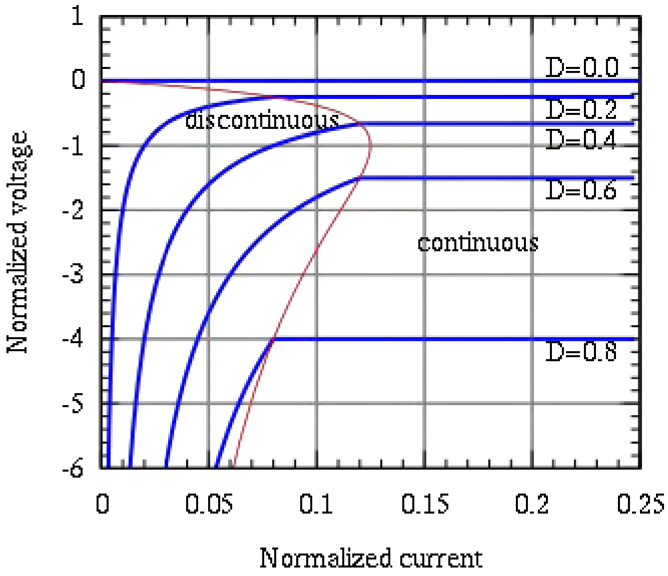


Figure 4.15: Evolution of the normalized output voltage with the normalized output current in a buck–boost converter.

From figure we can write as

$$DT + \delta T = T$$
$$D + \delta = 1$$

In this case Output current is given by

$$I_{o_{lim}} = I_D = \frac{I_{L_{max}}}{2}(1 - D)$$

Replacing ILmax given in the discontinuous mode

$$I_{o_{lim}} = \frac{V_i}{2L}(1 - D)$$

Between continuous and discontinuous mode current limit is I°lim. so it suits in both of the mode

$$I_{o_{lim}} = \frac{V_i DT}{2L}\frac{V_i}{V_0}(-D)$$

In continuous mode we have

$$V_0 = -\frac{D}{1 - D}$$

In discontinuous mode we have

$$V_0 = \frac{D^2}{2I_0}$$

As we said current limit between continuous and discontinuous mode is

$$I_{0_{lim}} = \frac{V_i}{2L}D(1 - D) = \frac{I_{o\,lim}}{2I_0}D(1 - D)$$

This expression is drawn in the above figure.

Chapter 5

Bidirectional DC-DC Buck-Boost Converter

5.1 Bidirectional DC-DC Buck-Boost Converter Simulation

Bidirectional buck-boost converters are used in applications such as Hybrid Electric Vehicles (HEV)s or Electric Vehicles (EV)s. Bidirectional Buck-Boost converters are used where power flow in both directions is needed.

When the main power is off, the battery should discharge and supply the load.

When the main power is on, the battery is charged from the load voltage.

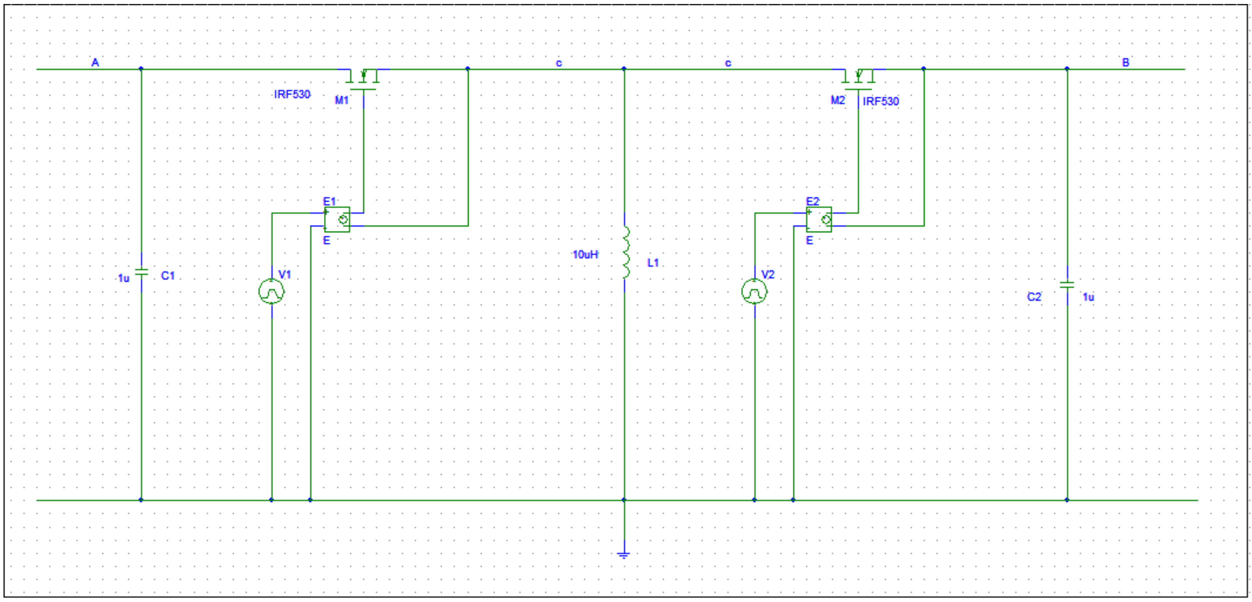


Fig: 5.1 Bidirectional Dc-Dc buck-boost converter circuit.

In Fig 5.1 we show the basic circuit diagram of a Bidirectional DC-DC buck-boost converter circuit. Here we have replaced the diodes with MOSFETS.

We are going to interchange the Voltage Source and Load within the terminals A and B.

5.2 Circuit Operations:

First, we are going to apply the Voltage Source at terminal A and Load Side Resistance at terminal B. Then we are going to demonstrate Boost Operation from Left to Right.

Then to show the Buck Operation from Left-Right we change the switching parameters.

Second, we are going to apply the Dc source voltage at terminal B. and Load Side Resistance at terminal A.

Then, we show the Boost and Buck Operations Right-Left respectively by changing the switching parameters.

For our simulations in Schematics PSpice software we take IRF530 as our MOSFET switches. After designing the circuits, we apply the corresponding impulses to the switches for their specific operations.

For our PSpice simulations we have taken frequency f = 500 kHz.

5.3 Step 1: Input at left side and Load at Right side with Boost Operation:

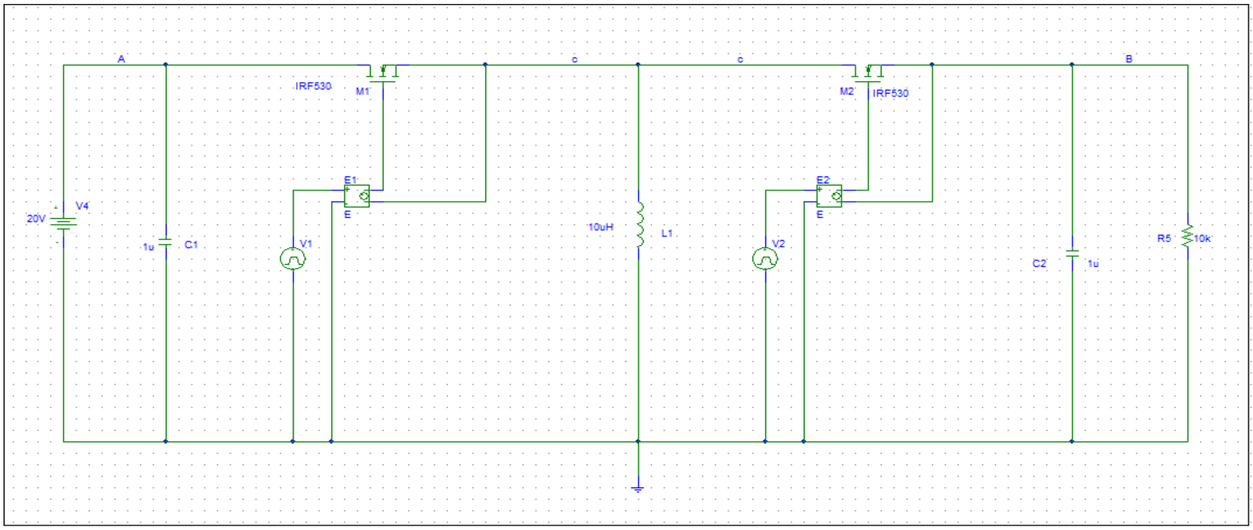


Fig: 5.2 Buck-Boost Operation Left-Right

For our simulation we have taken frequency f= 500kHz.

For the Boost Operation Left-Right we connect source voltage at A terminal and Load side resistance at terminal B.

Vdc = 20V and RLOAD =10kΩ.

For Figure 5.2 the following switching pulses are given to its respective switches.

Switch M1	Switch M2
V1=0V	V1=0V
V2=5V	V2=5V
TD=0s	TD=1.5us
TF=.1n	TF=.1ns
TR=.1n	TR=.1ns
PER=2us	PER=2us
PW=1.5us	PW=.5us

Table: 5.1 Boost Operation Switch Parameters (Left-Right)

Results of the simulation are given in the next section

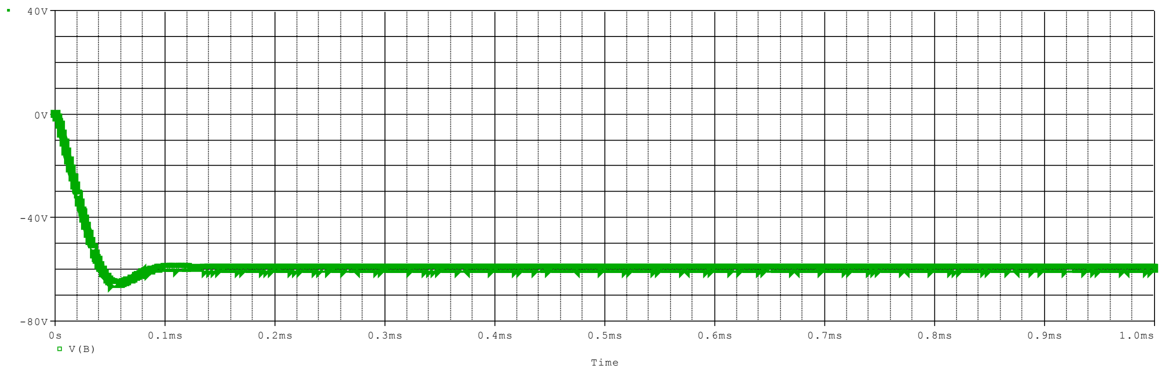


Fig 5.2(a): Boosted Voltage across Load.

From the figure above, we can see that we are getting |-60V| = 60V. But we had applied 20V at the input terminal A and getting inverted 60V, thus confirming the Boost Operation from Left-Right.

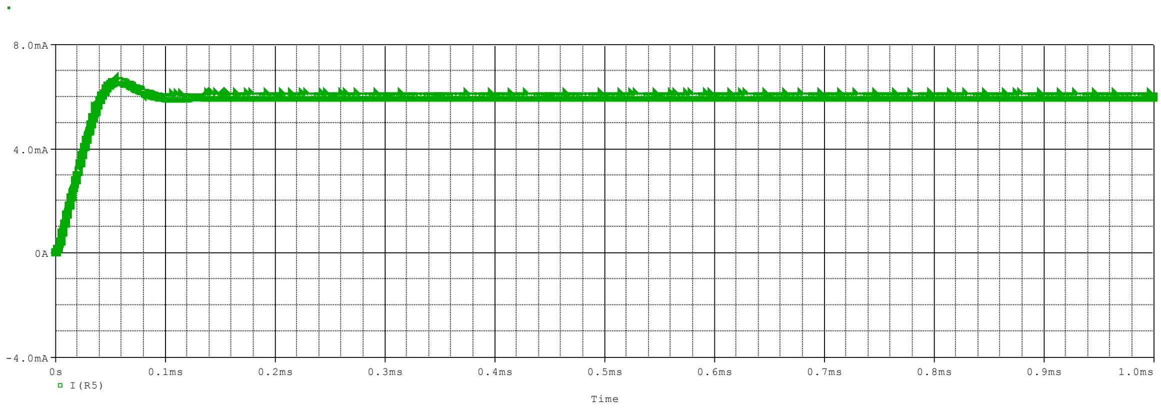


Fig: 5.2 (b) Current across Load.

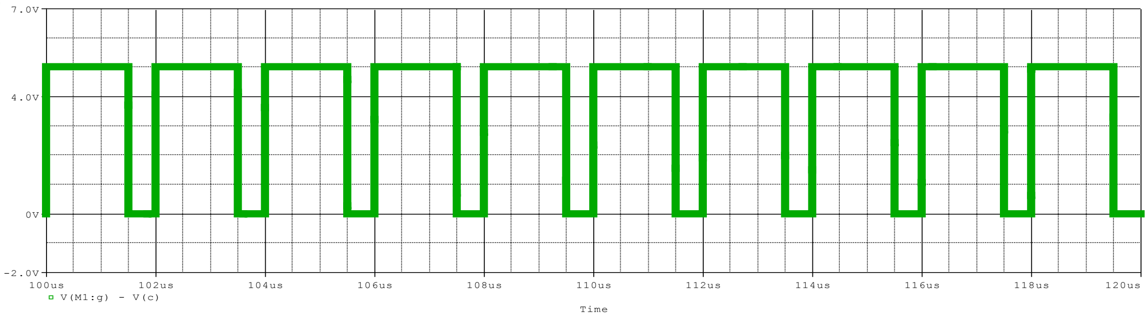


Fig: 5.2 (c) Gate-to-Source Voltage at M1

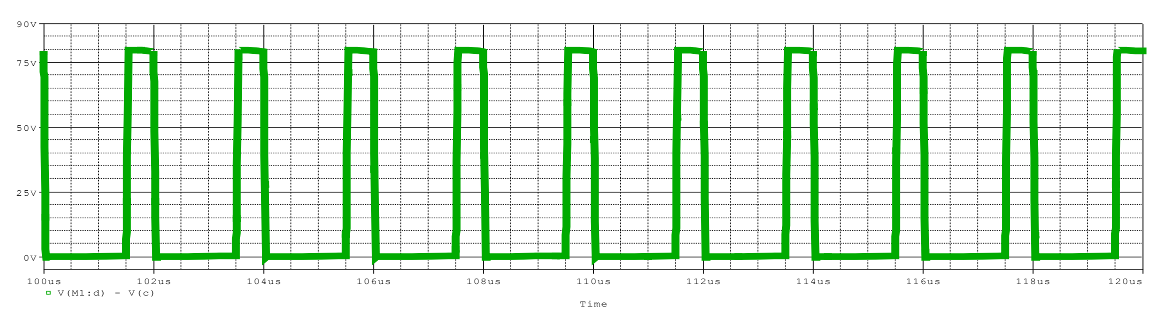


Fig: 5.2 (d) Drain-to-Source Voltage at M1

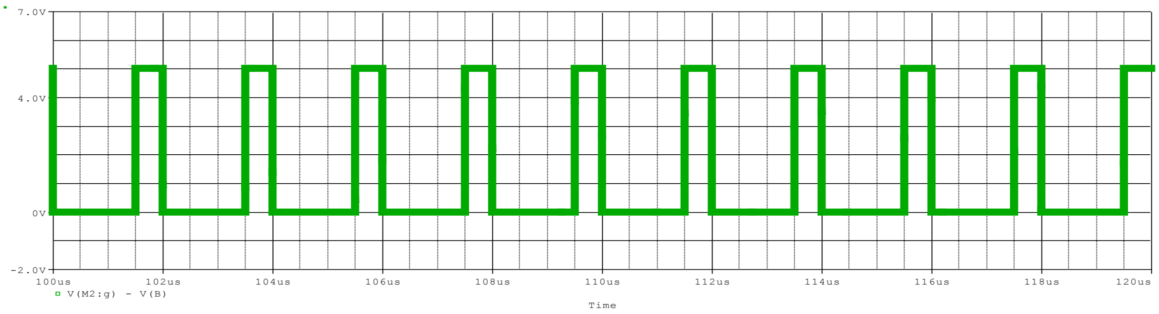


Fig: 5.2(e) Gate-to-Source Voltage at M2

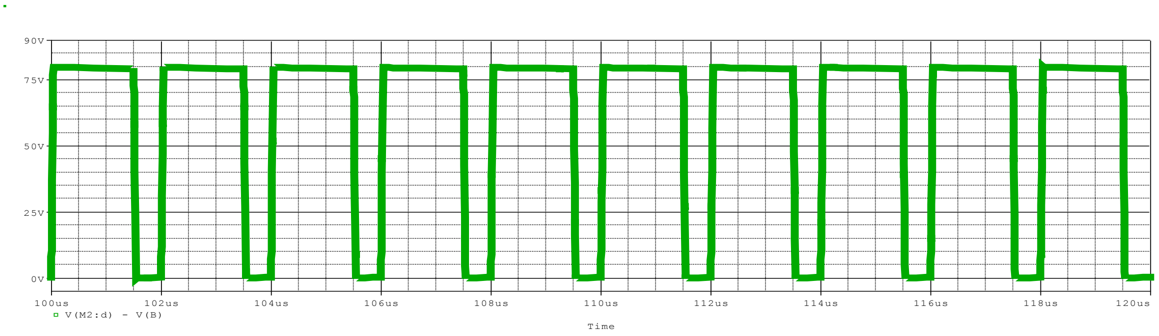


Fig: 5.2 (f) Drain-to-Source Voltage at M2

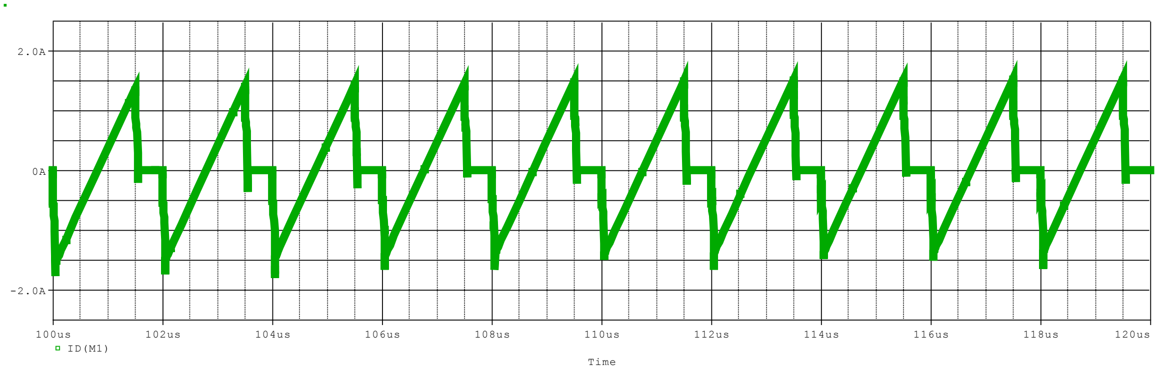


Fig: 5.2 (g) Drain current at M1

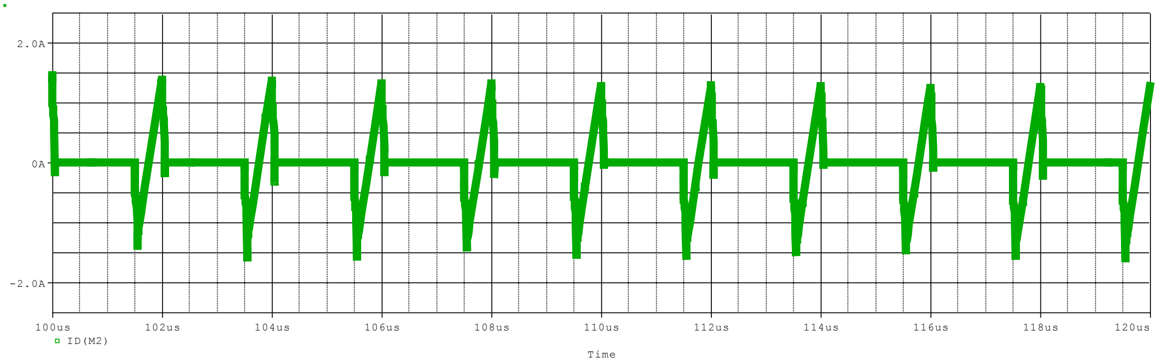


Fig: 5.2 (h) Drain current at M2

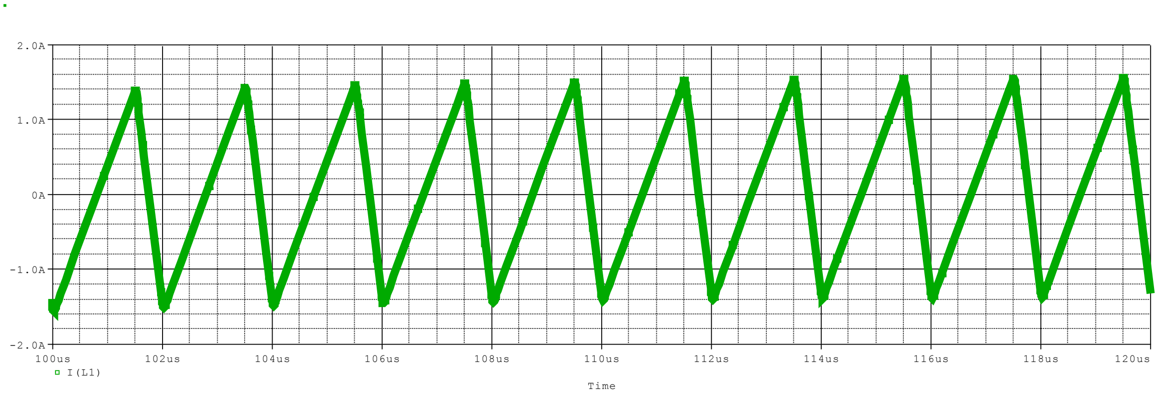


Fig: 5.2 (i) Current Across Inductor.

For the switch M1, we are keeping it “ON” for 1.5µs. And for the switch M2, we are keeping it “ON” for 0.5µs, which is less than the time we are keeping switch M1 “ON”.

Since we had taken frequency = 500kHz;

Period would be = (1/500kHz)

= 2µs

Among the 2µs time M1 is staying "ON" longer than M2, thus allowing more Current to be induced across the inductor from the Voltage Source to the Left. When M1 is kept "OFF" for 0.5µs, which is again less than the time than it was kept "ON", the induced Current across the inductor will go to the load side through M2 as M2 is kept "ON" for 0.5µs. But since M1 will become "ON" quickly, the inductor would not have finished transmitting all its induced voltage. Then when M1 will become "ON", it will add more induced Voltage across the inductor, then when M2 will be "ON", we can get more Voltage across the Load Side Terminal B.

From the Figure: 5.3 (i), we can see the Current across inductor IL is rising for 1.50µs, and falling for the remaining 0.50µs of the total 2µs period, since we had kept M1 "ON" for 1.5us and "OFF" for 0.5µs.

5.4 Step 2: Input at left side and Load at Right side with Buck Operation:

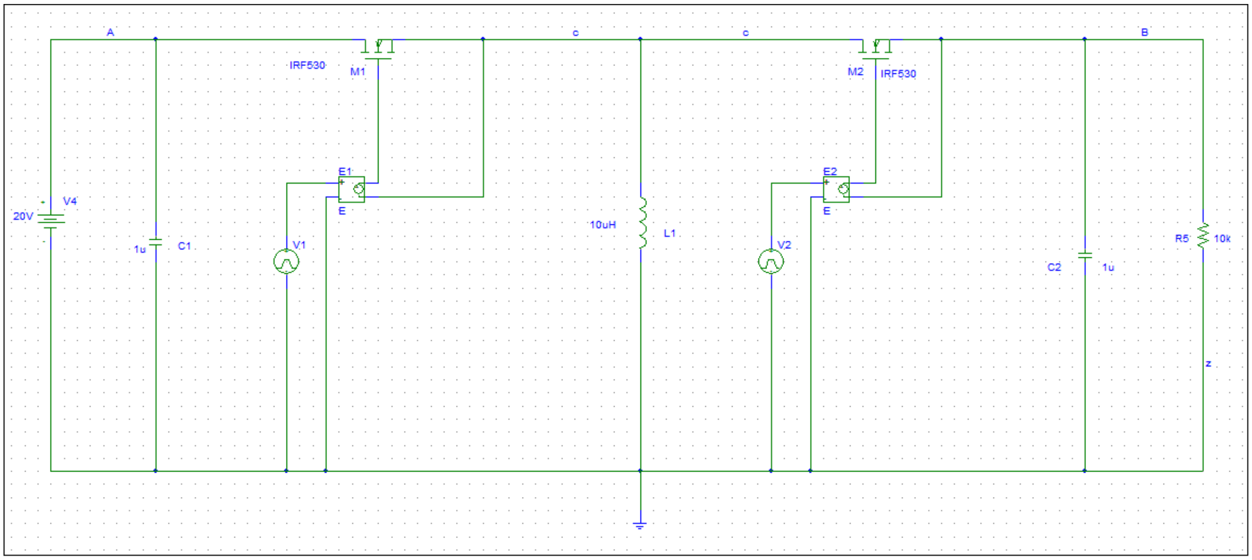


Fig: 5.4 Buck-Boost Operation Left-Right

For the Buck Operations Left-Right the following switching pulses are given to its respective switches.

Switch M1	Switch M2
V1=0V V2=5V TD=0s TF=.1n TR=.1n PER=2us PW=0.5us	V1=0V V2=5V TD=.5us TF=.1ns TR=.1ns PER=2us PW=1.5us

Table 5.2: Buck Operation Switching Parameters (Left-Right)

We obtain the following simulations results.

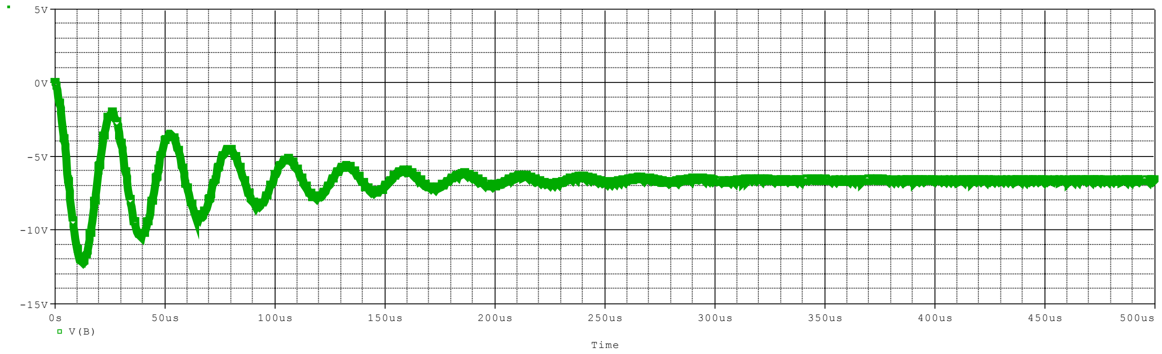


Fig: 5.4 (a) Voltage across Load (Buck mode Left-Right)

From the figure above, we can see that we are getting |-6.5V| = 6.5V. But we had applied 20V at the input terminal A and getting inverted 6.5V, thus confirming the Buck Operation from Left-Right.

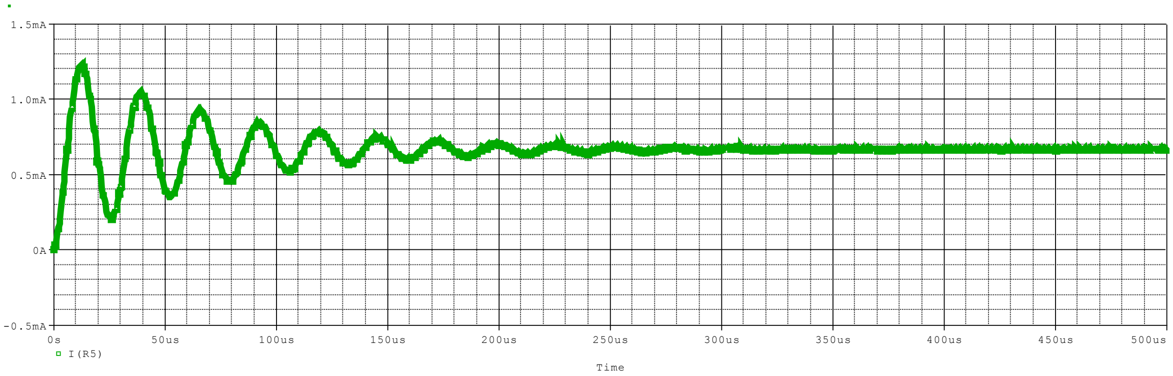


Fig: 5.4 (b) Current across Load (Buck mode Left-Right)

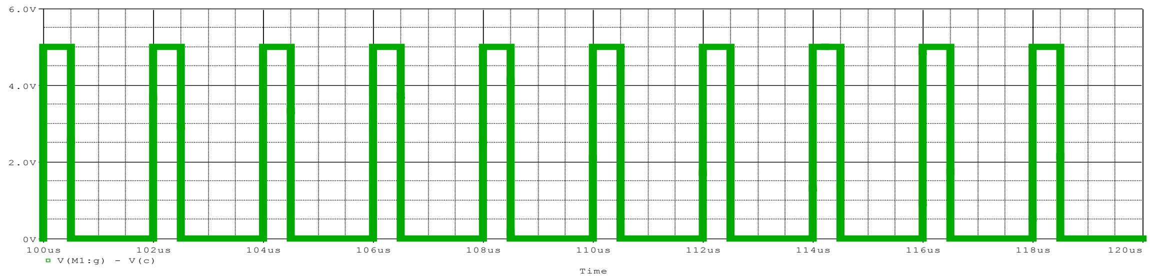


Fig: 5.4 (c) Gate-to-Source Voltage at M1 (Buck mode Left-Right)

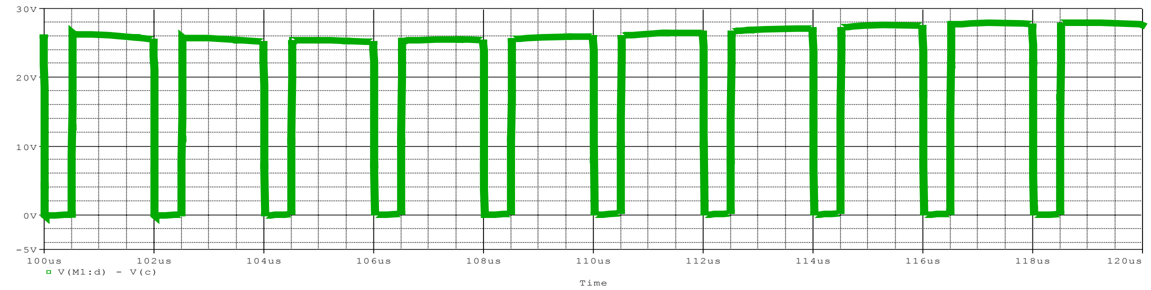


Fig: 5.4 (d) Drain-to-Source Voltage at M1 (Buck mode Left-Right)

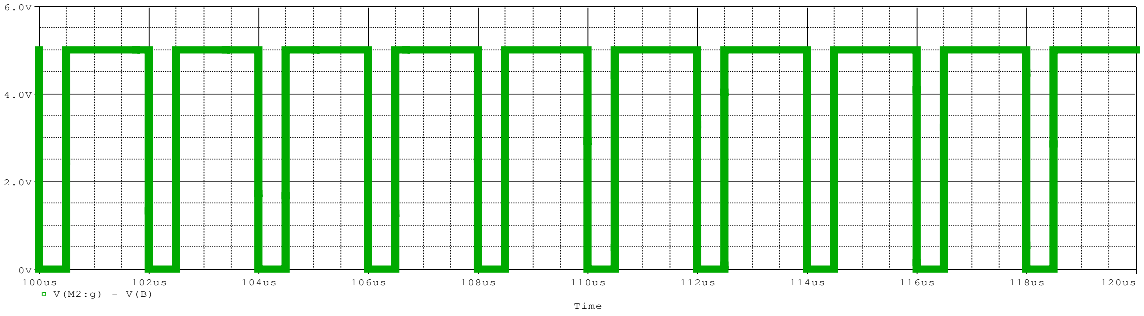


Fig: 5.4 (e) Gate-to-Source Voltage at M2 (Buck mode Left-Right)

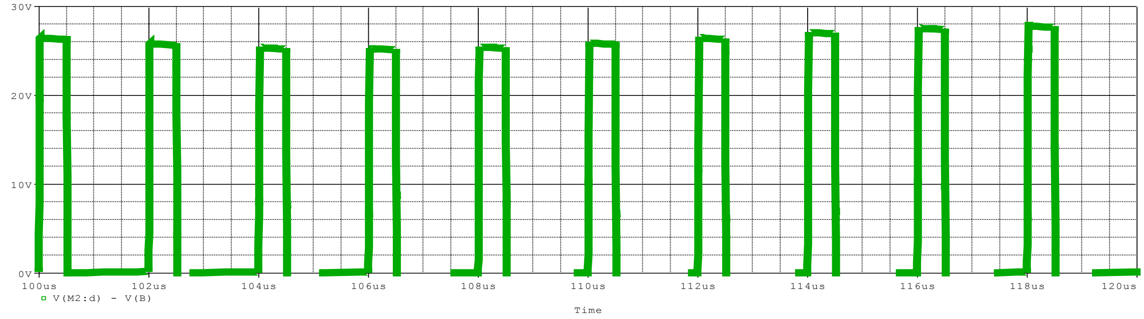


Fig: 5.4 (f) Drain-to-Source Voltage at M2 (Buck mode Left-Right)

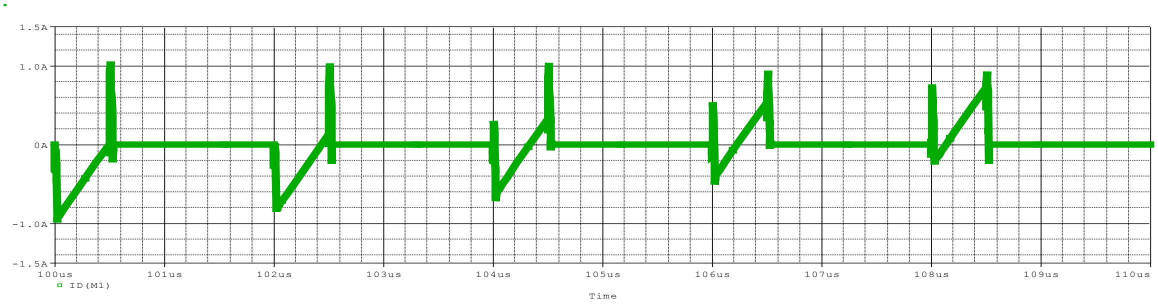


Fig: 5.4 (g) Current through M1 Drain (Buck mode Left-Right)

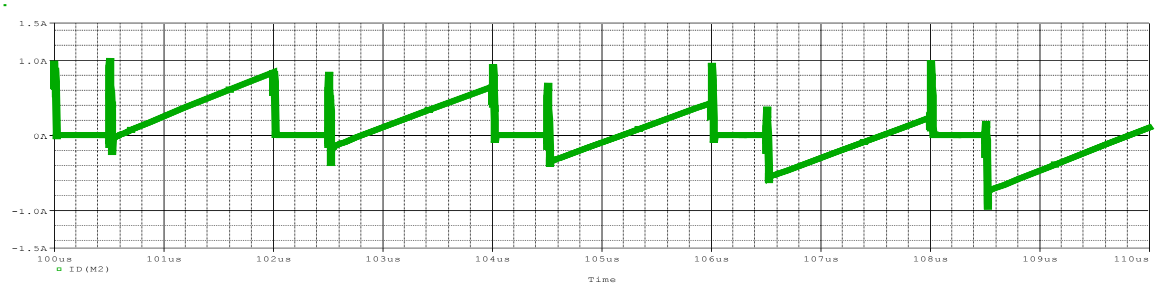


Fig: 5.4 (h) Current through M2 Drain (Buck mode Left-Right)

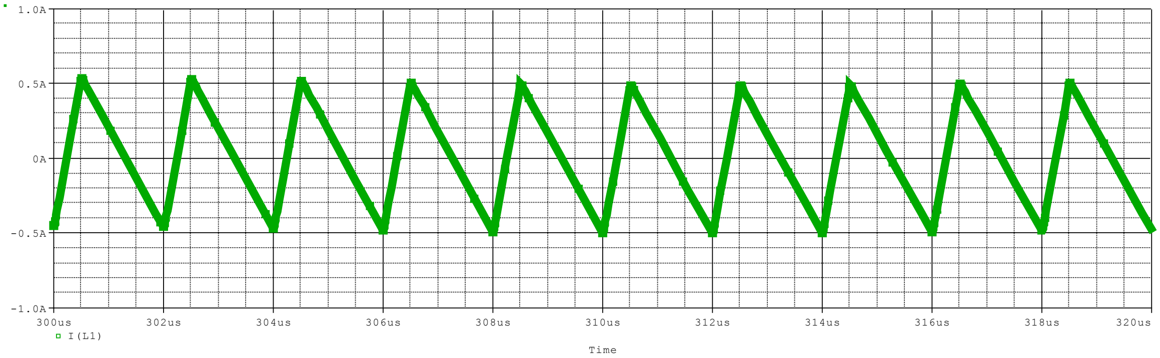


Fig: 5.4 (i) Current Across Inductor. (Buck mode Left-Right)

For Buck Operation Left-Right, we are keeping the switch M1 “ON” for 0.5µs. And for the switch M2, we are keeping it “ON” for 1.5µs, which is longer than the time we are keeping switch M1 “ON”.

We are keeping the switch M1 which is at the side of the Voltage Source at terminal A, “ON” shorter than keeping the switch M2 “ON”.

Since we had taken frequency = 500kHz;

Period would be = (1/500kHz)

= 2µs

Among the 2µs time M1 is staying “ON” shorter than switch M2, thus allowing less Current to be induced across the inductor from the Voltage Source to the Left. When M1 is kept “ON” for 0.5µs, which is again less than the time than it was kept “OFF” which is 1.5µs, the induced Current across the inductor will go to the Load Side through M2 as M2 is kept “ON” for 1.5µs. But since M1 will become “OFF” quickly, the inductor would not have finished inducing enough voltage as it had allowed more current to flow to the Load side when switch M2 was “ON” for 1.5µs. Then when M1 will become “ON”, it will not be able to add more induced Voltage across the inductor since M2 will be “ON” longer. Thus, we are getting less Voltage across the Load Side Terminal B.

From the Figure: 13.5 (i), we can see the Current across inductor IL is rising for 0.50µs, and falling for the remaining 1.50µs of the total 2µs period, since we had kept M1 “OFF” for 1.5us and “ON” for 0.5µs.

5.5 Step 3: Input at right side and Load at left side with Buck Operation:

Now we interchange the Dc Voltage source and Load Resistance to verify the Buck-Boost Operation from Right to Left.

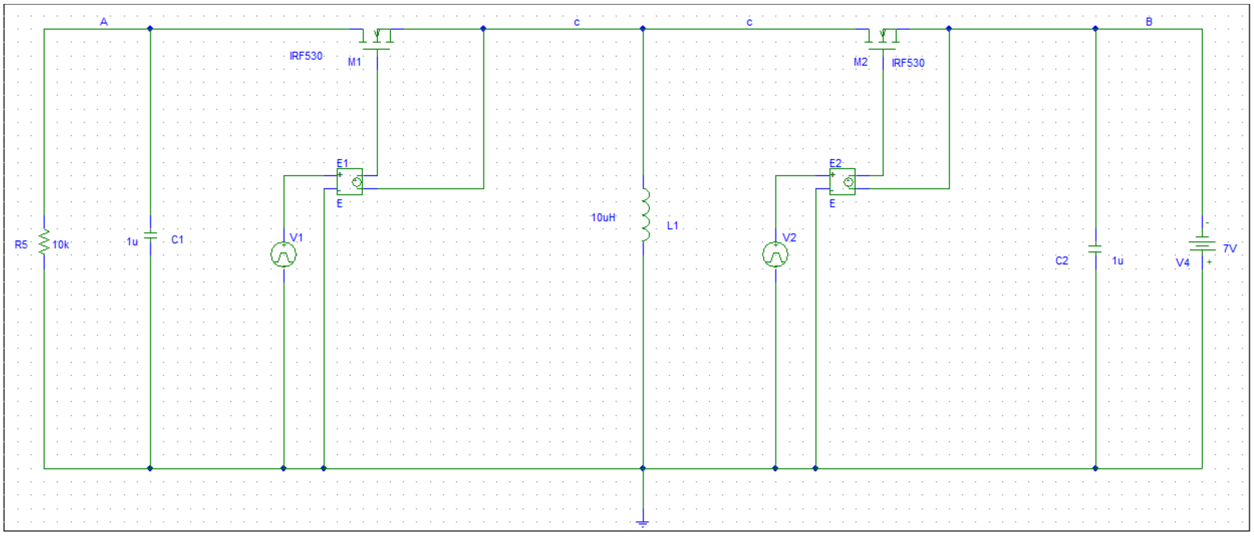


Fig: 5.5 Buck-Boost Operation (Right-Left)

Keeping switches M1 and M2 unchanged we apply the following Vpulses to its respective switches to conduct the Buck Operations from Right-Left.

Switch M1	Switch M2
V1=0V V2=5V TD=0.5us TR=0.1ns TF=0.1ns PER=2us PW=1.5us	V1=0V V2=5V TD=0 TR=0.1ns TF=0.1ns PER=2us PW=0.5us

Table 5.3: Buck Operation Right-Left Switching Parameters.

We obtain the following results.

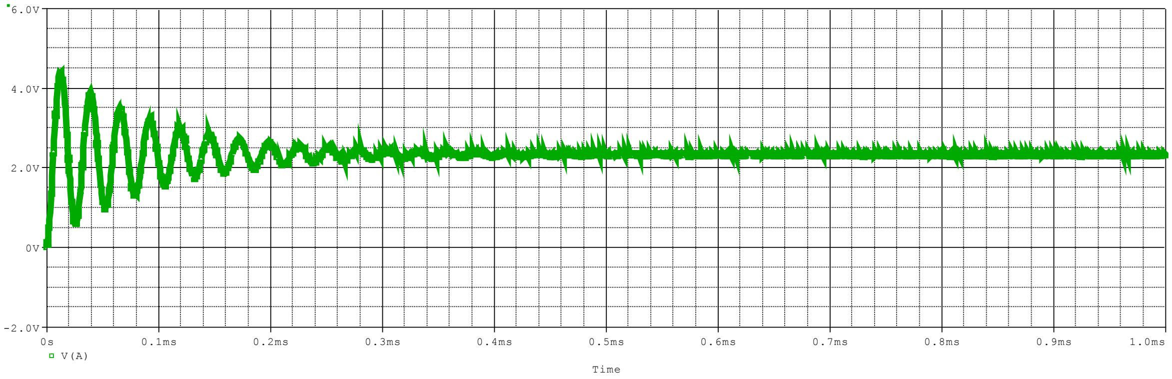


Fig: 5.5 (a) Output voltage at Load (Buck Operation Right-Left).

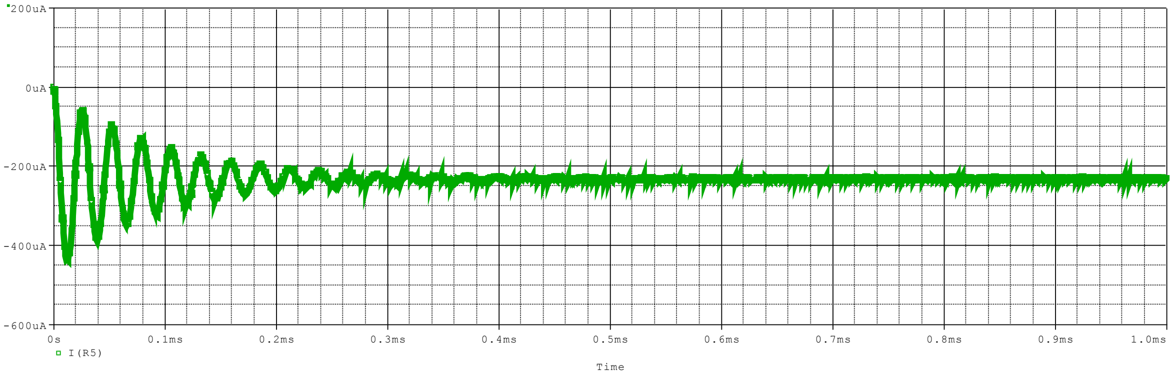


Fig: 5.5 (b) Output Current at Load (Buck Operation Right-Left).

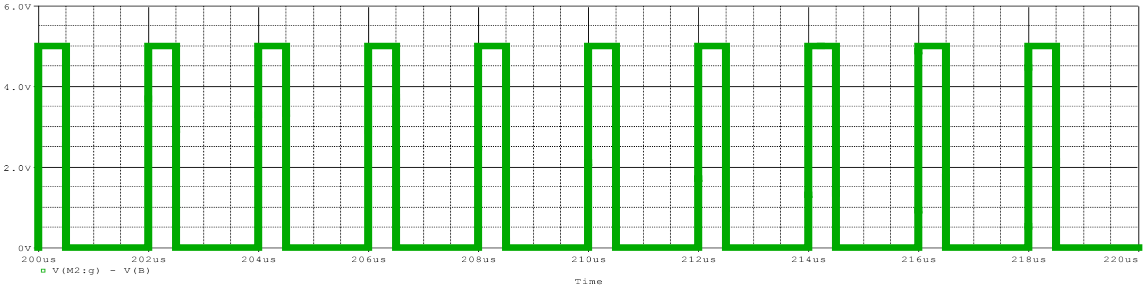


Fig: 5.5(c) Gate-to-Source Voltage at M2 (Buck mode Right-Left)

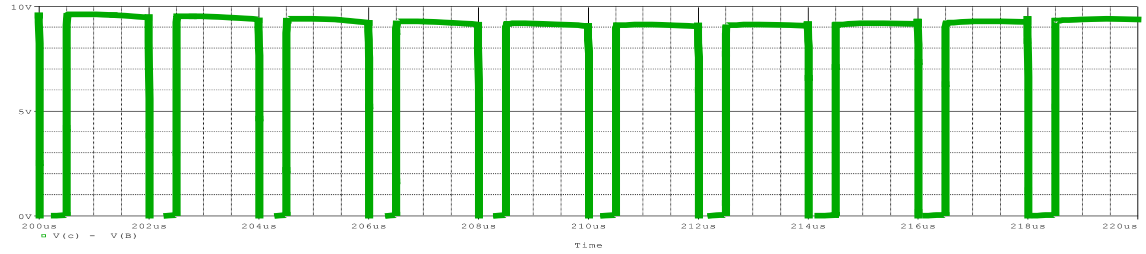


Fig: 5.5 (d) Drain-to-Source Voltage at M2 (Buck mode Right-Left)

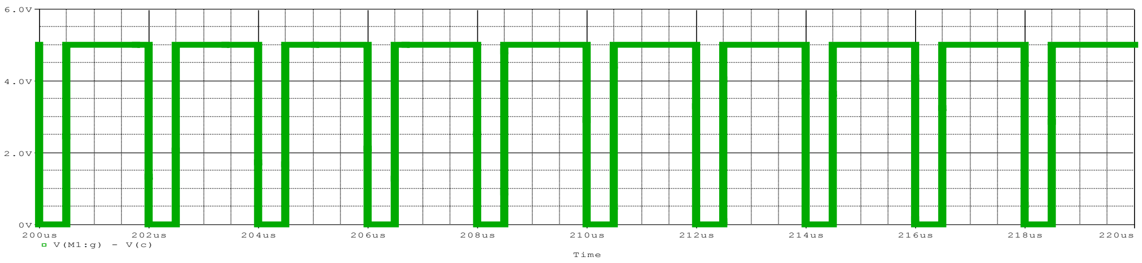


Fig: 5.5(e) Gate-to-Source Voltage at M1 (Buck mode Right-Left)

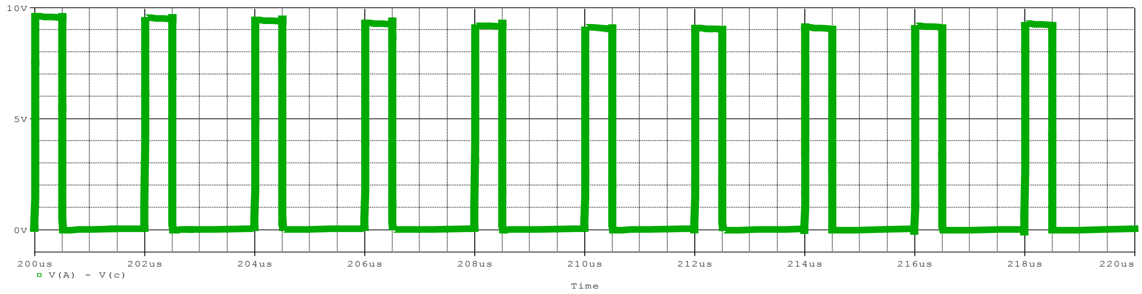


Fig: 5.5 (f) Drain-to-Source Voltage at M1 (Buck mode Right-Left)

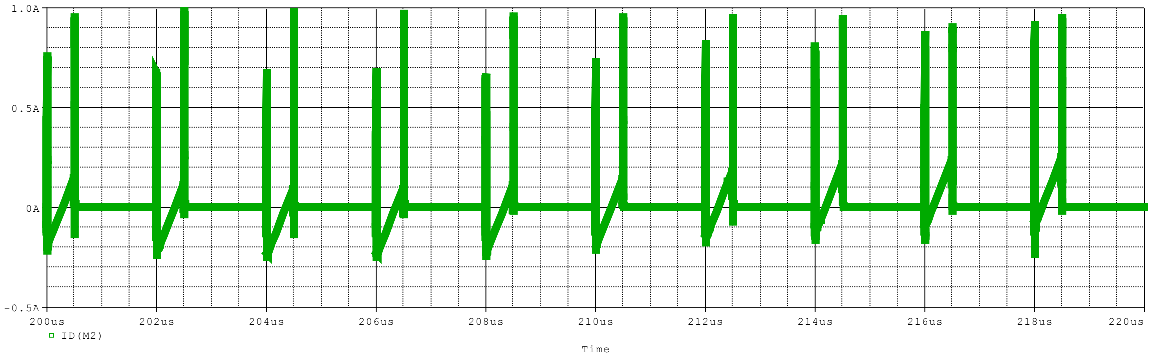


Fig: 5.5 (g) Drain Current of M2 (Buck mode Right-Left)

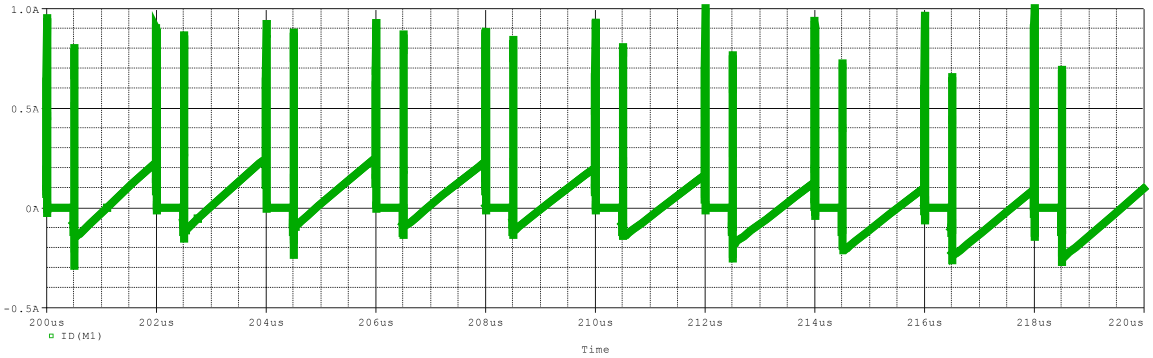


Fig: 5.5 (h) Drain Current of M1 (Buck mode Right-Left)

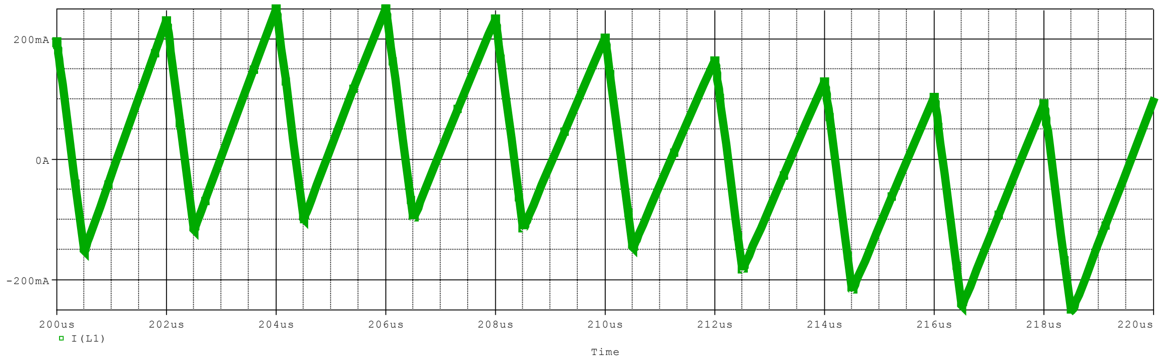


Fig: 5.5 (i) Inductor Current (Buck mode Right-Left)

For the Buck Operation from Right to left, we are applying inverted 7V at terminal B, which was the Load side earlier. And we are applying the Load Side at terminal A which used to be the Voltage Source side.

For Buck operation from Right-Left we are keeping switch M2 “ON” for 1.5µs, M1 “ON” for 0.5µs.

We are getting output voltage 2.2V at terminal A.

5.6 Step Input at right side and Load at left side with Boost Operation:

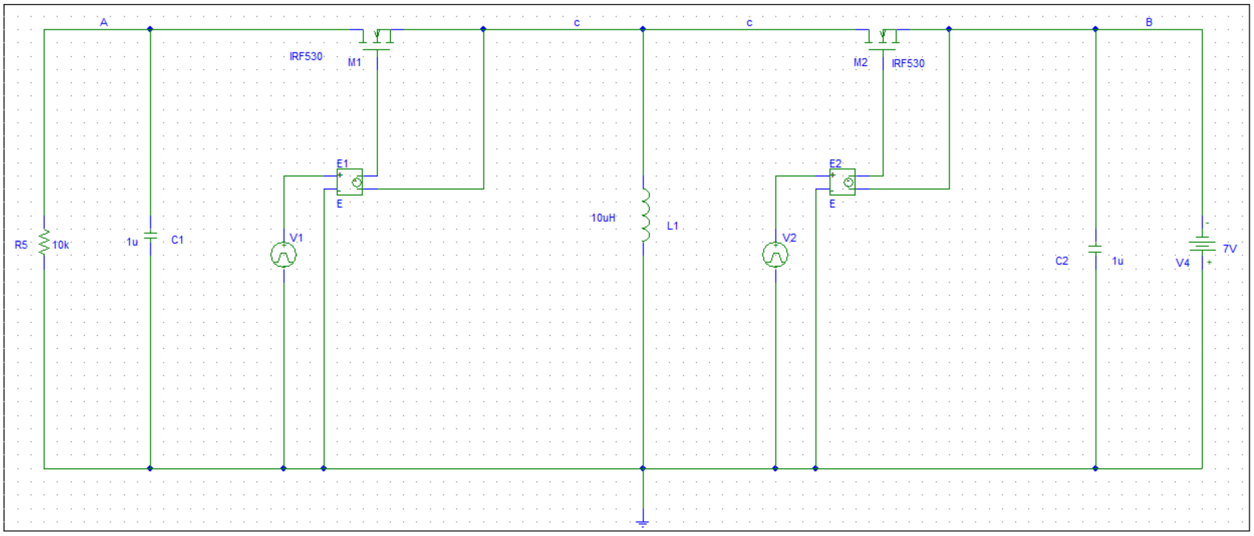


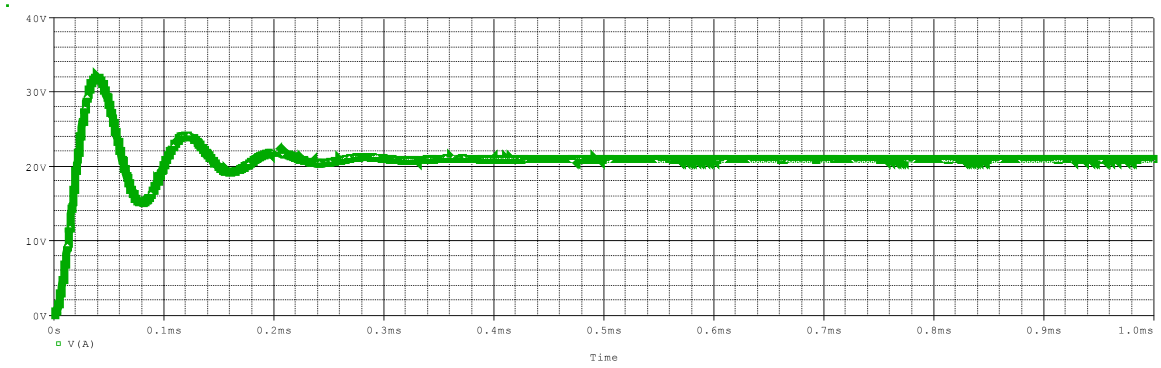
Fig: 5.6 Buck-Boost Operation (Right-Left)

For the Boost Operation from Right-Left we set Vpulses for the switches as follows.

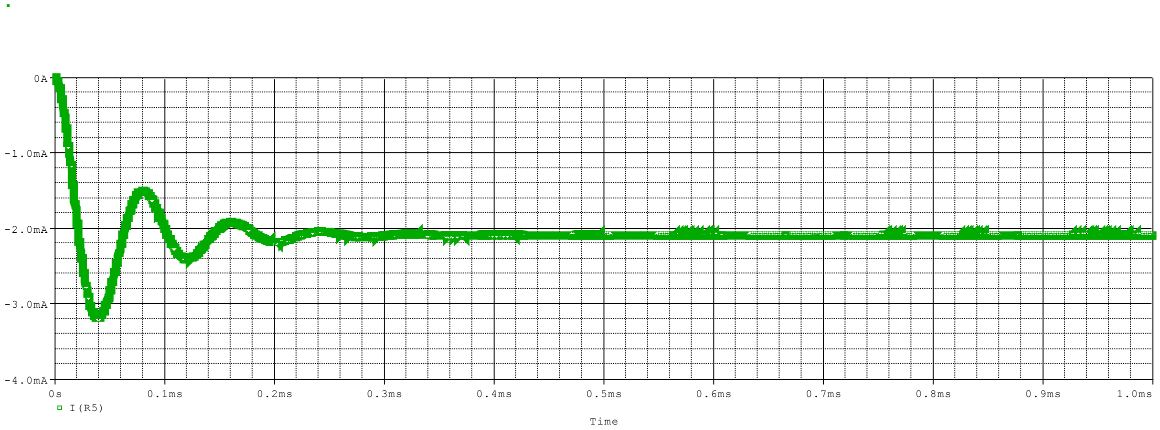
Switch M1	Switch M2
V1=0V V2=5V TD=1.5us TR=0.1ns TF=0.1ns PER=2us PW=0.5us	V1=0V V2=5V TD=0 TR=0.1ns TF=0.1ns PER=2us PW=1.5us

Table: 5.4 Right-Left Boost Switching Parameters

We obtain the following graphs.



Fig; 5.6 (a) Output Voltage at terminal A (Boost Operation Right-Left)



Fig; 5.6 (b) Current at terminal A (Boost Operation Right-Left)

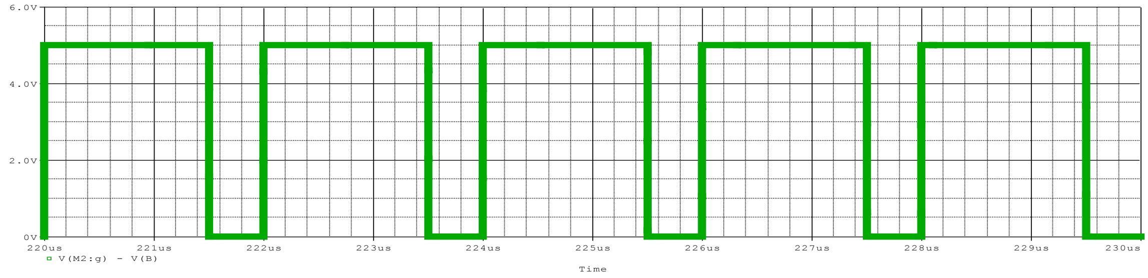


Fig: 5.6 (c) Gate-to-Source Voltage at M2 (Boost mode Right-Left)

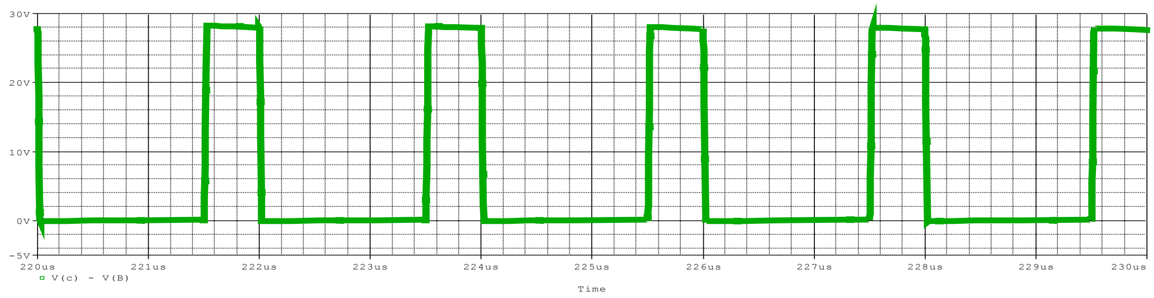


Fig: 5.6 (d) Drain-to-Source Voltage at M2 (Boost mode Right-Left)

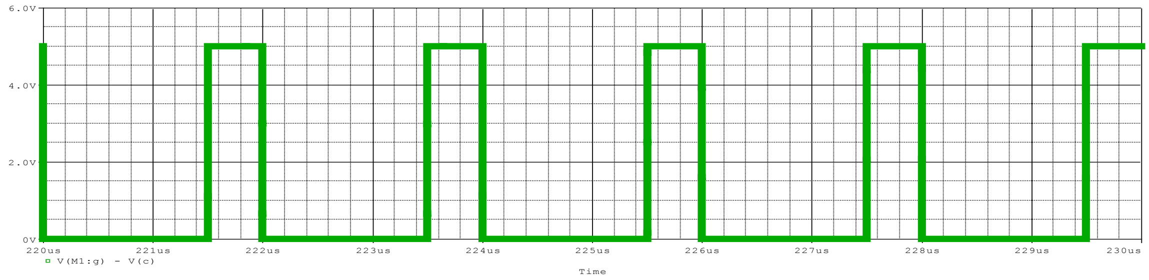


Fig: 5.6 (e) Gate-to-Source Voltage at M1 (Boost mode Right-Left)

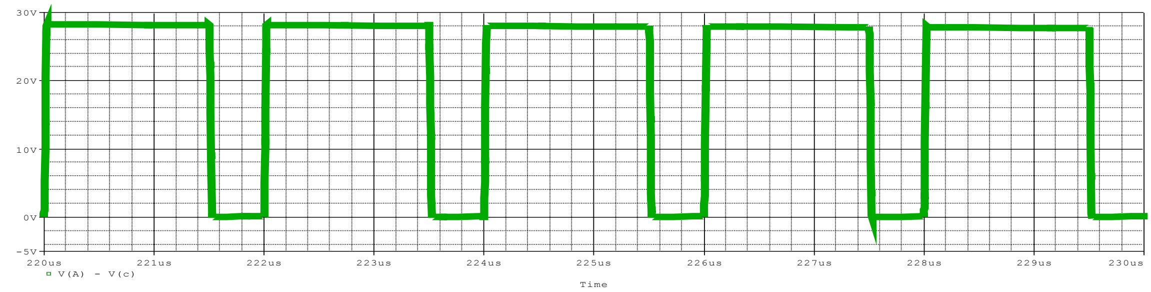


Fig: 5.6 (f) Drain-to-Source Voltage at M1 (Boost mode Right-Left)

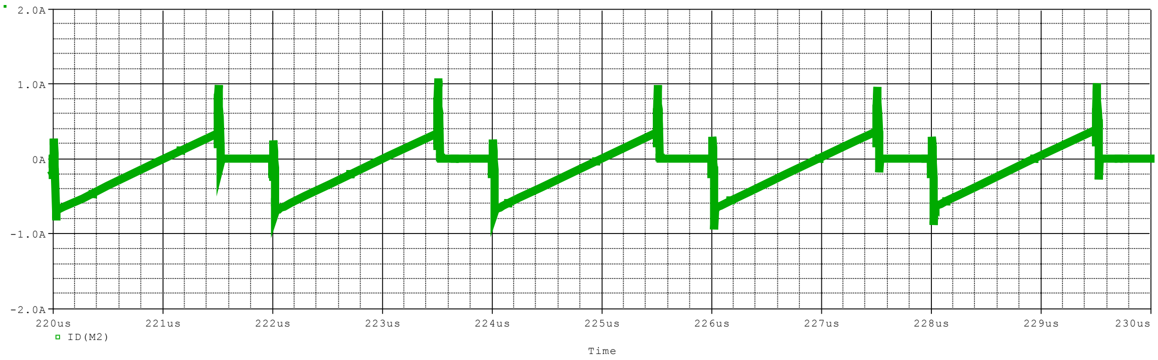


Fig: 5.6 (g) Drain Current of M2 (Boost mode Right-Left)

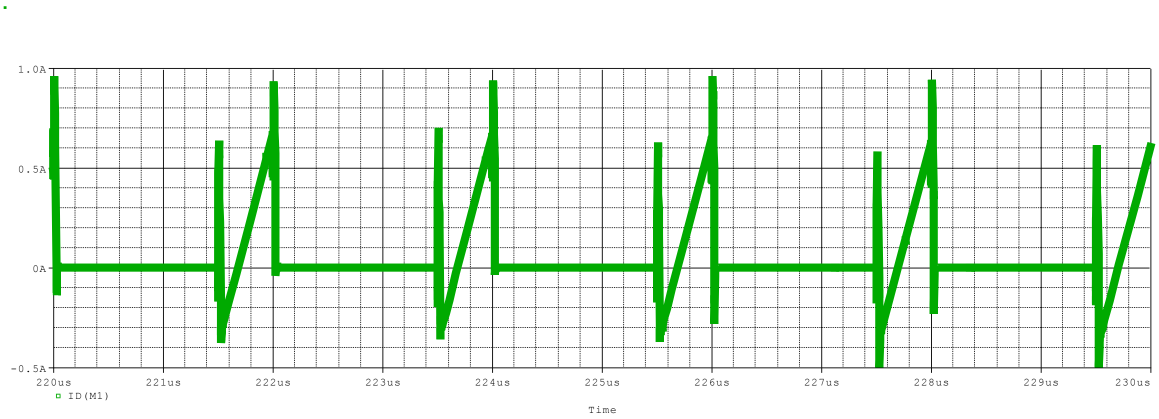


Fig: 5.6 (h) Drain Current of M1 (Boost mode Right-Left)

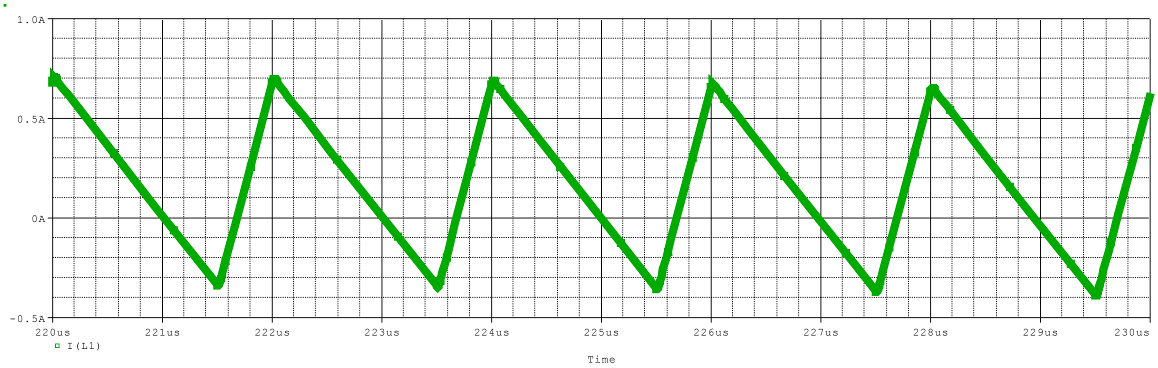


Fig: 5.6 (i) Inductor Current (Boost mode Right-Left)

For the Boost Operation we are getting 21V at Terminal A, since we had kept Switch M2 “ON” for 1.5µs, which is longer than it was kept “OFF” for 0.5µs.

From Left-Right we have shown Boosted Voltage 60V, and Bucked Voltage 6.5V when Input Voltage was 20V.

From Right-Left we have shown Bucked Voltage 2.2V and Boosted Voltage 21V when Input Voltage was 7V.

Thus, confirming the Buck-Boost Bidirectional Operation.

Chapter 6

Conclusion

In our thesis presentation, we have explained Distributive Energy Resources (DER) technologies which can play a very essential role in our day to day lives. DER technologies can provide us with power supplies during emergency situations. It can also enhance our power efficiency. By using DER technologies, we can also save money by consuming less electricity from the utility grid.

In our thesis, we have explained different types of DER technologies which are suitable for different situations and sectors. Then we have explained the converter topologies which are quite often used to create to different types of DER technologies interfaces.

Among these DER technologies interfaces, for our simulation, we have shown bidirectional DC-DC Buck-Boost converter which can increase and decrease power from both side of the terminals. These types of converters are mainly used in modern Hybrid Electric Vehicles and they have future possibilities by integrating it to Smart grid, Micro grids.

Chapter 7

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