Analysis of power converters and smart power factor correction

A thesis submitted to the department of electrical and Electronics Engineering , BRAC University

In partial fulfillment of the requirements for the Bachelor of Science degree in Electrical and

Electronics Engineering.

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Declaration

We do hereby declare that thesis titled "Analysis of power converters and smart power factor correction" is submitted to Department of Electrical and Electronics Engineering of BRAC University in partial fulfillment of Bachelor of Science in Electrical and Electronics Engineering. This is our original work and was not submitted anywhere else for award of any other degree or any other publication.

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Abstract

Converter circuits are one kind of power electronics circuit which allows us to convert direct current voltage from one level into another level. With this pace of development in power electronics field and industry, now we can now switch, convert power or eliminate higher harmonic unwanted component out of output energy with much improved power factor. Low power factor leads to low efficiency, increased line loss, heat issue in machine and high total harmonic distortion.

Therefore, it is essential to improve power factor and reduce line current harmonics for an efficient system. Also, power factor varies according to the load the source is connected to. With Smart Power Factor Correction unit, it is possible to get a constant output DC voltage in spite of variable load using Arduino, passive filter and pulse width modulation (PWM)

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Chapter 1

Introduction

1.1 Introduction:

At present time there is an increasing demand for efficient systems whenever we talk about power consumptions and so to keep up with these demands engineers have been coming forward developing efficient conversion techniques and also been able to design circuits with high efficiency. However, technology in this field is still improving with facing new challenges everyday

Applications of power electronics range in size from a switched mode power supply in an AC adapter, battery chargers, audio amplifiers, through variable frequency drives and DC motor drives used to operate pumps, fans, and manufacturing machinery, up to giga watt -scale high voltage direct current power transmission systems used interconnect electrical grids. Power electronic systems are found in virtually every electronic device.

Our thesis project is about designing a smart power factor correction circuit unit using buck and boost converters, and also design a controller whose purpose will be to control its efficiency by simply changing the duty cycle for a certain range of load.

1.2 Rectifier

A rectifier is an electrical device that converts alternating current, which periodically reverses direction, to direct current, which flows in only one direction. The procedure is known as rectification. Physically, rectifiers take various structures, including vacuum tube diodes, mercury-bend valves, copper and selenium oxide rectifiers, semiconductor diodes, silicon-controlled rectifiers and other silicon-based semiconductor switches. Rectifiers have numerous utilizations, yet are regularly discovered serving as components of DC power supplies and high-voltage direct current power transmission systems. Rectification may serve in roles other than to generate direct current for use as a source of power. As noted, locators of radio signs serve as rectifiers. In gas heating systems flame rectification is used to detect presence of a flame. As a result of the substituting way of the information AC sine wave, the process of rectification alone delivers a DC current that, however unidirectional, comprises of beats of current. Numerous uses of rectifiers, for example, power supplies for radio, television and computer equipment, require a consistent steady DC current. In these applications the output of the rectifier is smoothed by an electronic filter to deliver a consistent current. More complex circuitry that performs the opposite function, converting DC to AC, is called an inverter. Prior to the improvement of silicon semiconductor rectifiers, vacuum tube thermionic diodes and copper oxide-or selenium-based metal rectifier stacks were utilized. With the presentation of semiconductor hardware, vacuum tube rectifiers got to be out of date, aside from some enthusiasts of vacuum tube audio equipment. For power rectification from very low to very high current, semiconductor diodes of different sorts are generally utilized. Rectifier circuits might be single-stage or multi-stage. Most low power rectifiers for local hardware are single-phase, but three-phase rectification is essential for modern applications and for the transmission of energy as DC.

In half-wave rectification of a single-phase supply, either the positive or negative portion of the AC wave is passed, while the other half is blocked. Since one and only half of the input waveform reaches the output, mean voltage is lower. Half-wave rectification requires a single diode in a single-phase supply, or three in a three-phase supply. Rectifiers yield a unidirectional but pulsating direct current. Half-wave rectifiers produce significantly more ripple than full-wave rectifiers, and much more filtering is required to eliminate harmonics of the AC frequency from the output. A full wave rectifier accomplishes two peaks for each cycle, the best possible with a single-phase input. For three-phase inputs a three-phase bridge gives six peaks for each cycle. Higher quantities of peaks can be achieved by utilizing transformer networks placed before the rectifier to convert to a higher phase order. To further reduce ripple, a capacitor-input filter can be used. This complements the reservoir capacitor with a choke and a second filter capacitor, so that a steadier DC output can be obtained across the terminals of the filter capacitor. The choke presents high impedance to the ripple current.

1.3 Switching devices

Switching device is one of the important components in power electronics that needs to be taken in consideration before designing any circuit, assuming the power electronics devices behave as an ideal switch, but practically this is not true. Power devices can be classified in two groups:

Uncontrolled Switching Device–A diode is an example of this, whose state is completely dependent on the external power circuit they are connected to. An ideal diode has two states, ON state or forward biased state and OFF state or reverse biased state. When forward-biased, the voltage across the terminals remains zero, no matter what current flows through it. In reverse-biased state, the current flowing through remains zero for any given voltage. The transition between on and off states is instantaneous. Diodes are used in designing rectifiers, voltage clamper and voltage multiplier.

Controlled switching device– In this category, there are semi-controllable switches like thyristors, and fully-controllable switches like BJT, MOSFET, JFET, IGBT etc.

A thyristor has three-terminals, and is a device with four layers of semiconductor material. Thyristors operate in three states, Reverse blocking mode, forward blocking mode and Forward controlling mode.

In Reverse blocking mode, the voltage is applied in the direction that would be blocked by a diode, i.e reverse biased state. In Forward blocking mode, the Voltage is applied in the direction same as a diode having forward biased mode, but the trigger of thyristor into conduction is controlled. In Forward conducting mode, the thyristor has been triggered into conduction and will remain conducting until the forward current drops below a threshold value known as the "holding current”.

Thyristors are usually used in controlled AC-DC converters Static VAR controls and motor controls.There are different types of thyristors. SCR, GTO, MOS-controlled thyristor, Static induction thyristor, optically triggered thyristor are some of them. One of the disadvantages of thyristor is that once it has been latched into the On state, the device acts like a diode, and has to change it back to reverse bias mode to turn it off.

BJT- Bipolar Junction Transistor or BJT is a current-controlled switch that can be considered as two diodes with a shared anode. BJT has a base, collector and an emitter terminal and a base current is needed to be supplied to turn it On. However, now BJTs are being replaced by MOSFETs and IGBTs for better purpose and efficiency.

Metal-Oxide-Semiconductor Field Effect Transistor or a MOSFET is a device controlled by an electric field. A MOSFET has a gate, drain, and source terminal that have similarities to the base, collector, and emitter of BJT, with an additional fourth terminal called the body, base, or substrate. It is the fastest power switching device.

In this project an IGBT is used. Some of the advantages of IGBT over MOSFET and BJT are the IGBT has a high impedance gate, thus requires only a small amount of energy to switch the device and the IGBT has a small on-state voltage and it can also be designed to block negative voltage.

1.4 Classification of Rectifiers

Rectifier circuits are basically of two types depending on the alternating voltage they take as input. They are:

(a) Single phase rectifiers

(b) Poly-phase rectifiers (example: three phase rectifier)

Based on switching device used on the rectifier we can categorize rectifiers into two categories.

(a) Uncontrolled rectifiers

(b) Controlled rectifiers

Also, depending of functionality limitation of switching device we can consider half controlled rectifiers as a sub division also. Rectifiers may be classified in to two categories depending upon the period of conduction. They are:

(a) Half-waver rectifiers

(b) Full–wave rectifiers

Full wave rectifiers may further be classified in to two categories depending upon nature of the circuit connection. They are

(a) Centre tapped full-wave rectifier

(b) Bridge full-wave rectifier

In general, the focus more oriented from the approach of power electronics and semiconductor devices used on the circuit. In same configuration the efficiency varies a lost only by the use of different switching semiconductor devices.

Here, as semiconductor switching device diodes are used, which has only two states which are on state operating on forward bias and off state operating on reverse bias. It is not possible to connect external current or voltage to get more controlled switching, hence limiting functionality. The problem with this arrangement is low power efficiency and unavailability of options. Controlled reciter configuration offer much more versatile output. With advancements in semiconductor industry we can now control each and every aspect of output rating. Furthermore, we can activate or deactivate circuit by only via controlling current or voltage depending on the semiconductor switch type. This provides us with unparalleled functionality over output voltage. For this reason, in modern engineering this has more dominance over the regular diode controlled devices. In **Figure 1.1** the classification of rectifiers is organized in a sequential order. **Figure 1.2, 1.3, 1.4** are some commonly used rectifier using variable switching devices

1.5 Application of rectifiers

The rectifiers considered here have limited applications for the ordinary industrial and traction sectors. They therefore are mainly used as (i) mercury-arc convertors for wide-range grid control, and (ii) silicon rectifiers, e.g. SCR, for electrochemical service, for railway traction, and for nearly all other purposes. Rectifiers are now being increasingly used for field excitation of rotating machines; and improvements in variable-speed AC motors may be expected. It is also used in the construction of semiconductor-diode cells and the methods of over-current and over-voltage protection. Another very recent feature has been the combination of the transformer and rectifier as a single unit. Importance is given of the construction and characteristics of the SCR, and of the circuit considerations that arise in its use. The traditional power supplies, which is known as ‘linear’ power supplies use a mains frequency transformer to provide step-down voltages and galvanic isolation. These transformers are inefficient, in some cases wasting more power than they actually deliver to the load. Modern switched-mode AC and DC converters process energy at high frequencies, typically between 30 kHz and 100 kHz, resulting in a much smaller and more efficient solution than the traditional linear supply.

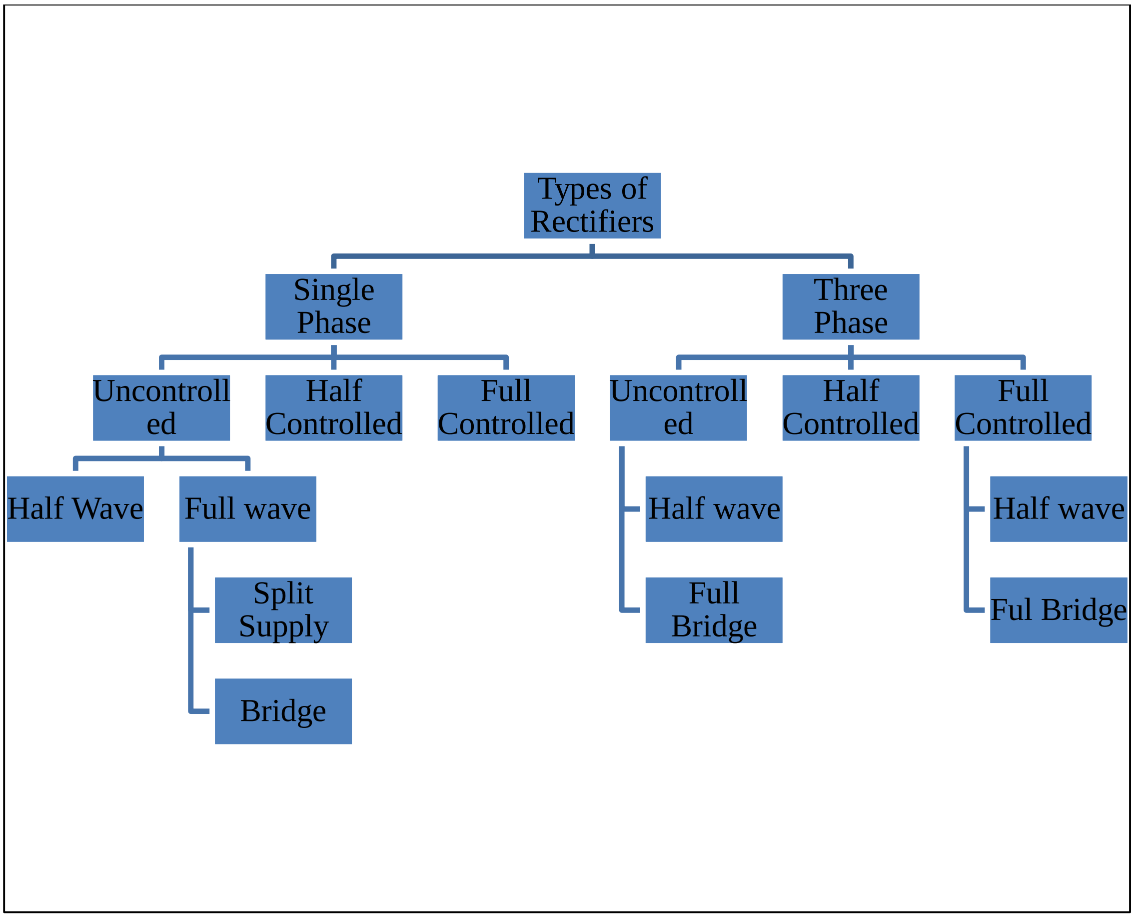


Figure.1.1 Rectifier Tree

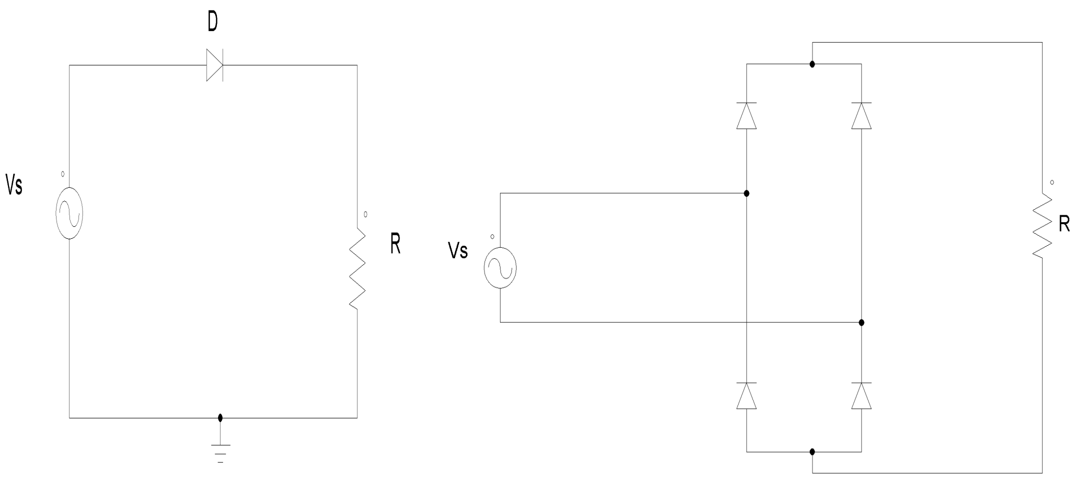


Figure 1.2 Uncontrolled Rectifiers

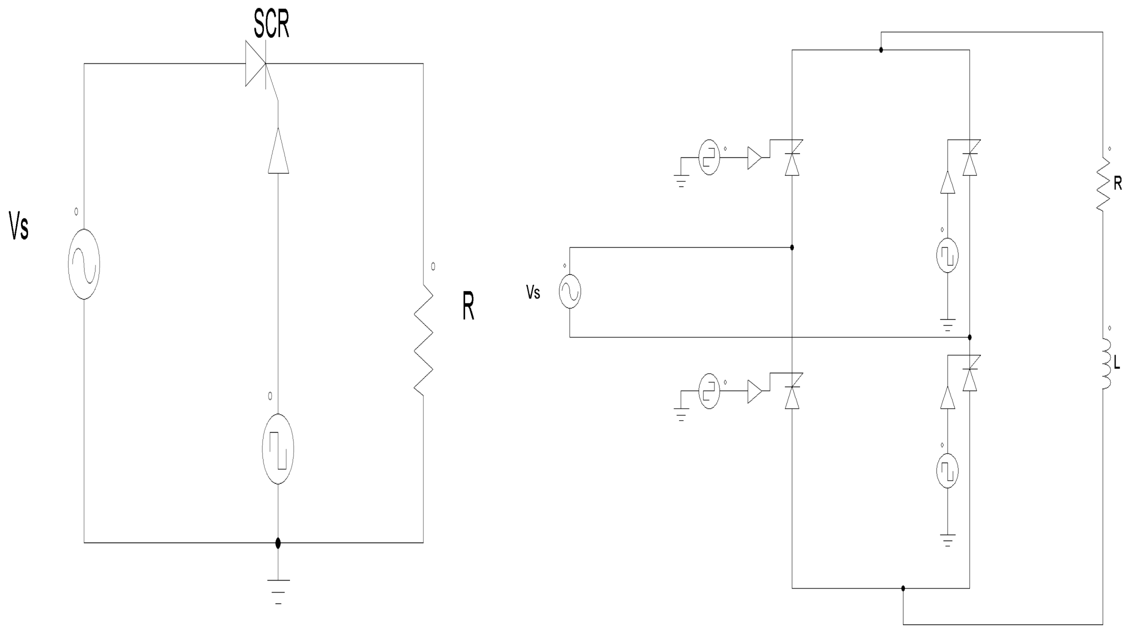


Figure 1.3 SCR Controlled Rectifiers [9]

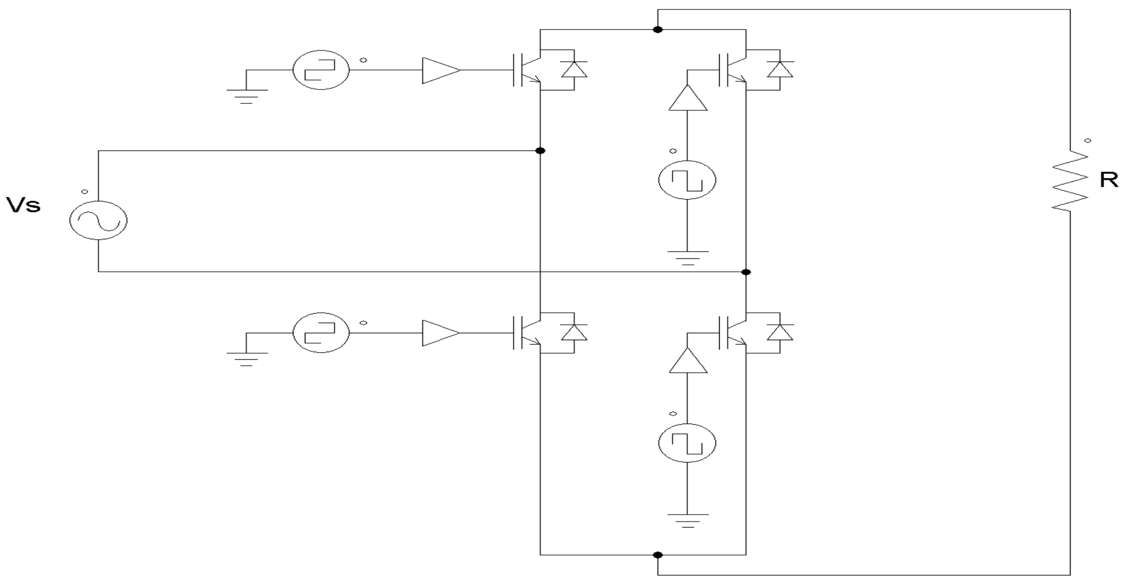
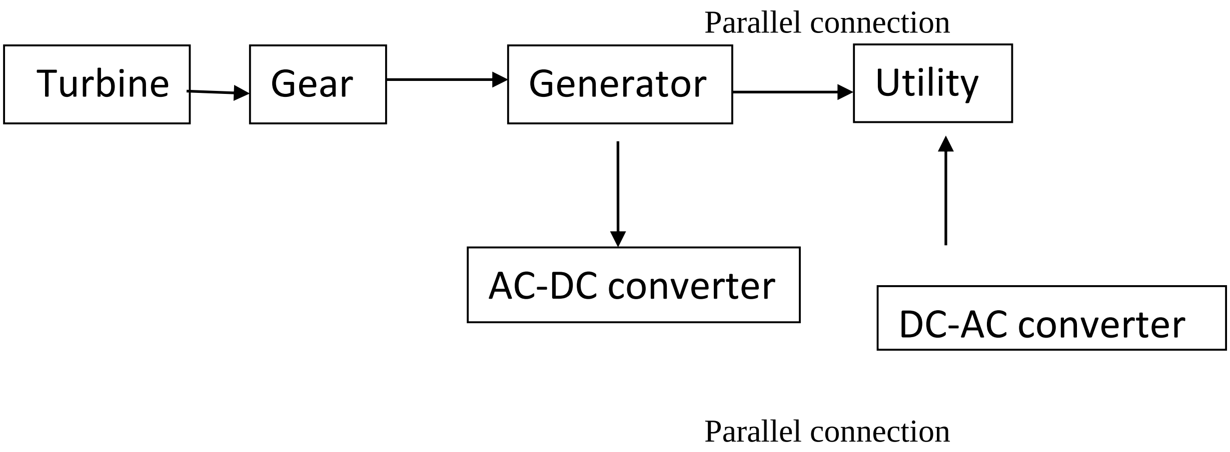


Figure 1.4 PWM Rectifiers

1.6 Application of converter

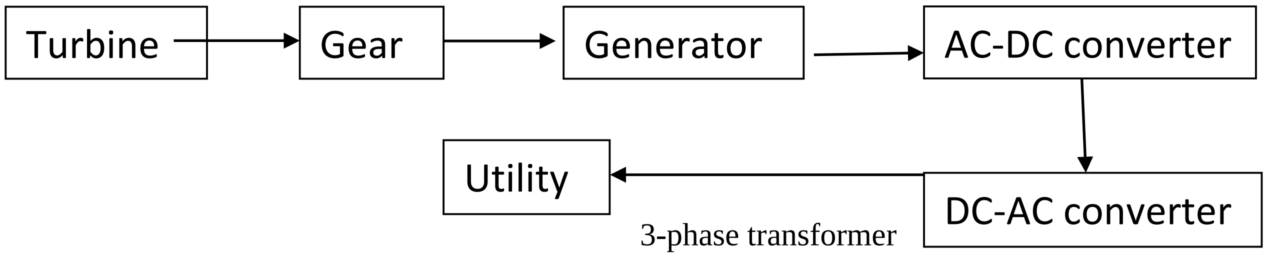
Induced generator turbine combination



In wind turbines, asynchronous 3 phase generator, i.e. induced generator is used because if the torque to the generator is increased (sudden blow of wind), the generator will produce electromagnetic force to resist an increase in speed. So, a blow of wind leads to large stresses on the wind turbines drive train. The wind turbine power generator system needs power converters for adjusting generator frequency and voltage to the grid. In diode rectifier based converter. a variable frequency and variable magnitude AC power from the wind turbine generator is firstly converted to a DC power by a diode rectifier circuit and then converted back to an AC power at different frequency and voltage level by a controlled inverter. The diode rectifier (uncontrolled rectifier) based converter system transfers power in a single direction e.g. from generator to the grid.

Externally excited generators are widely used for regenerative breaking of hoists driven by the three phase induction motors. Self-excited generators are used in the wind mills. Thus this type of generator helps in converting the unconventional sources of energy into electrical energy.

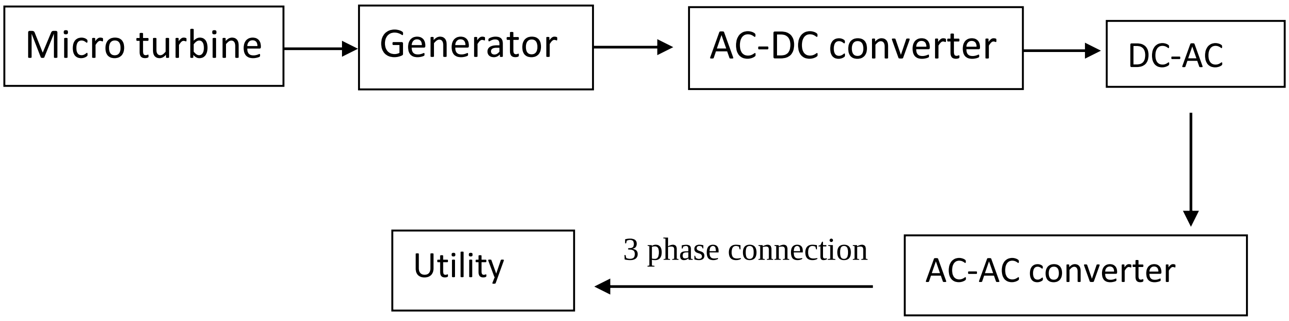
Synchronous generator turbine combination



Here, the generator is synchronized, so no parallel connection is needed, because the speed is regulated by the rotor itself. Only the converter is connected in a 3-phase to the utility to get maximum efficiency and so that we can get the required current and voltage.

The power for electrical system of modern vehicles produces from synchronous generator. Although the electrical system of motor vehicles generally requires direct current but still asynchronous generator along with diode rectifier instead of a DC generator is better choice as the complicated commutation is absent here. This special type of generator which is used in vehicle is known as automotive synchronous generator. Another use of synchronous generator is in diesel electric locomotive. Actually the engine of this locomotive is nothing but asynchronous generator driven by diesel engine. The alternating current produced by this generator is converted to DC by integrated silicon diode rectifiers to feed all the dc traction motors. And these dc traction motors drive the wheel of the locomotive. This machine is also used in marine similar to diesel electric locomotive. The synchronous generator used in marine is specially designed with appropriate adaptations to the salt-water environment. The typical output level of marine alternator is about 12 or 24 volt. In large marine, more than one units are used to provide large power. In this marine system the power produced by synchronous generator is first rectified then used for charging the engine starter battery and auxiliary supply battery of marine.

Micro turbine

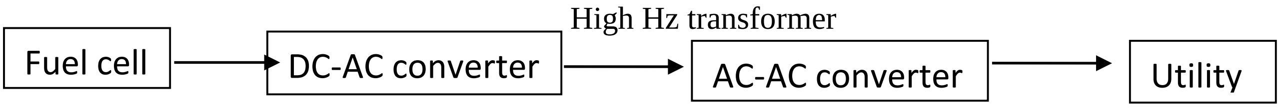


The highest efficiency operating speeds of micro turbines tend to be quite high. The speeds are generally variable over a wide range (i.e., from 50,000 rpm to 120,000 rpm) to handle varying loads while maintaining both high efficiency and optimum long-term reliability.
The micro turbine drives a high-frequency generator that may be either synchronous or asynchronous. The caged rotor design in asynchronous generators tends to make it a alternative to synchronous generators. High frequency voltage is generated. So converter is used to first stabilize it into direct current and then convert it back to AC voltage which is of line frequency, and connected in a 3-phase system to get maximum power output.

An increasing number of Oil & Gas companies are utilizing micro turbine technology in order to:

- Improve Reliability
- Get off the Grid
- Reduce Emissions
- Reduce cost of Maintenance
- become more efficient

Fuel cell



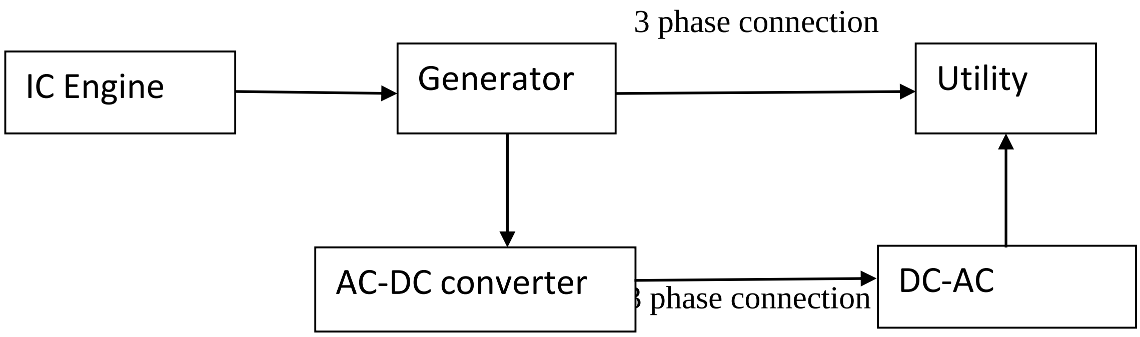
Fuel cells, however, are typically known to be slower than any other power sources due to the complex dynamics associated with mass and heat balances inside and outside the stack. To address these limitations, a PEM fuel cell system is typically combined with a battery or capacitor into a hybrid power generation system.

A complete PEM fuel cell power system includes several components apart from the fuel cell stack and battery, such as an air delivery system which supplies oxygen using a compressor or a blower, a hydrogen delivery system using pressurized gas storage or reformer, a thermal and water management system that handles temperature and humidity, converters to condition the output voltage and/or current of the stack and finally electric loads.

The DC-DC converter transforms unregulated DC power of the FC to regulated DC bus power. It is then converted to AC power and the frequency is shifted using High frequency transformer and stabilized by another AC-AC converter before sending it to the utility.

Portable power generation, stationary power generation, and power for transportation. We also include a category for fuel and infrastructure, relating to the production, distribution, storage and dispensing of fuels for fuel cells, as this is crucial to implementing fuel cell technology. Fuel cells have long been used in the space program to provide electricity and drinking water for the astronauts. Terrestrial applications can be classified into categories of portable, stationary, or transportation power uses.

IC Engine



In IC engine the utility requires AC current at a stable low frequency, so it is first converted to DC stable voltage and then converted again to AC current of lower frequency to be delivered at the utility.

IC Engines drive some of the large electric generators that power electrical grids. They are found in the form of combustion turbines in combined cycle power plants with a typical electrical output in the range of 100 MW to 1 GW. The high temperature exhaust is used to boil and superheat water to run a steam turbine. Thus, the efficiency is higher because more energy is extracted from the fuel than what could be extracted by the combustion turbine alone. In combined cycle power plants efficiencies in the range of 50 % to 60 % are typical. In a smaller scale Diesel generators are used for backup power and for providing electrical power to areas not connected to an electric grid. Aircraft typically uses an ICE which may be a reciprocating engine. Airplanes can instead use jet engines and helicopters can instead employ turbo shafts, both of which are types of turbines. In addition to providing propulsion, airliners employ a separate ICE as an auxiliary power unit.

1.7 Power Factor

For a linear system we know that power factor is the ratio between the real power(P) and the apparent power (S). It also indicates the cosine of the angle between voltage and current. From the **figure 1.5** power triangle, we can see that,

$$pf = \frac{P_{avg}}{S} = \frac{P_{avg}}{V_{rms} I_{rms}}$$

For the purely sinusoidal case,

$$pf_{true} = pf_{disp} = \frac{P_{avg}}{\sqrt{P^{2} + Q^{2}}} = \frac{\frac{V_1}{\sqrt{2}}\frac{I_1}{\sqrt{2}}\cos(\delta 1 - \theta 1)}{\frac{V_1}{\sqrt{2}}\frac{I_1}{\sqrt{2}}} = \cos(\delta 1 - \theta 1)$$

Again,

| P | = | S | Cos α, where α is the impedance angle.

$$\text{PF} = \frac{|\,P\,|}{|\,S\,|} = \frac{|\,P\,|}{|\,\text{Vrms}\,|\,|\,\text{Irms}\,|} = \cos\alpha$$

This cos α or cos(θ) is known as power factor (PF). Generally, it is represented is percentage value. Power factors are usually stated as "leading" or "lagging" to show the sign of the phase angle. Capacitive loads are leading (current leads voltage), and inductive loads are lagging (current lags voltage). Resistive load has a power factor 1 because its apparent and real power is same.

This is only applicable if only the system is linear. It means voltage or current in the system is sinusoidal and there is no amplitude found in higher harmonics. But, if the system is non-linear we can observe amplitude over various harmonics in frequency domain. As a result, the input current is no longer sinusoidal. If we take line frequency as the fundamental frequency, we can observe the gradually declining amplitude in higher harmonics. If the fundamental harmonics is set at fifty hertz, then the harmonics will go in a multiple of fifty hertz manner.

For this reason, the equation above is no longer valid in a nonlinear system and general capacitor compensation fails to solve the problem.

In non-linear system some to measure power factor firstly we need to know some terms as Displacement Factor(DF), Total Harmonic Distortion(THD), Distortion Power Factor (DPF) etc.

Let us consider current of a linear system is I_{rms} and current of a no-linear system is I_{nrms}.
So I_{nrms} will be root mean square of all the harmonics found the frequency domain. We know that the dot product of orthogonal set vector is zero. So beside fundamental frequency all other harmonics will be zero. That is why we only consider that amplitude in first harmonic which is I_{1rms}.
Displacement factor is the ration between the first harmonic current amplitude and the linear load amplitude.

$$DF = \frac{\mathrm{I1rms}}{\mathrm{Irms}}$$

Total harmonic distortion is the whole root square difference between linear and nonlinear current in ratio with the nonlinear current.

$$THD = \sqrt{(\frac{\mathrm{Irms}}{\mathrm{I1rms}})^2 - 1}$$

THD can also be expressed as a function of DF and the relation is,

$$DF = \sqrt{1/\ (1 + \mathrm{THD}^2}$$

From this equation we can observe that the lower the value of THD we can achieve, the lower the DF will get. Small THD indicates sinusoidal property of input current. So, Power factor can be written as

$$PF = \frac{(\mathrm{I1rms})(\cos(\theta))}{\mathrm{Irms}}$$

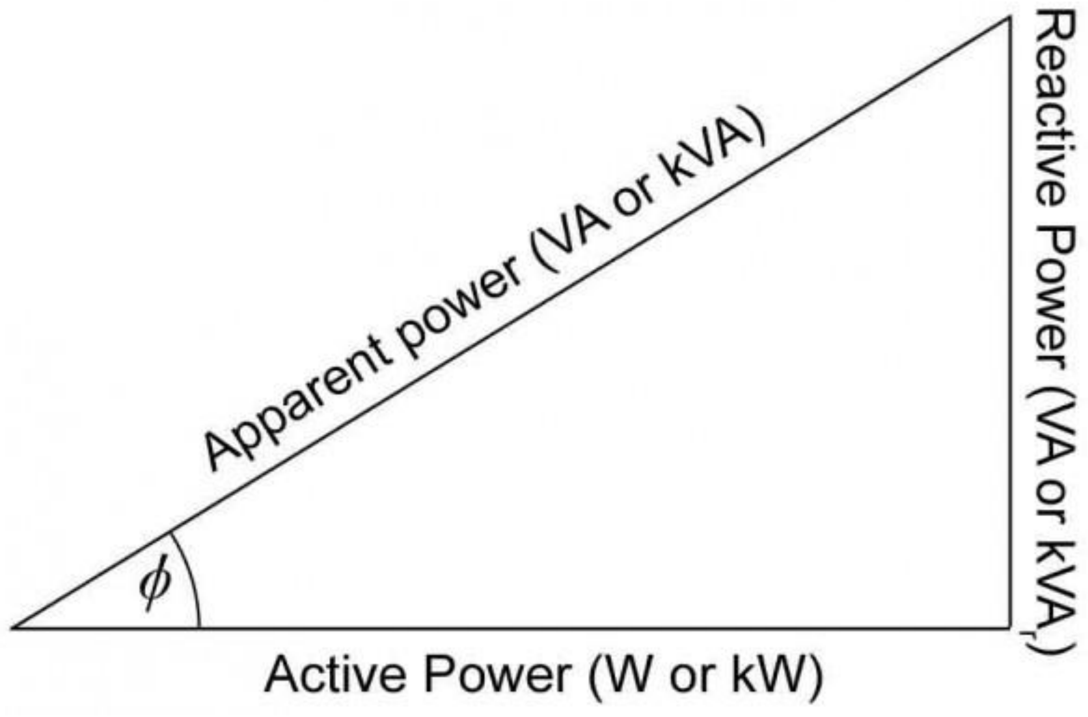


Figure 1.5 Power triangle

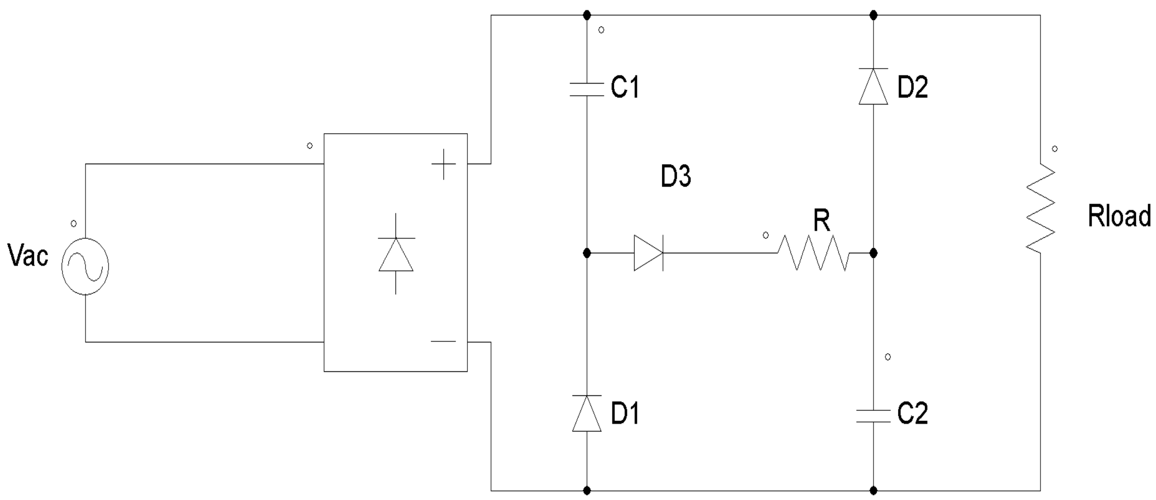


Figure 1.6 Valley-fill circuit

1.8 Power factor Correction

For linear system a capacitive bank or automated switching capacitive bank is enough to compensate the reactive power loss. But that is not the case. As we mentioned earlier, this cannot correct the low power factor in the output side. There are two possible ways to correct this possible. They are,

Passive Power Factor Correction:

By applying a modified filter constructed of capacitor, register and diode in the output side of the AC /DC converter we can correct some portion of the power factor. There are many filters used in this type of passive PFC. Among them, in **figure 1.6** Valley-fill circuit [4] is one of the most common one.

The problem we find that these passive power filter are unable to correct the power factor to a very noticeable amount. The output voltage can ripple voltage up to fifty present of the peak voltage. Furthermore, total harmonic distortion can be up to thirty-five present, which is very high. Also requires large capacitor to correct some portion of power factor [6].

Active Power Factor Correction:

Active power factor correction is an application of power electronics. Using high-speed switching device and DC/DC converter, active PFC changes waveform of the current used by the load. According to the output power rating buck, boost, buck-boost, cuk DC/DC converter is used to correct the power factor. With help of Switched-mode power supply(SMPS), it is possible to achieve power factor above ninety percent.

From the formula of power factor, we know,

$$PF = \frac{DPF}{\sqrt{1 + THD^2}}$$

Where DPF is the displacement power factor and THD is the total harmonic distortion. We can explain DPF as the fundamental harmonic of the current that has a delay angle θ (or φ), that is, DPF = cos θ. THD. All three-phase uncontrolled and con- trolled rectifiers have the input current fundamental harmonic delaying its corresponding voltage by an angle 30◦ plus α, where α is the firing angle of the controlled rectifier. Con-sequent, AC/DC rectifiers naturally have poor PFs. In order to maintain power quality, PFC is necessary. Implementing the PFC means

• Reducing the phase difference between the line voltage and current (DPF = >1).

• Shaping the line current to a sinusoidal waveform (THD = >0).

The first condition requires that the fundamental harmonic of the current has a delay angle θ = >0◦. The second condition requires that the harmonic components are as small as possible. In recent research, the following methods have been used to implement PFC:

1. DC/DC converter zed rectifiers.
2. Pulse-width modulation (PWM) boost-type rectifiers.
3. Tapped-transformer converters.
4. Single-stage PFC AC/DC converters.
5. VIENNA rectifiers.
6. Other methods.

1.9 Why Power Factor Correction using Boost Converter:

As we all know, the greatest challenge to in terms of engineering is minimizing the loss in any system. Previously, to minimize power loss capacitor bank and switches were used to compensate the reactive power loss. But, capacitive bank can cause overvoltage in load side and can cause resonance and amplifies capacitor switching transients. For these reasons in our opinion power factor correction using boost converter is a better solution for minimizing the loss.

Furthermore, boost converter has application on High Voltage Direct Current (**HVDC**) systems. From statistic we can see that for longer transmission HVDC is more cost effective solution. By studying DC/DC converters and power factor correction unit we will have a better understanding in reactive power compensation and power electronics. Also, we will be able to have a better knowledge in advance semiconductor switching devices such as Insulated Gate Bipolar Transistor **(IGBT)**, Silicon-Controlled Rectifier **(SCR)** and Metal Oxide Semiconductor Field Effect Transistor ***(MOSFET).***

1.10 Smart Power Factor Correction:

Our smart power factor correction system is a three step system. In the first step full bridge rectification will be applied to utility supply. So, the output of the rectifier will be in direct current form. Next, in the boost DC/DC converter power factor will be corrected. The voltage will be taken in an intermediate state. In our design we fixed the intermediate voltage to 400 volts. As a result, we will be able to notice a fall of THD. In third stage the voltage will be reduced to 100 volts constant. DC/DC buck circuit will be applied here. Using PWM, Arduino and numerical method we will set an upper and a lower limit of load that the system can sense and give constant output. Any other load can be handled by the system but the output can differ some volts.

1.11 Conclusion:

In this chapter we studied different types and applications of converter circuits and further we looked into different types of bridge rectifiers and analyzed every circuit using simulations, learned about power factor correction technique and total harmonic distortion.

Next, we will learn further more about the rectifiers we got introduced to.

Chapter 2

Circuit analysis

We have studied various types of rectifier circuits for our project. As the input of our converter circuit is coming from the grid so we have to rectify this ac sinusoidal to use in out converter circuit. It is very important to study and understand how the rectifier circuits works. We measured input current, input voltage and output voltage of these rectifier circuits to understand its work.

For the Half wave rectifier, we studied:

1. Half wave rectifier with resistive load
2. Half wave rectifier with RL load
3. Inductor source load
4. The Freewheeling diode
5. Half wave rectifier with capacitive load

For full wave we studied:

1. Full wave bridge rectifier
2. Full wave bridge rectifier with RC load
3. Full wave bridge rectifier with RL load

Circuit diagram and the corresponding wave shapes of input current, input voltage and output voltage of these circuits are given bellow.

2.1 Half wave rectifier with resistive load

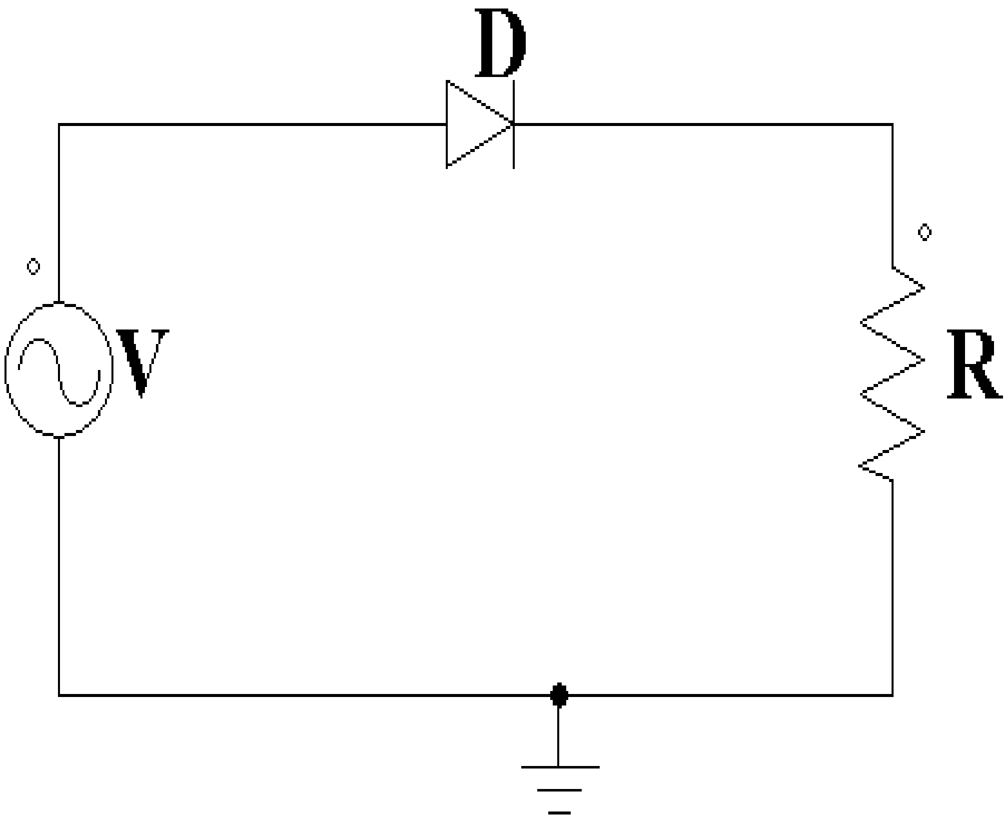


Figure 2.1: Circuit diagram of half wave rectifier with resistive load

Symbol	Value
V	220V, 50Hz
R	1KΩ
PF	1
THD%	0.99980307
Vo	155.55451 V

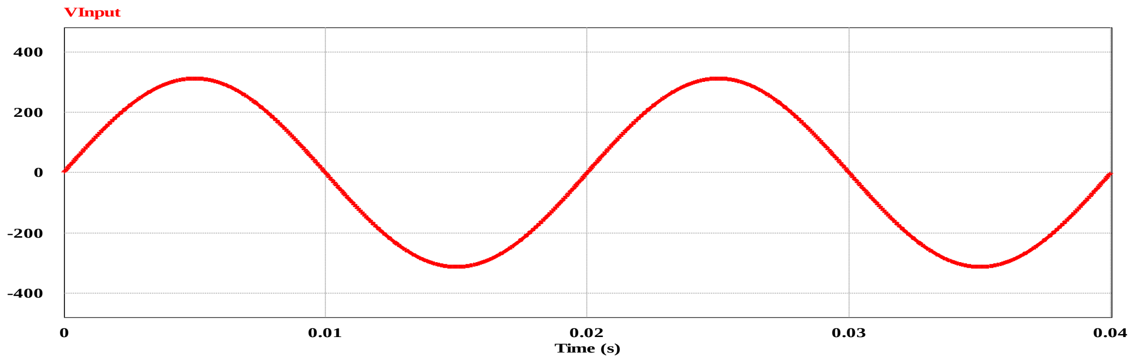


Figure 2.1(a): Wave shape of figure 2.1 input voltage

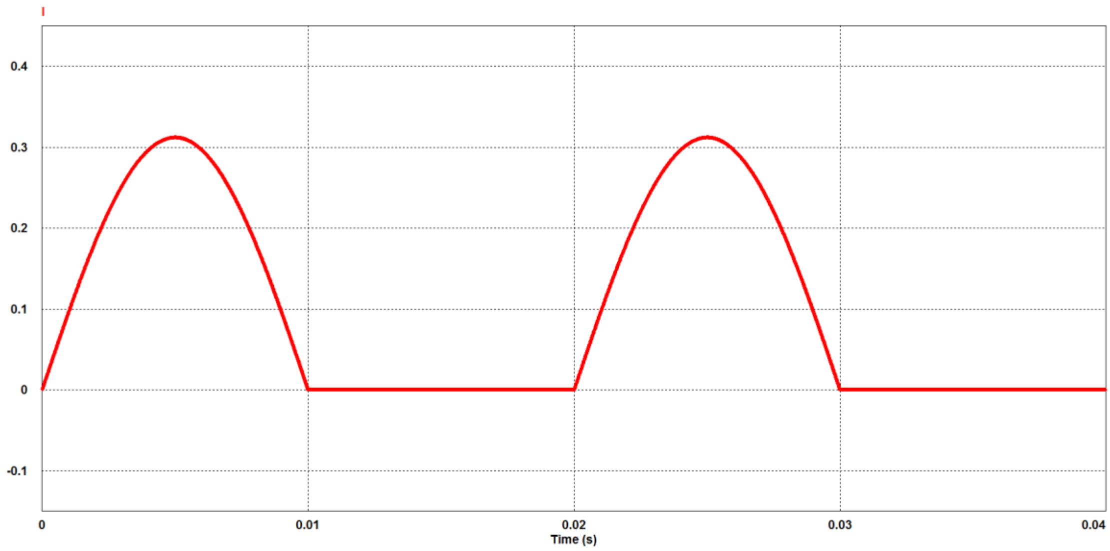


Figure 2.1(b): Wave shape of figure 2.1 input current

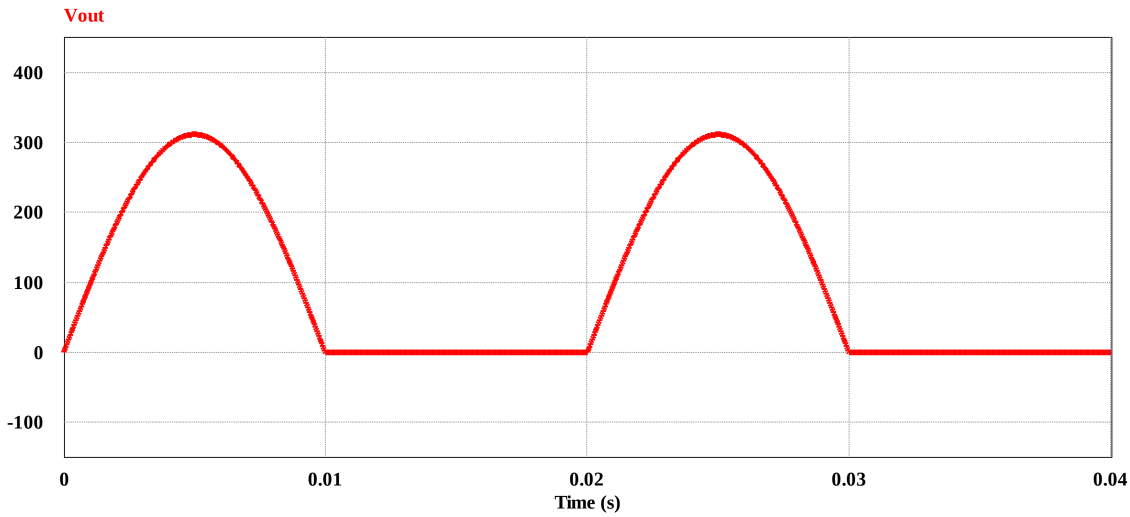


Figure 2.1(c): Wave shape of figure 2.1. Output voltage

2.2 Half wave rectifier with RL load

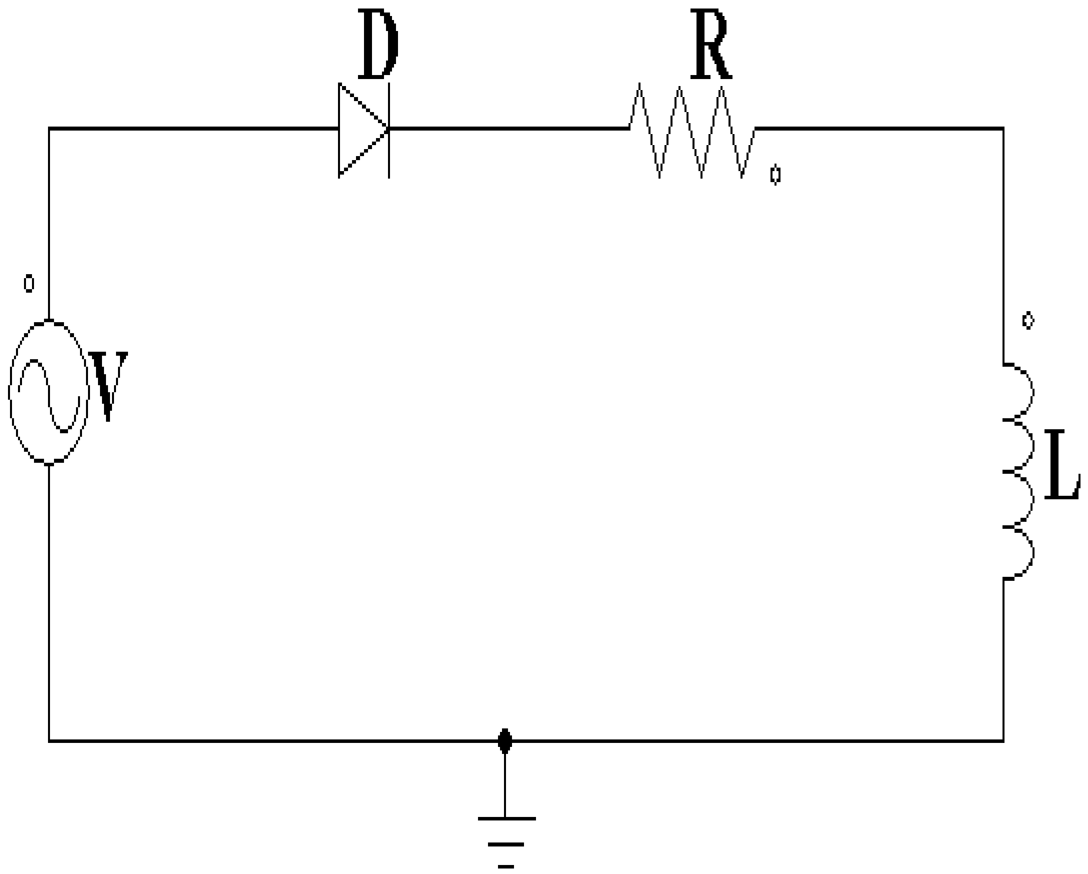


Figure 2.2: Circuit diagram of half wave rectifier with RL load

Symbol	Value
V	220V, 50Hz
R	1kΩ
L	0.01H
PF	1
THD%	99.980297
Vo	164.10661 V

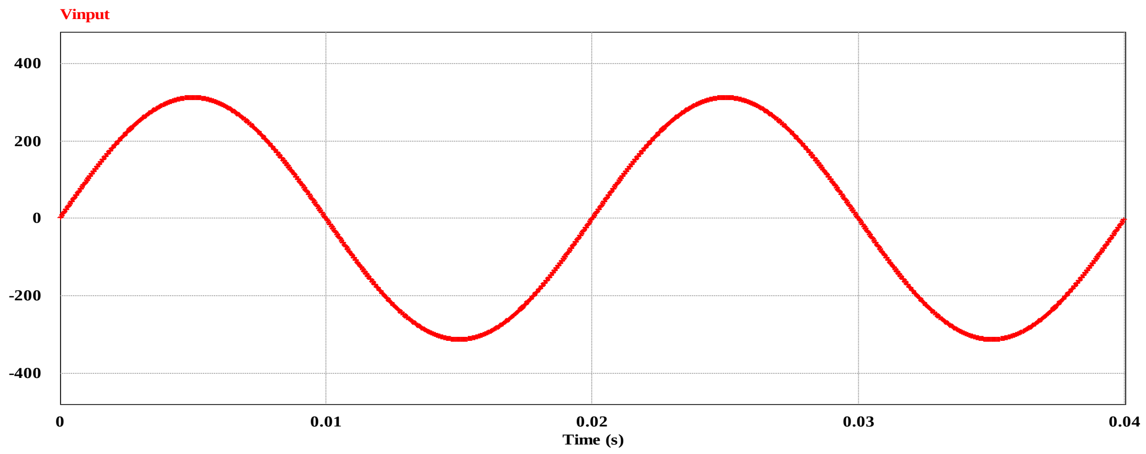


Figure 2.2(a): Wave shape of figure 2.1. Input voltage

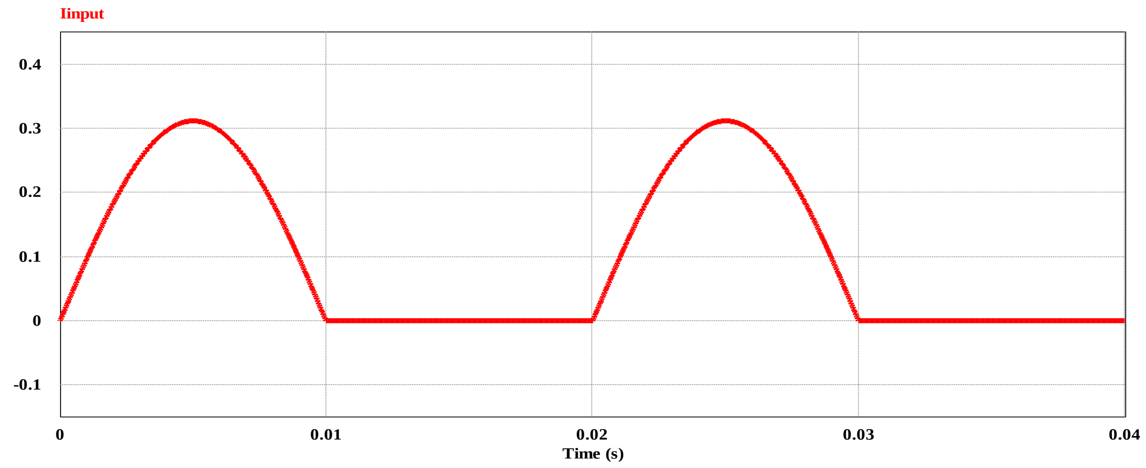


Figure 2.2(b): Wave shape of figure 2.2 Input current

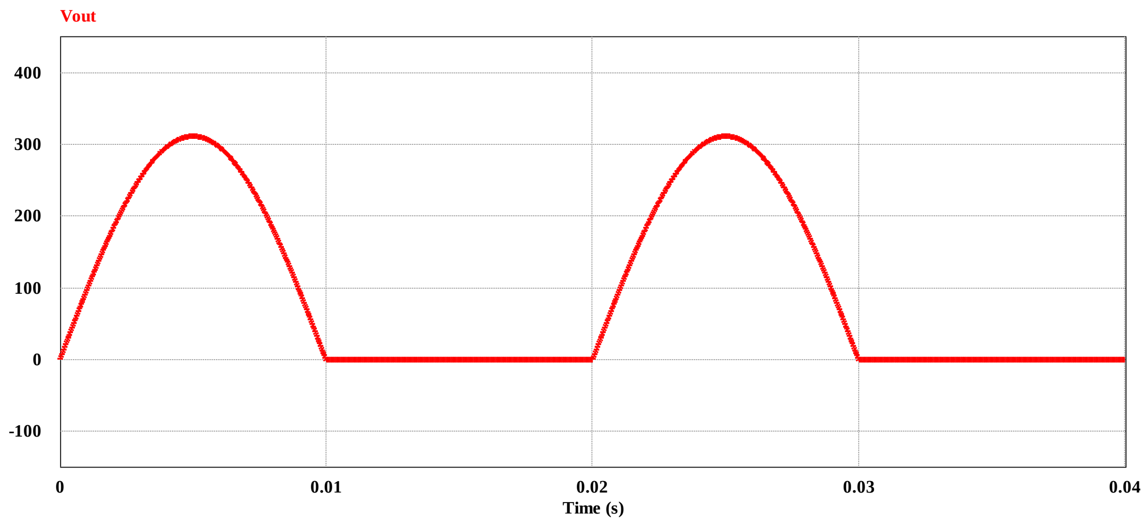


Figure 2.2(c): Wave shape of figure 2.2 Output voltage

2.3 Half wave rectifier with inductor source load

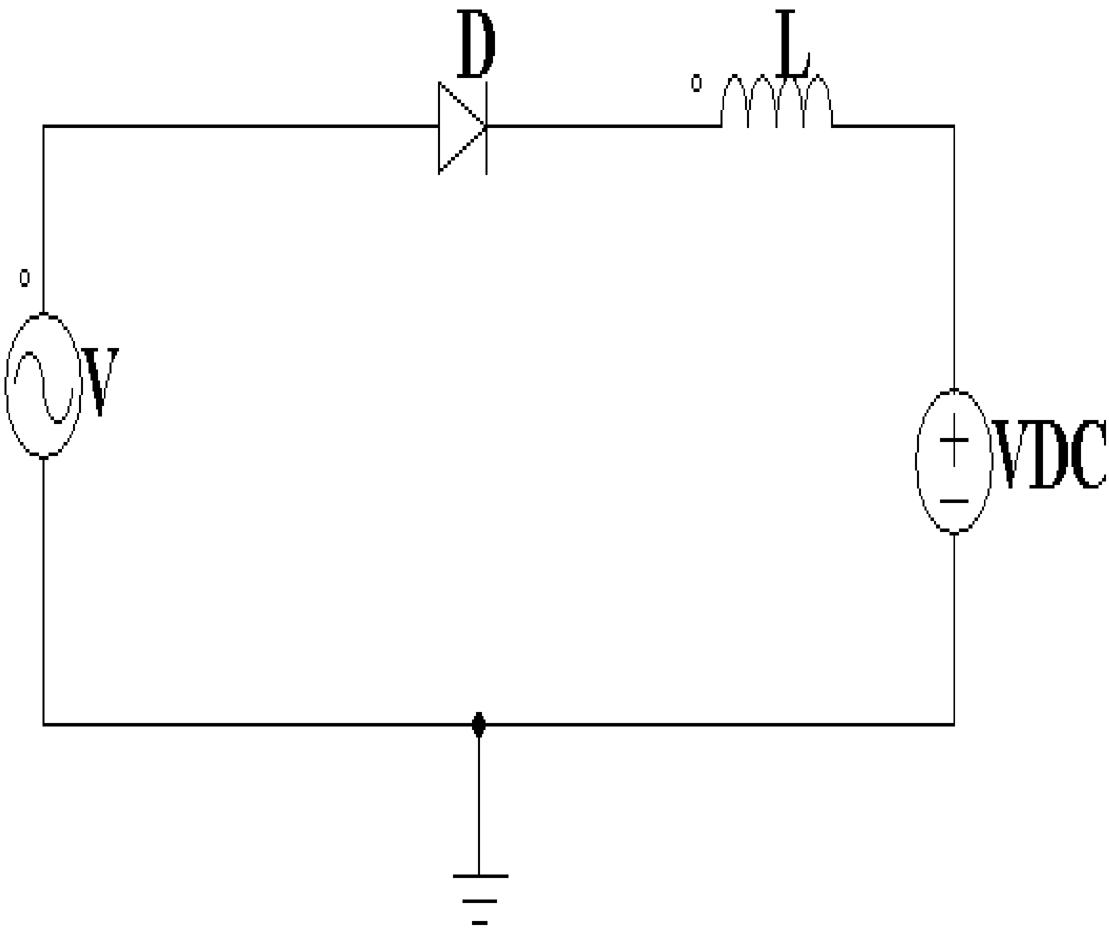


Figure 2.3: Circuit diagram of half wave rectifier with inductor source load

Symbol	Value
V	220V, 50Hz
L	20mH
PF	1
THD%	103.34701
Vo	185.7079 V

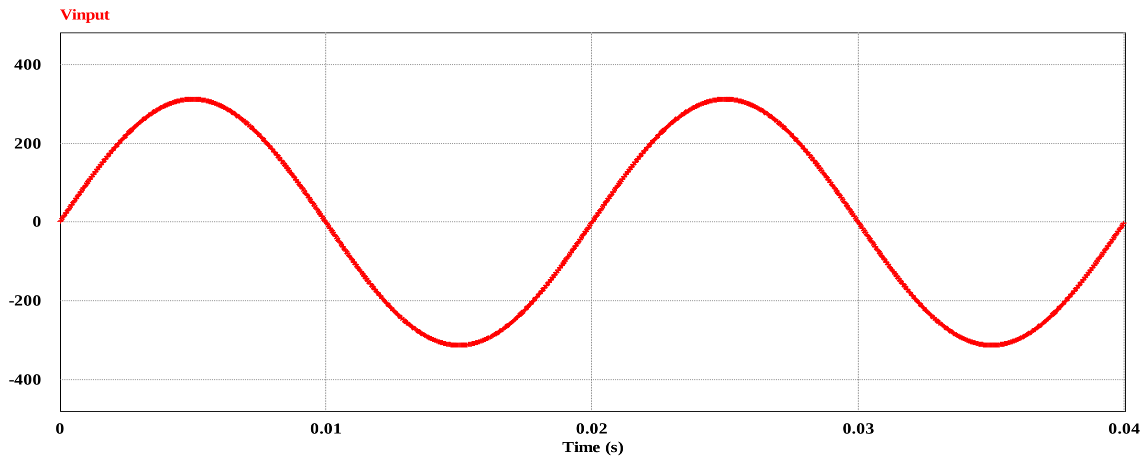


Figure 2.3(a): Wave Shape of 2.3 Input voltage.

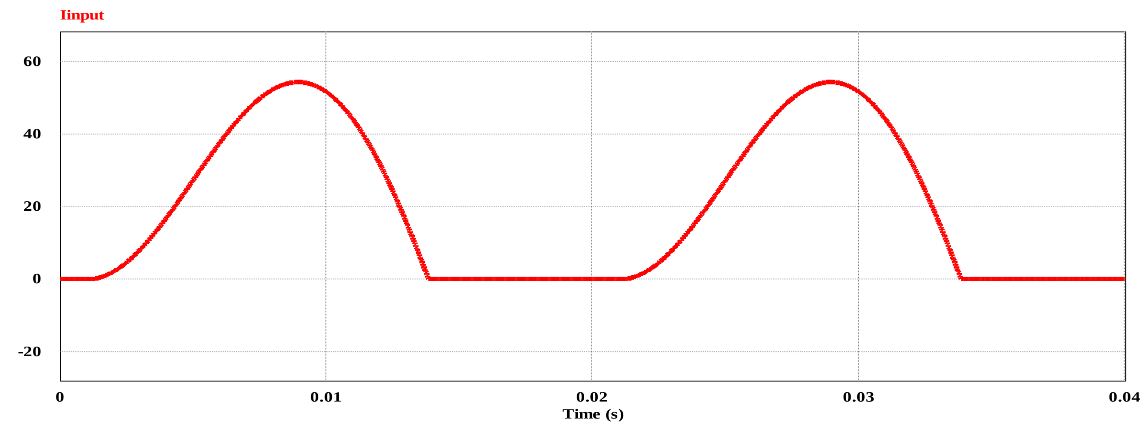


Figure 2.3(b): Wave Shape of 2.3 Input current.

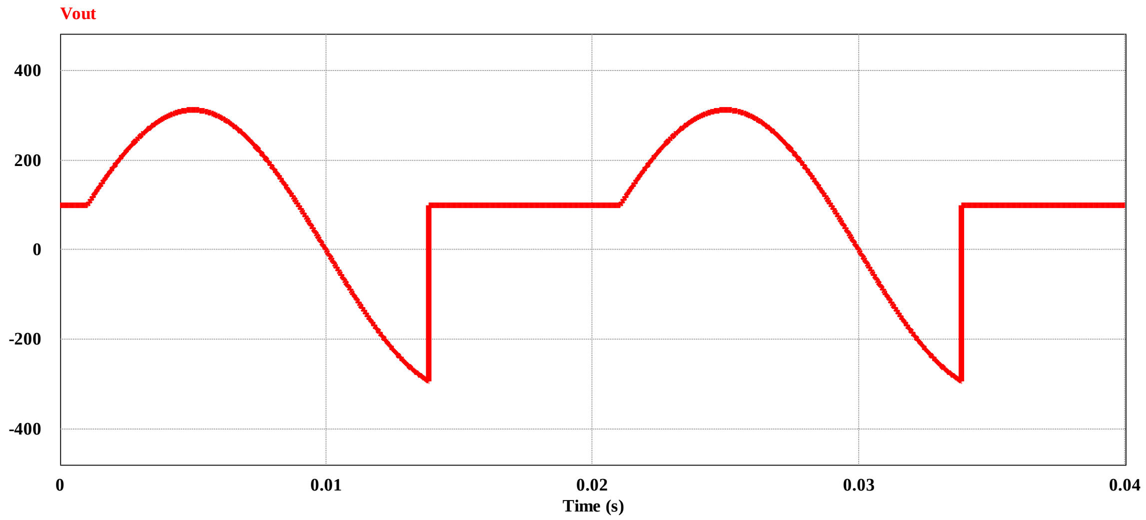


Figure 2.3 (c): Wave Shape of 2.3 Output voltage.

2.4 Freewheeling diode

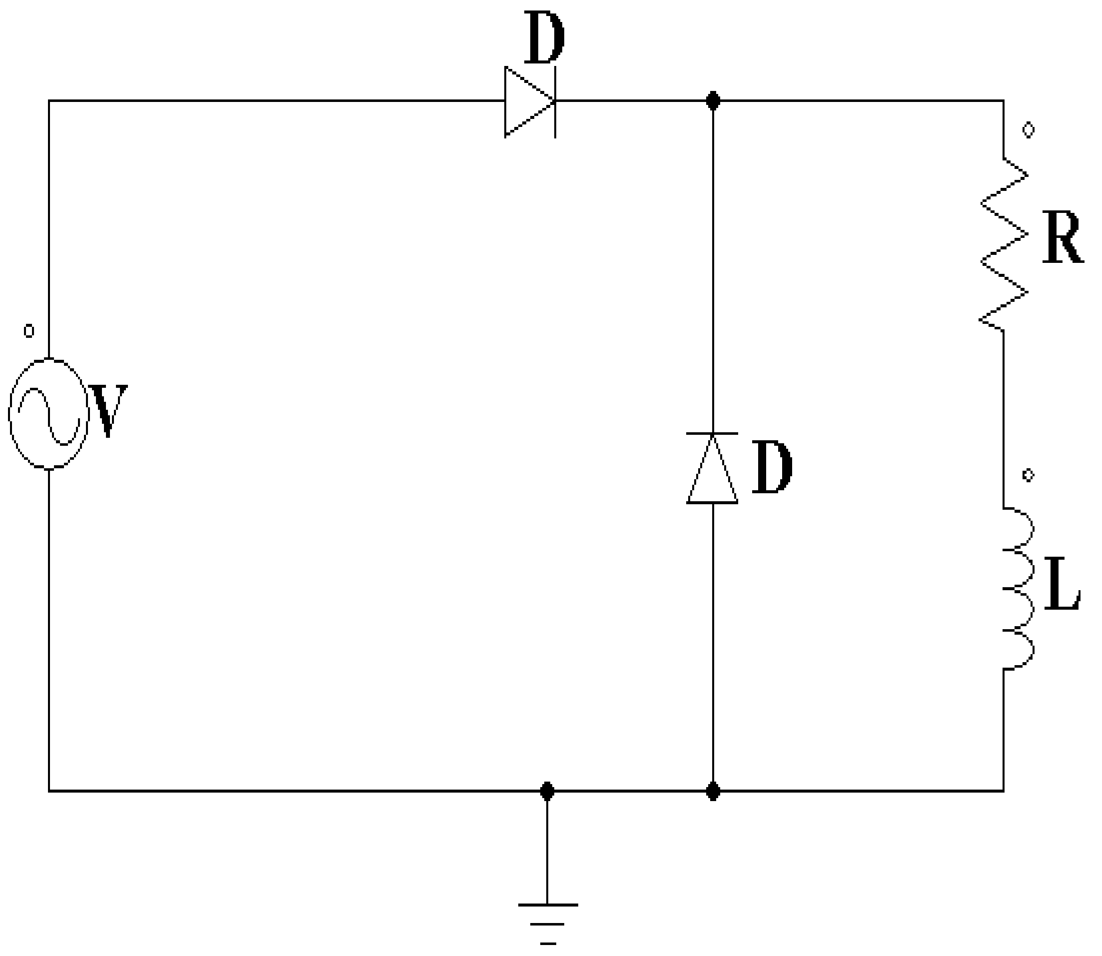


Figure 2.4: Circuit diagram of the freewheeling diode

Symbol	Value
V	220V, 50Hz
R	1KΩ
L	10μH
PF	1
THD%	99.980301
Vo	155.55451 V

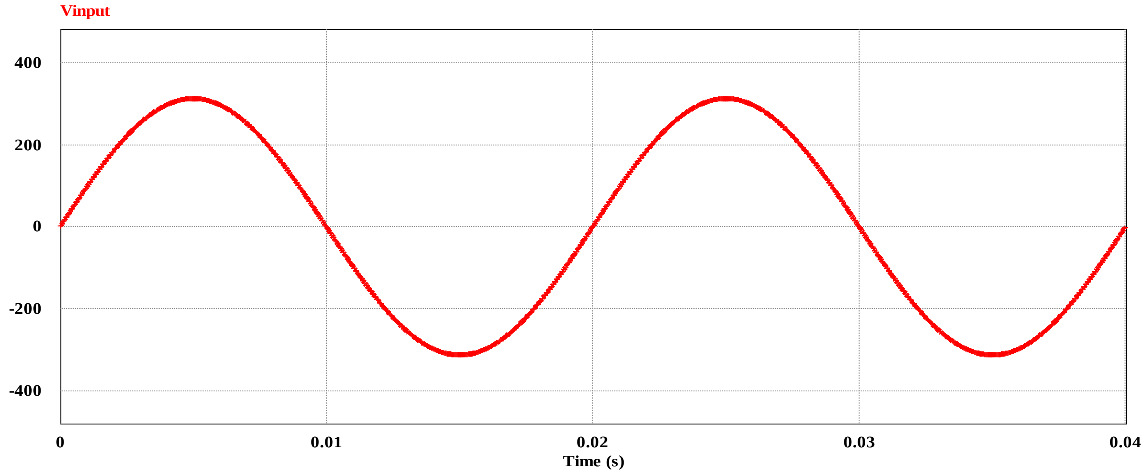


Figure 2.4 (a): Wave shape of figure 2.4. Input voltage

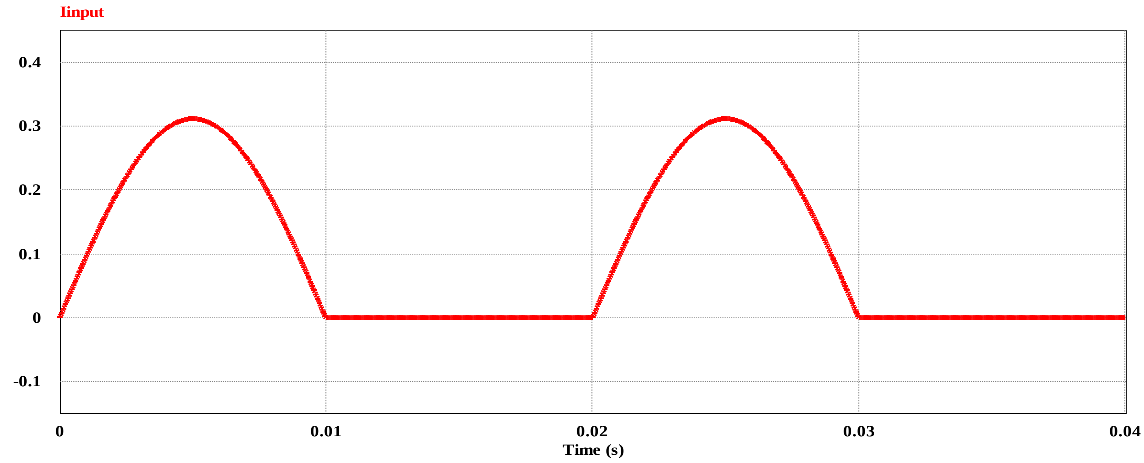


Figure 2.4 (b): Wave shape of figure 2.4 Input current

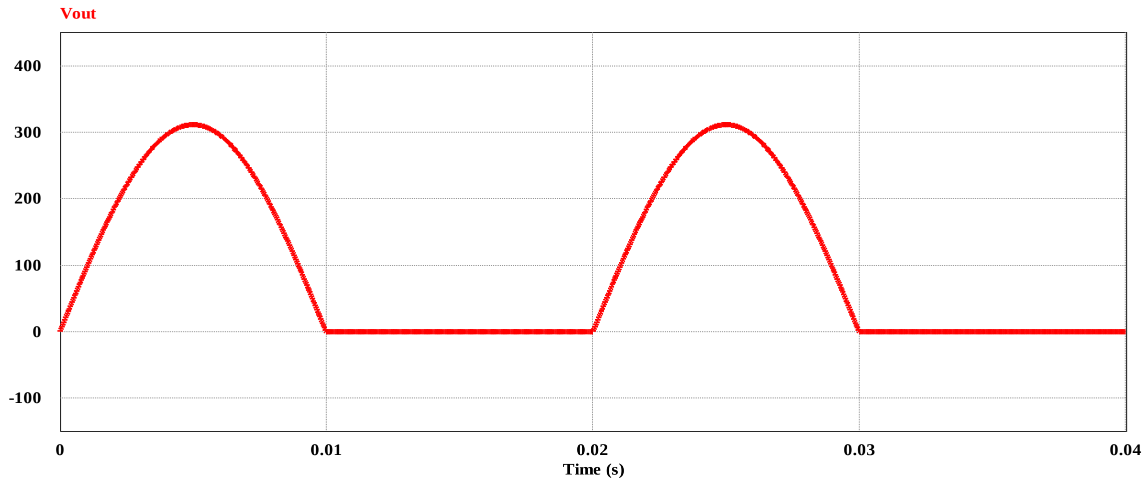


Figure 2.4 (c): Wave shape of figure 2.4 Output voltage

2.5 Half wave rectifier with RC load

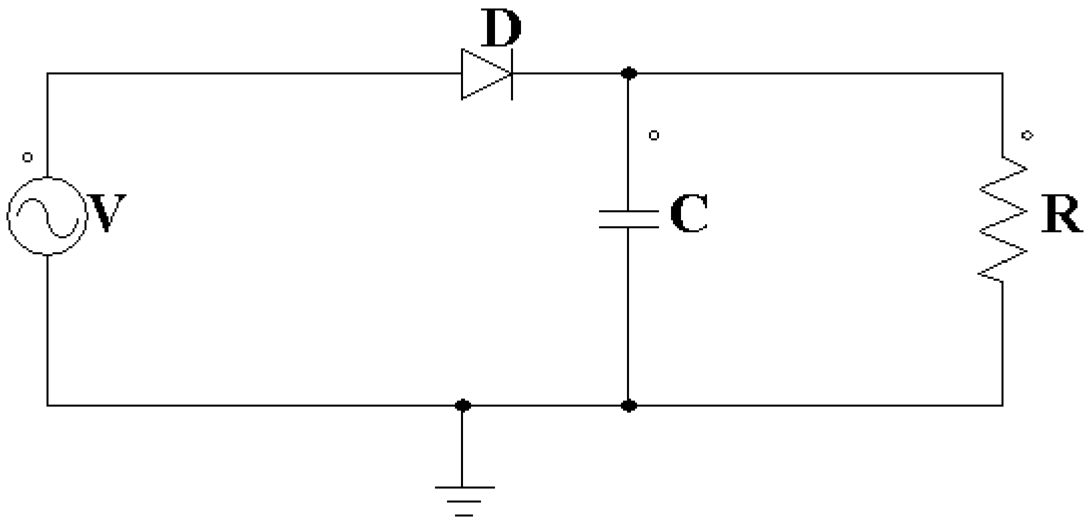


Figure 2.5: Circuit diagram of half wave rectifier with capacitive load.

Symbol	Value
V	220V, 50Hz
R	1kΩ
C	47µF
PF	0.31233126
THD%	197.09646
Vo	263.81024 V

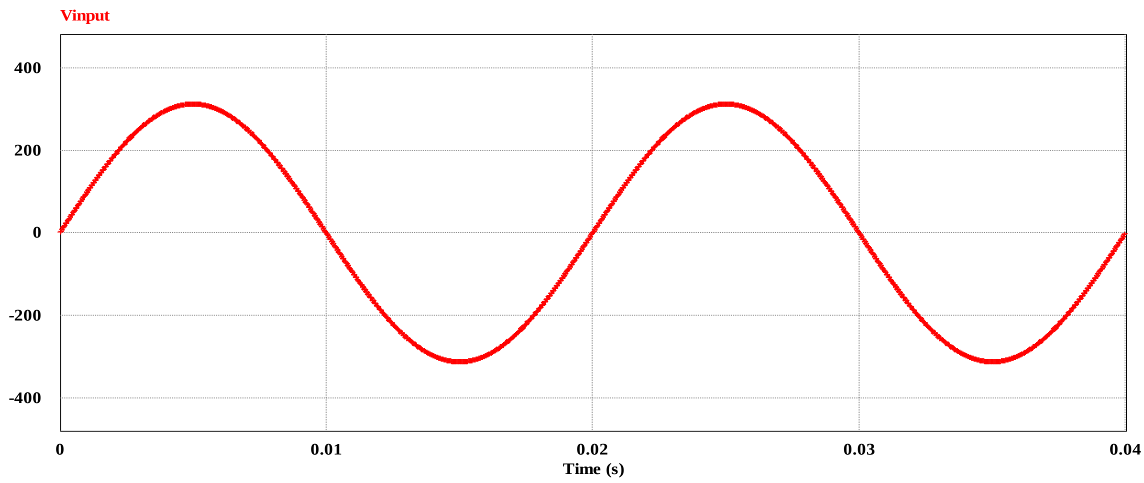


Figure 2.5 (a): Wave shape of figure 5.1. Input voltage.

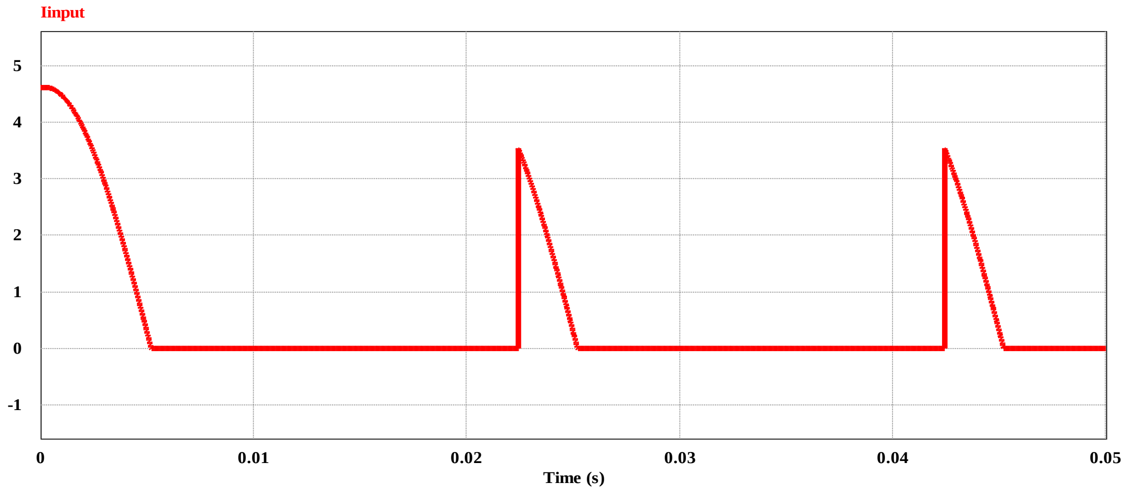


Figure 2.5 (b): Wave shape of figure 5.1. Input current.

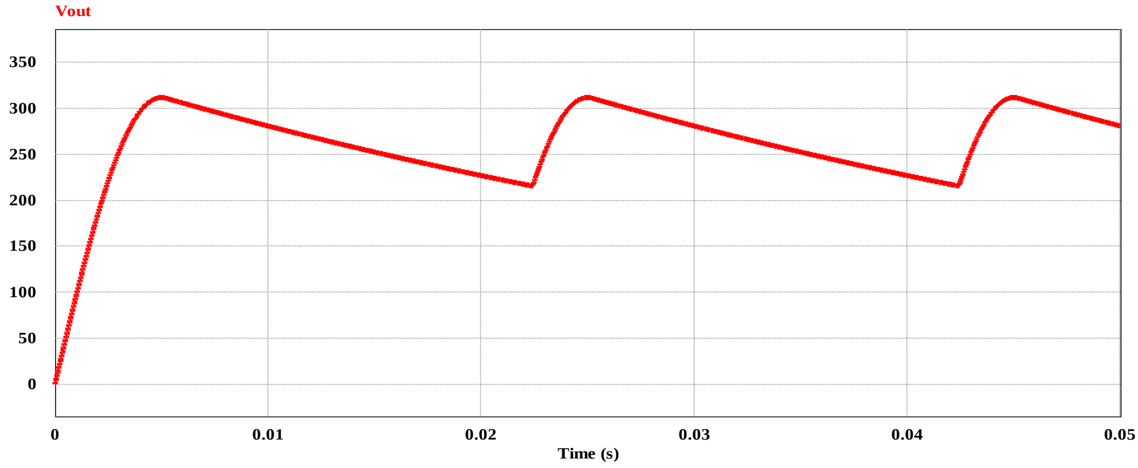


Figure 2.5 (c): Wave shape of figure 2.5 Output voltage

2.6 Comparison between half wave rectifiers

	Symbol	Value
Half wave rectifier with resistive load	V	220V, 50Hz
	R	1KΩ
	PF	1
	THD%	0.99980307
	Vo	155.55451 V
Half wave rectifier with RL load	Symbol	Value
	V	220V, 50Hz
	R	1kΩ
	L	0.01H
	PF	1
	THD%	99.980297
	Vo	164.10661 V
Inductor source load	Symbol	Value
	V	220V, 50Hz
	L	20mH
	PF	1
	THD%	103.34701
	Vo	185.7079 V
The Freewheeling diode	Symbol	Value
	V	220V, 50Hz
	R	1KΩ
	L	10μH
	PF	1
	THD%	99.980301
	Vo	155.55451 V

Half wave rectifier with capacitive load	Symbol	Value
	V	220V, 50Hz
	R	1kΩ
	C	47μF
	PF	0.31233126
	THD%	197.09646
	Vo	263.81024 V

2.7 Full wave bridge rectifier

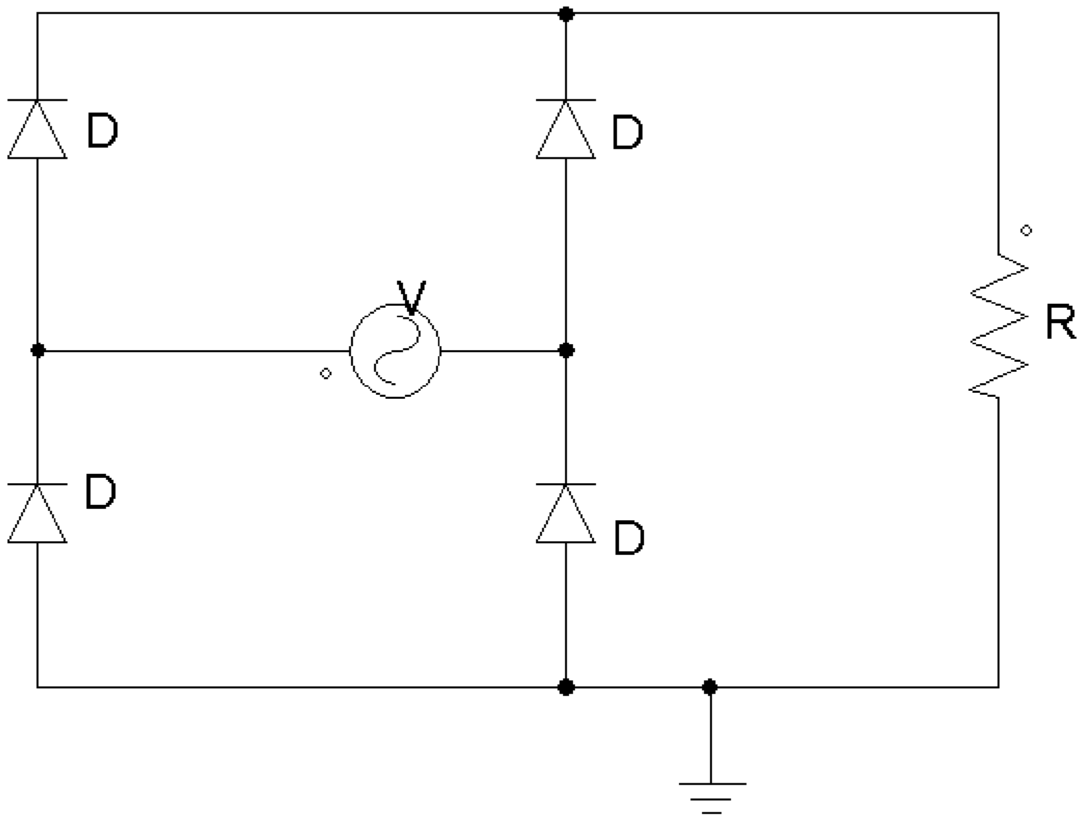


Figure 2.7: Circuit diagram of full wave bridge rectifier

Symbol	Value
V	220V, 50Hz
R	1KΩ
PF	0.70703617
THD%	99.980056
Vo	219.35771 V

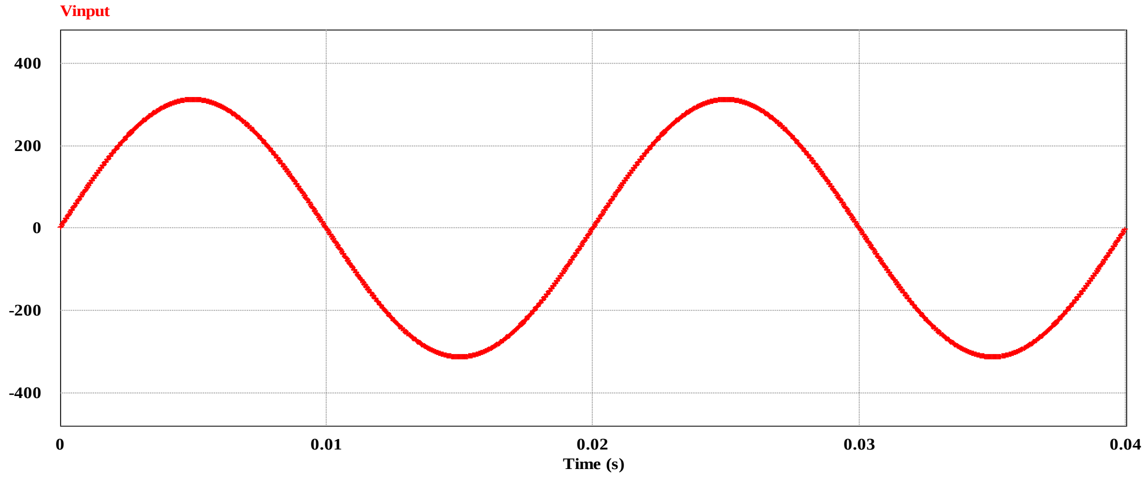


Figure 2.7(a): Wave shape of figure 2.7 Input voltage.

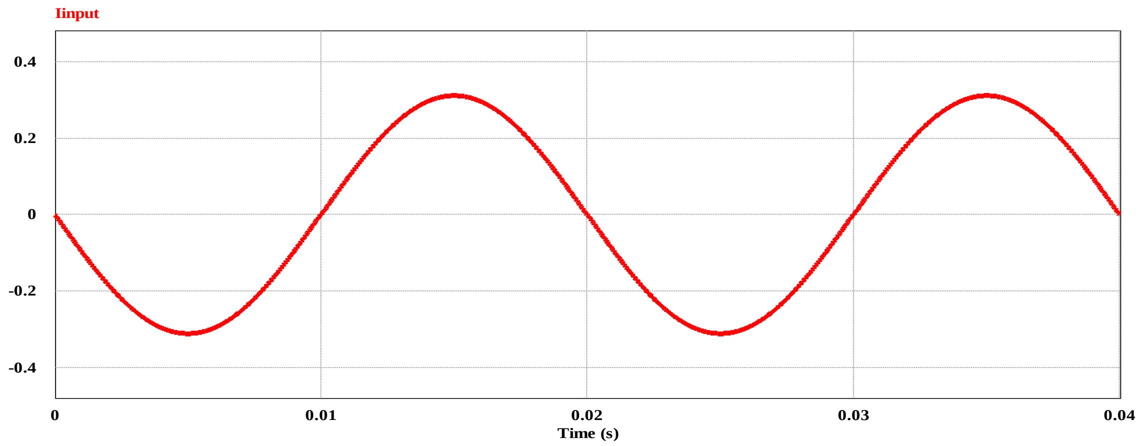


Figure 2.7 (b): Wave shape of figure 2.7 Input current

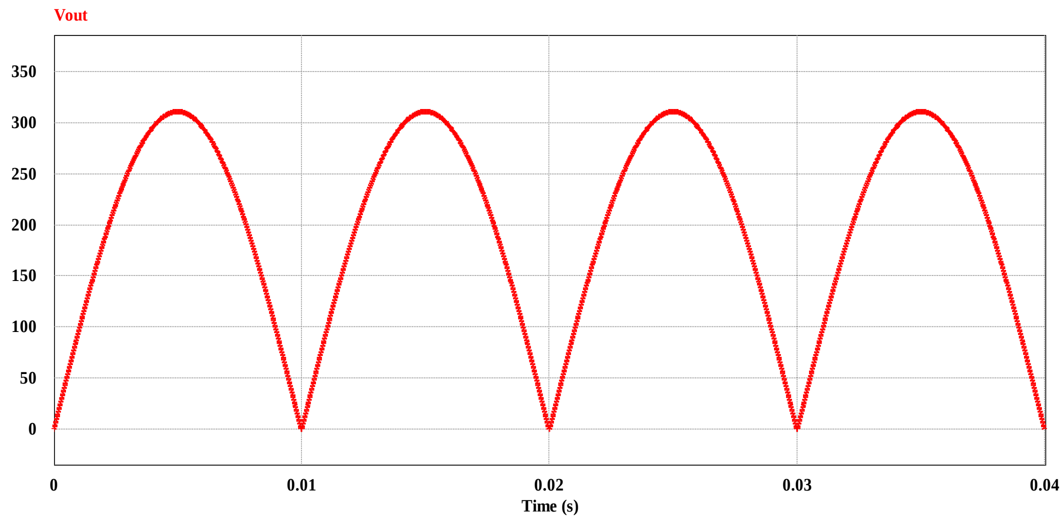


Figure 2.7 (c): Wave shape of figure 2.7 Output voltage.

2.8 Full wave bridge rectifier with RC load

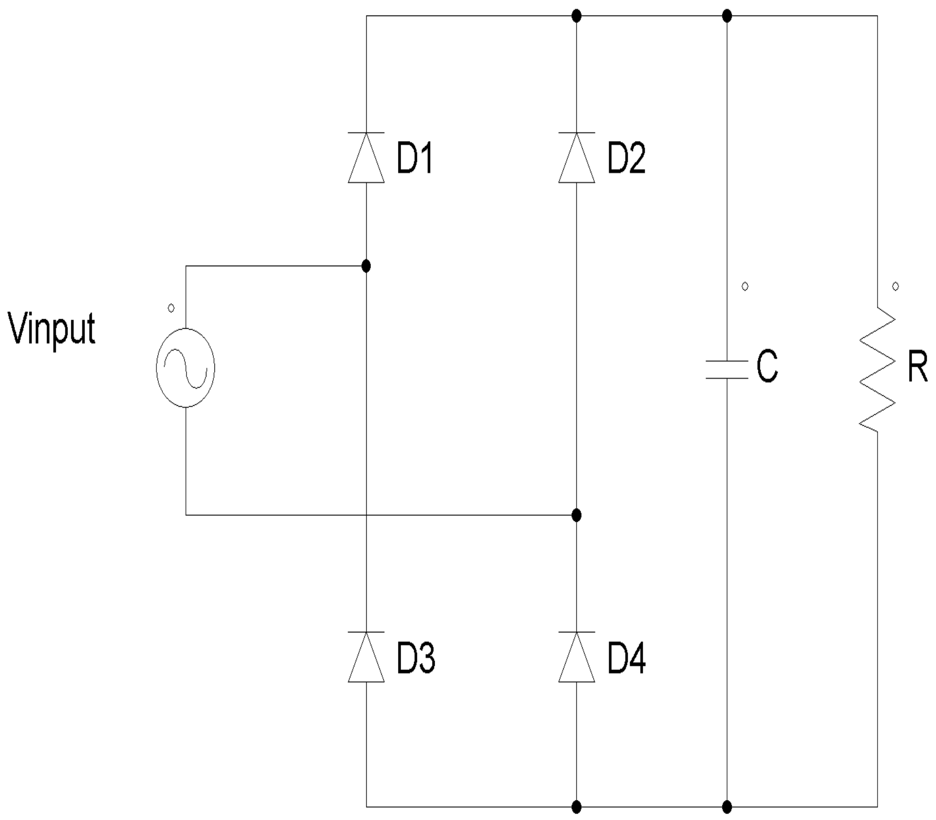


Figure 2.8: Circuit diagram of full wave bridge rectifier with RC load.

Symbol	Value
V	220V, 50Hz
R	1KΩ
C	47μf
PF	0.90004998
THD%	238.0404
Vo	283.21279 V

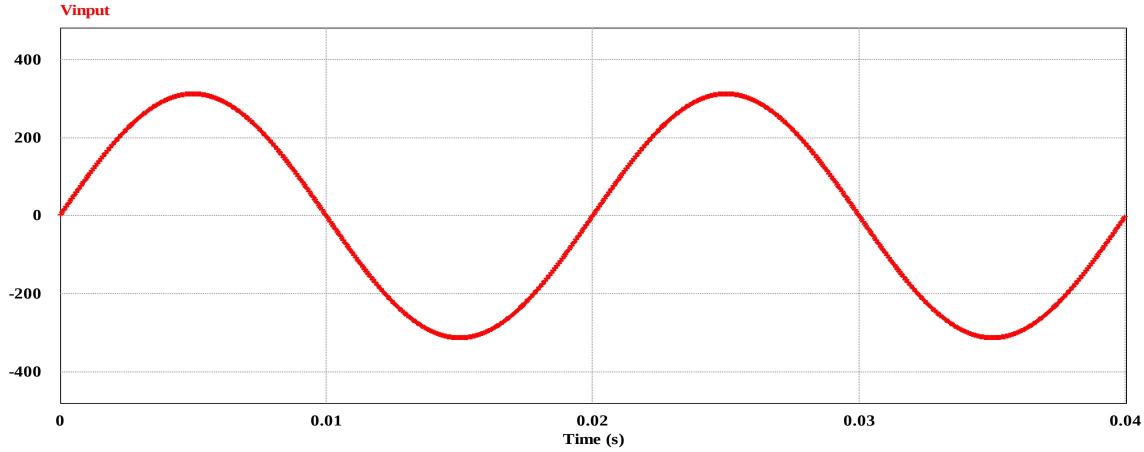


Figure 2.8 (a): Wave shape of figure 2.8 Input voltage

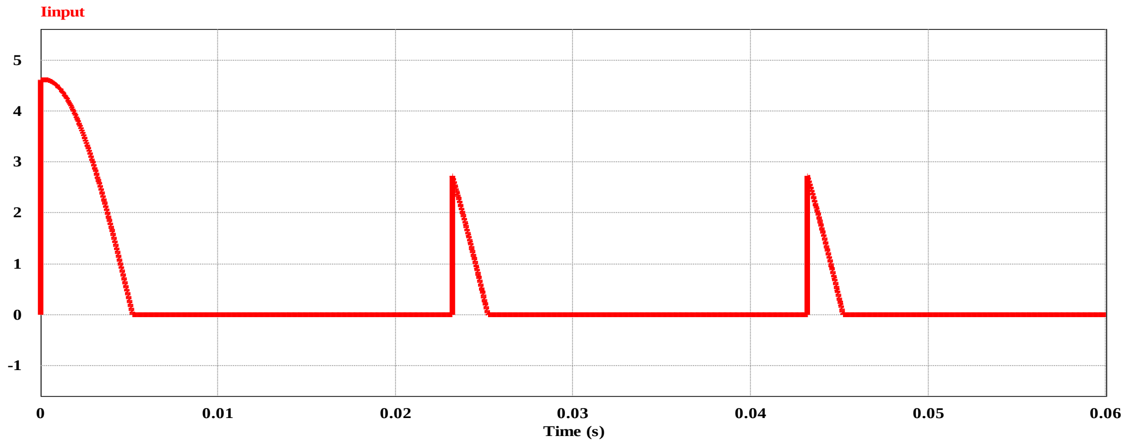


Figure 2.8(b): Wave shape of figure 2.8 Input current

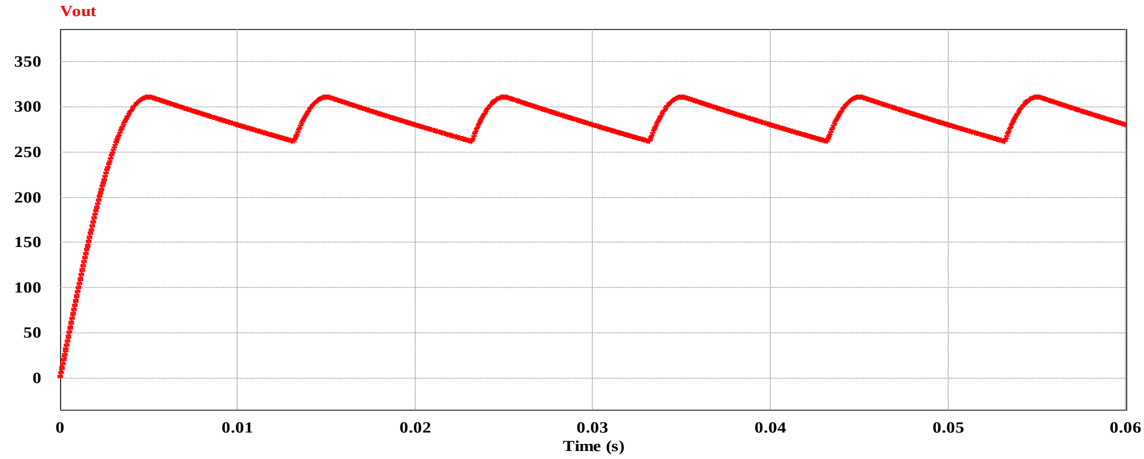


Figure 2.8 (c): Wave shape of figure 2.8 Output voltage

2.9 Full wave bridge rectifier with RL load

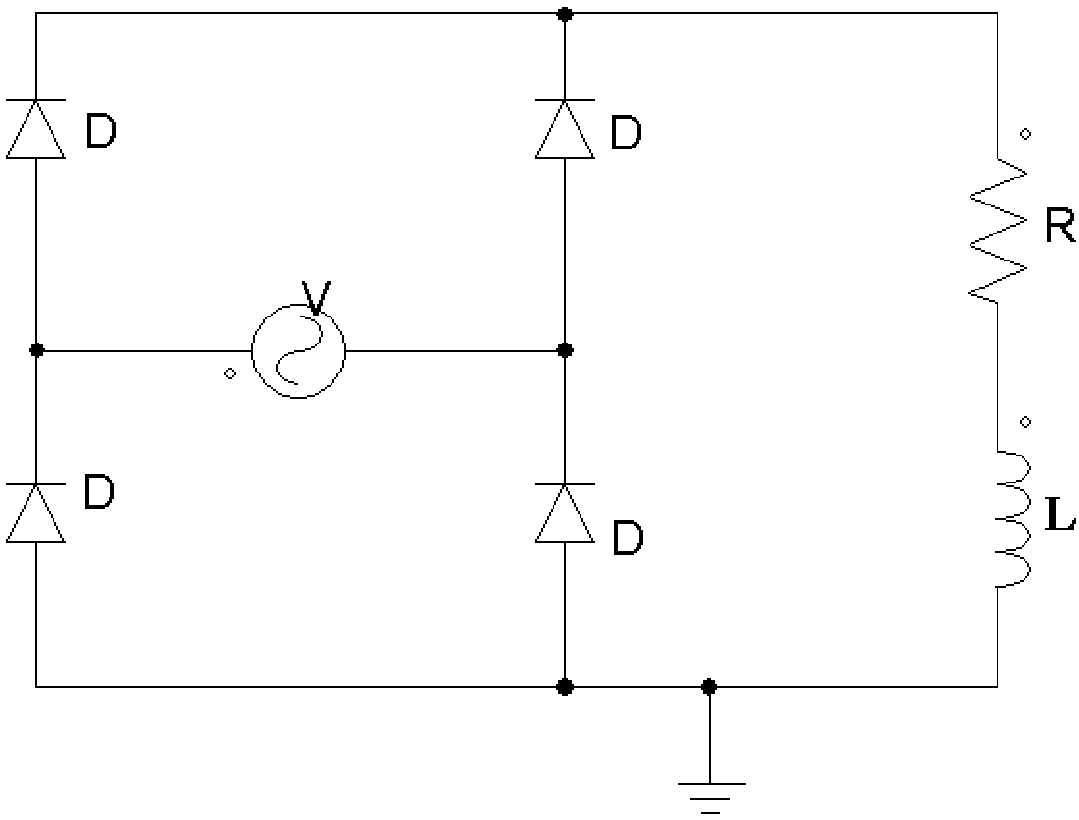


Figure 2.9: Circuit diagram of Full wave bridge rectifier with RL load.

Symbol	Value
V	220V, 50Hz
R	1KΩ
L	100mH
PF	0.70703401
THD%	99.983388
Vo	219.35771

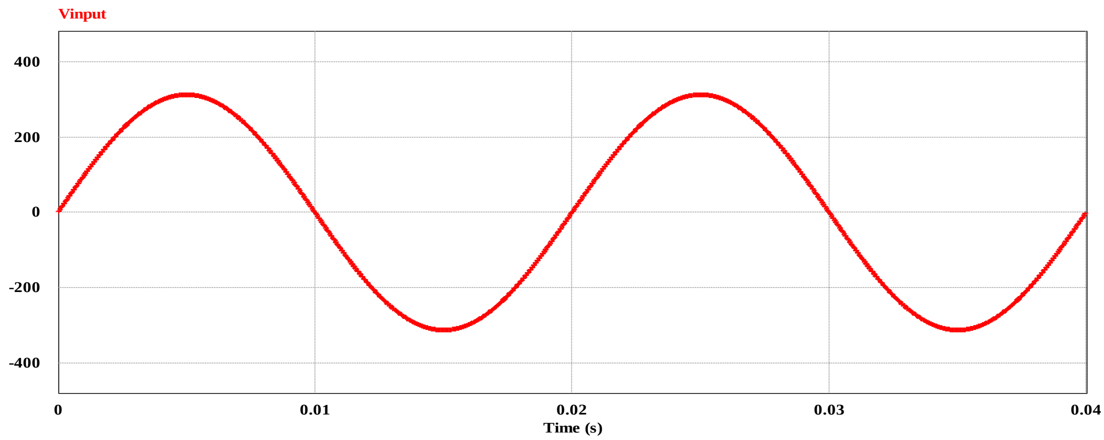


Figure 2.9 (a): Wave shape of figure 2.9 Input voltage

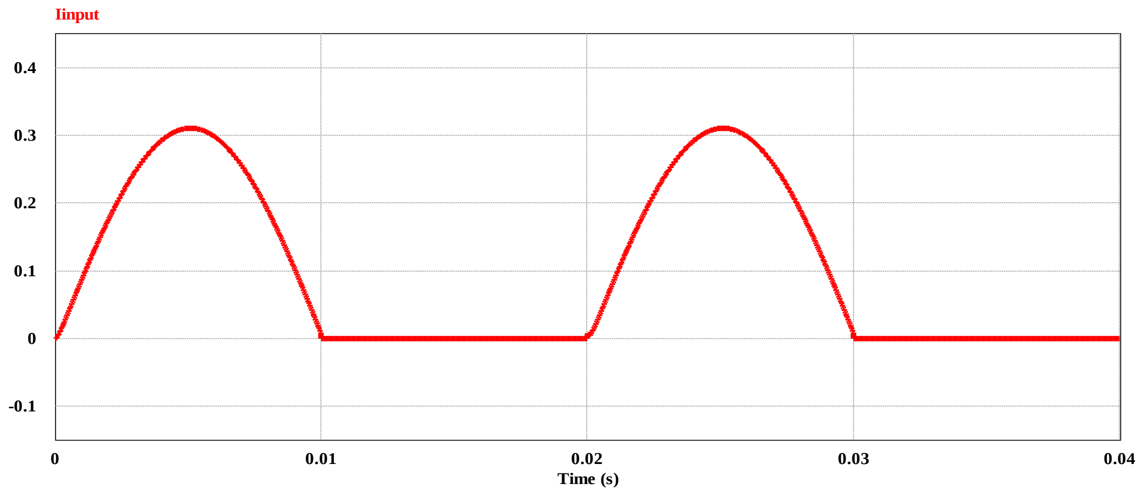


Figure 2.9 (b): Wave shape of figure 2.9 Input current

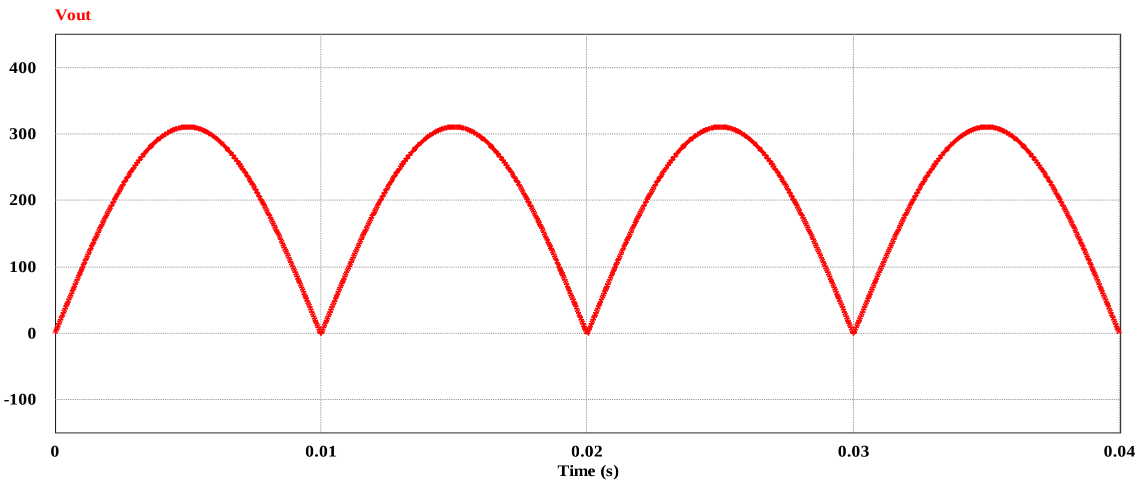


Figure 2.9 (c): Wave shape of figure 2.9 Output voltage

2.10 Comparison between full wave rectifiers

	Symbol	Value
Full wave bridge rectifier:	Symbol	Value
	V	220V, 50Hz
	R	1KΩ
	PF	0.70703617
	THD%	99.980056
	Vo	219.35771 V
Full wave bridge rectifier with RC load	Symbol	Value
	V	220V, 50Hz
	R	1KΩ
	C	47µf
	PF	0.90004998
	THD%	238.0404
	Vo	283.21279 V
Full wave bridge rectifier with RL load	Symbol	Value
	V	220V, 50Hz
	R	1KΩ
	L	100mH
	PF	0.70703401
	THD%	99.983388
	Vo	219.35771

2.11 Conclusion:

In this chapter we learned more about rectifier circuits and the differences between them.

Now that we have seen all the combinations of rectifiers along with its simulation, we have a clear idea about each rectifiers function.

Now let us look into our converter circuits and see how they work to get a better idea about them.

Chapter 3

DC-DC converters

3.1 Rectification System:

As input source we take common utility line of two hundred twenty-volt AC voltage. The wave is sinusoidal with frequency of fifty hertz and three hundred and twelve-volt peak amplitude. Firstly, we need to convert the AC voltage to DC voltage. One of the best way of converting AC voltage to DC voltage is to use full bridge rectifier.

A full bride rectifier uses diode and its principle of biasing to convert AC voltage to DC voltage. We all know that diode in reverse bias prevents flow of current. The diode bridge creates two pathways for the sinusoidal input voltage for the positive cycle and the negative cycle. With minor drop the positive cycle stays the same and the negative cycle gets inverted in the output. From **figure 3.2** we can observe the change in amplitude of the load. **figure 3.1** show the configuration of the full-bridge rectifier circuit.

Another importance factor is to minimize the ripple in output voltage. For that reason, we use a smoothing capacitor which minimizes the ripple voltage. The ripple voltage depends on the load current. It follows the following equation.

$$V_{(ripple)} = \frac{Iload}{(f)(C)}$$

In **figure 3.2** the value of the capacitor is used as 100volts AC input voltage1000µF and the load resistance is 100ohm.

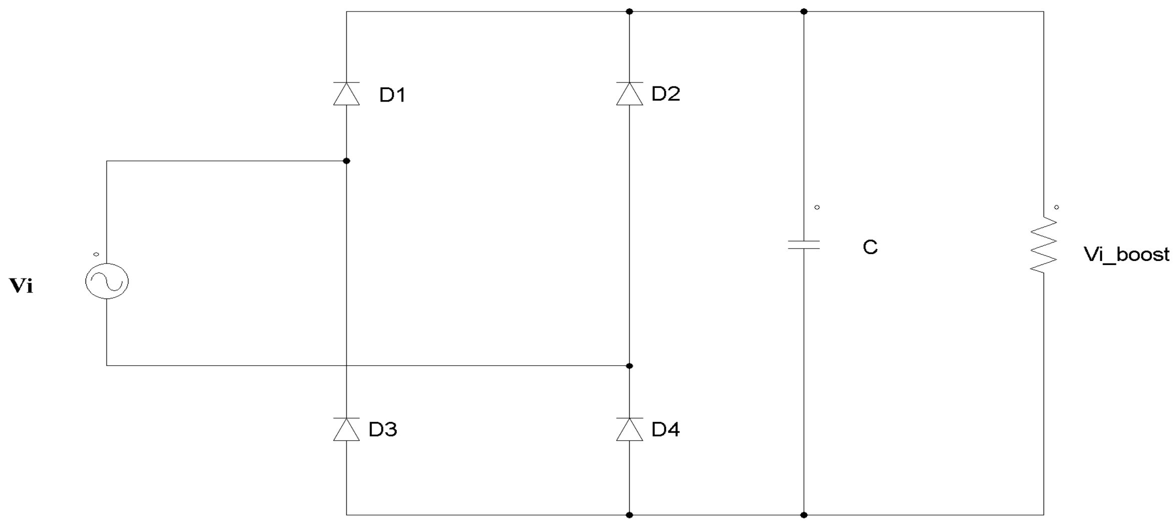


Figure 3.1 Rectifier

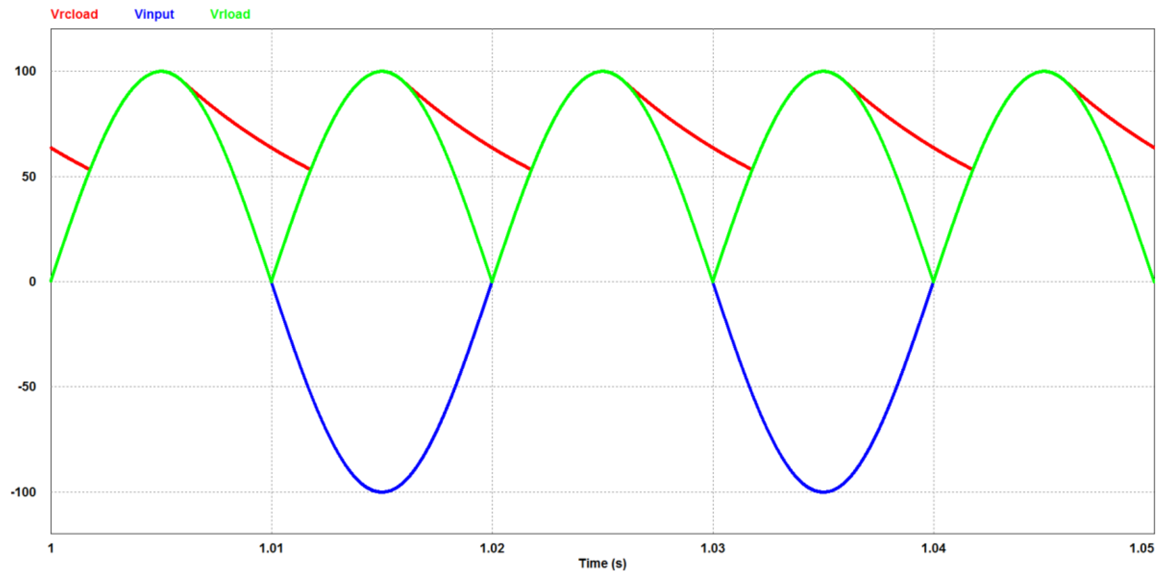


Figure 3.2 Rectification and effect of smoothing capacitor

3.2 Boost Converter or regulator:

The boost converter circuit has many similarities to the buck converter but the circuit design and application for the boost converter is slightly different. The fundamental circuit for a boost converter or step up converter consists of an inductor, diode, capacitor and a switch, which is controlled by a pulse width modulator. **Figure 3.4** represents the configuration of a boost DC/DC converter.

A boost converter is a DC-to-DC step-up power converter that amplifies voltage lowering the current in process from its input to the load. It is an example of switched-mode power supply (SMPS) and the simplest circuit contains a diode, a transistor, a capacitor and/or an inductor. Like the buck circuit, filters are used to stabilize the voltage ripple at the input end or output end or both depending on its application.

In a boost converter circuit, he input and output voltage and load current are determined as per application, but the Inductance and ripple current is independent, they only depending on each other, that is the inductance is inversely proportional to the ripple current. So, to reduce the ripple, a larger inductance is selected.

When the switch is ON, the inductor is grounded and the voltage Vin is connected across it. The inductor current increased during a period is determined by:

I = Vi/L.

When the switch is OFF, the voltage across the inductor is

V= Vout-Vin.

And the current decreased is, I= (Vout-Vi)/L.

3.3 Buck converter or regulator:

The basic circuit for a simple buck converter consists of an inductor, diode, and capacitor with switch control circuit system. It is also known as a step-down converter. The circuit operates by varying the amount of time in which inductor receives energy from the source. The switch is controlled by a pulse width modulator and a fixed frequency oscillator is used to drive the switching. It is a DC-to-DC power converter which steps down voltage, amplifying current in process, from its input to its output (load). It can be used as an example of switched-mode power supply (SMPS). The diode is replaced with a second transistor used for synchronous rectification in some cases. To reduce voltage ripple, filters made of capacitors and inductors are normally added to the converter's output and/or input, depending on its application. **Figure 3.6** represents the configuration of a boost DC/DC converter [8].

The buck converter has the current in an inductor controlled by two switches i.e. the diode and transistor. The switch and the diode have zero voltage drop when the switch is on and zero current flow when off and the inductor has zero resistance. Further, it is assumed that the input and output voltages do not change over one whole cycle.

When the switch is on, having voltage (Vin - Vo) across the inductor, the increase in current is determined by

$$\Delta I / \Delta T = (Vi - Vo) / L$$

The capacitor makes the inductor current smooth, and changes into a stable voltage at Vo. Also, the capacitor chosen is big enough such that Vo doesn't change significantly during one switching cycle.

When the switch is off, current falls linearly through the inductor. The change in current, i.e. the amount decreased is again determined by the voltage across inductor and its inductance.

$$\Delta I / \Delta T = (Vo + Vo) / L$$

Here the direction of current stays the same, but voltage is reversed. The inductor now is maintaining current flow by reversing its voltage when the applied voltage is removed and diode turns ON providing a path for inductor's current to flow.

These converters can operate in two modes:

1) Continuous mode- A buck converter operates in continuous mode if the current through the inductor I never falls to zero during the commutation cycle.

2) Discontinuous mode- In this case, the current through the inductor falls to zero during first half of the period and the inductor is completely discharged at the end of the commutation cycle.

3.4 Smart Power Factor Correction:

Our smart power factor correction system is a three step system. In the first step full bridge rectification will be applied to utility supply. So, the output of the rectifier will be in direct current form. Next, in the boost DC/DC converter power factor will be corrected. The voltage will be taken in an intermediate state. In our design we fixed the intermediate voltage to 400 volts. As a result, we will be able to notice a fall of THD. In third stage the voltage will be reduced to 100 volts constant. DC/DC buck circuit will be applied here.

With fixed duty cycle at Boost DC/DC converter and Buck DC/DC converter the power factor correction will have limited functionality. In **figure 3.7** the configuration of smart power factor is shown. If we just change load the system will face difficulty able to adjust according to that change. Moreover, for small fault current of transients the system will be unstable causing overheating of switching device to total system failure. For that reason, we need to apply control system for both DC/DC converters. With proper gain and phase margin the control systems will improve stability and correct changes in system. Using PWM, Arduino and numerical method we will set an upper and a lower limit of load that the system can sense and give constant output.

3.5 Design of the system:

In order to calculate parameters of converters, appropriate formulas will be applied [5].

AC/DC Converter Parameters:

If the peak voltage of AC voltage is Vm(=312V) then the output DC and RMS voltage, we get is

$V_{dc} = \frac{2\,Vm}{\pi} = 0.6366\ V_{m.} = 198.6192$ Volts

$Vrms = 0.707\ V_{m.} =$ 220volts

In output voltage the value of AC voltage is,

$V_{ac} = \sqrt{Vrms^2 - Vdc^2} = 95.498$

The form factor(FF) indicates the shape of the output voltage,

$FF = \frac{Vrms}{Vdc} = 1.11$

The efficiency we get for the rectifier is,

$\text{Efficiency} = \frac{Vdc^2}{Vrms^2} = 81\%$

Ripple Factor(RF) is the measurement of ripple in the output voltage,

$$RF = \frac{Vac}{Vdc} = 48\%$$

The problem of ripple is fixed after the smoothing capacitor 100 μF is installed. Also for capacitors discharging property on RC parallel circuit we can observe that before complete discharge of capacitor occurs another cycle of sinusoidal wave starts. As a result, we can observe an almost fixed Vrms value in the output side. From **figure 3.3** the input and the output voltage of AC/DC converter can be observed.

DC/DC Boost Converter Parameters:

Pre-charge diode:

To fix short-circuit of the startup in the boost converter 'Pre charge diode' is required to improve the stability of the system. this circuit works during the start-up phase when the output capacitor is not charged and the VIN is greater than VOUT. This condition forces the switch to absorb more current than the steady-state operation, therefore the switch could work with current exceeding the maximum ratings. Using the "pre-charge" circuit, the current doesn't flow through the switch since it flows through the diode of the "pre-charge" circuit until VIN > VOUT. In figure 3.4 and figure 3.5 this pre charge diode is noted as 'D_Pre'[11].

Diode:

In boost or buck converter, the switching frequency we set is very high. But, simple silicon diode is not suitable for handling such a fast change. It is ideal to use Schottky diode in this condition.

Since Silicon Carbide (SiC) Schottky Diodes have capacitive charge, Qc, rather than reverse recovery charge, Qrr. Their switching loss and recovery time are much lower compared to silicon ultrafast diode, and will show an enhanced performance. Moreover, SiC diodes allow higher switching frequency designs, hence, higher power density converters are achieved. The newer generations of SiC diodes are not just Schottky devices, but are merged structure diodes known as MPS diodes - Merged PN/Schottky. They combine the relatively low voltage for forward bias and capacitive charge characteristics of Schottky diodes with the high peak current capability of PN diodes, while avoiding the high junction voltage penalty (typically 2.5-3 V at room temperature) of a pure PN wide bandgap diode **[1]**.

Boost DC/DC converter parameters:

If duty cycle(D) and we need to step 220-volt DC(V_s) to 400-volt DC(V_o) output then,

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

From this equation we got D = 0.45

The current flowing through inductor will be,

$$I_L = \frac{Vs}{R(1-D)^2}$$

From this equation for load of 100 ohms we get I_L = 7.27A

If the switching frequency minimum inductor value will be.

$$L_{boost} = \frac{(D)(R)(1-D)^2}{2f} = 68.92\ \mu H$$

For designing purpose, we take 150uH.

The deviation in I_L will be,

$$\Delta I_L = \frac{(\boldsymbol{Vs})(\boldsymbol{D})}{(\boldsymbol{L})(\boldsymbol{f})} = 6.6\ A$$

The more capacitance it is used in the circuit; the less ripple voltage will be found in the output side. Capacitance also depends on the voltage hold-up time of the capacitor and the output power. For a 500W system

$$C_{boost} = \frac{2\ (Po)\ (Thold)}{Vo^2 - Vo{,}min^2} = 400\ \mu F$$

For designing purpose, we can take 470uF.

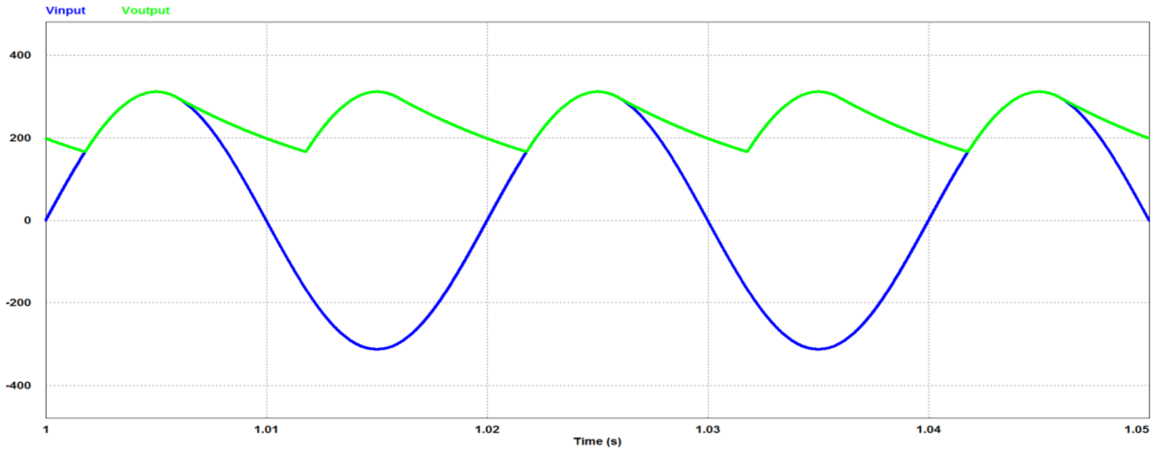


Figure 3.3: Input and output voltage of full bridge rectifier with smoothing capacitor

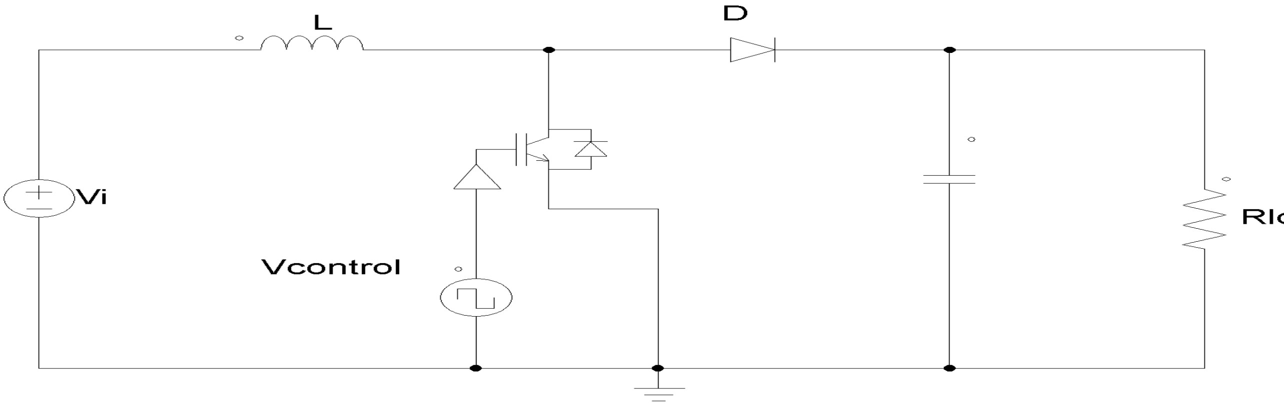


Figure 3.4 : Boost converter

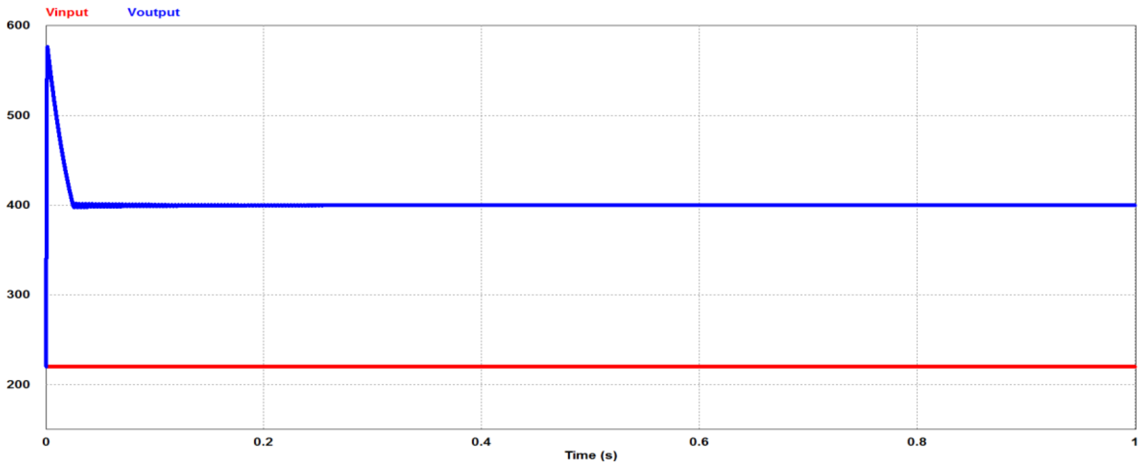


Figure 3.5: Input and output voltage of boost converter

Buck DC/DC converter parameters:

The converter will take four-hundred-volt DC as input and step it down to hundred volts [10].

Duty Cycle, D = $\frac{Vo}{Vi}$ = 0.25

The current flowing through inductor will be,

$I_L = \frac{Vo}{R}$

From this equation for load of 100 ohms we get I_L = 1A

The value of inductor, $L_{buck} = \frac{R(1-D)}{2f}$ = 0.375 mH.

The close value we can use is 0.5mH inductor.

The deviation in I_L will be,

$\Delta I_L = \frac{(\boldsymbol{Vo})(\mathbf{1}-\boldsymbol{D})}{(\boldsymbol{L})(\boldsymbol{f})} =$ 1.5A

Let us consider the ripple in output voltage $\mathbf{\Delta V}$ is 5 volt.

$$\frac{\mathbf{\Delta V}}{\boldsymbol{Vo}} = \frac{\mathbf{1}-\boldsymbol{D}}{\mathbf{8}(\boldsymbol{L})(\mathbf{Cbuck})(\boldsymbol{f})^{\mathbf{2}}}$$

From this equation we calculate C_{buck} = 0.375 µF

For designing we can take a near value 0.47 µF as alternative.

In figure 3.7 the input and the output voltage can be observed.

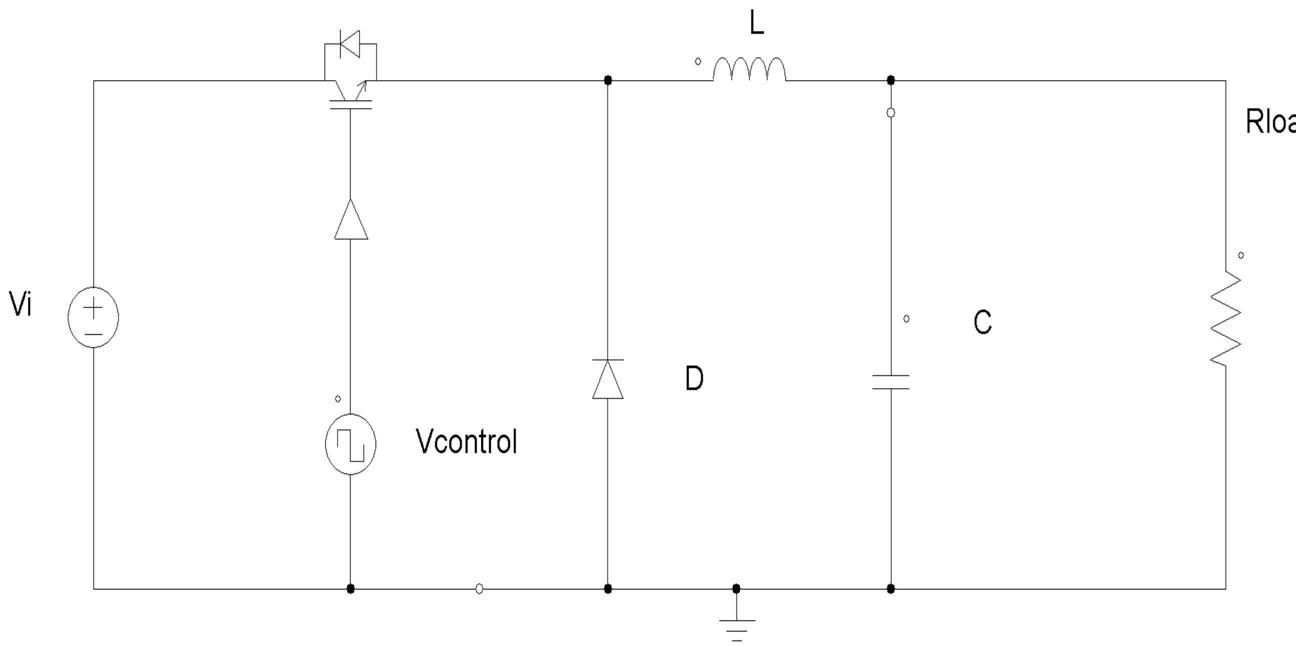


Figure 3.6 Buck Converter

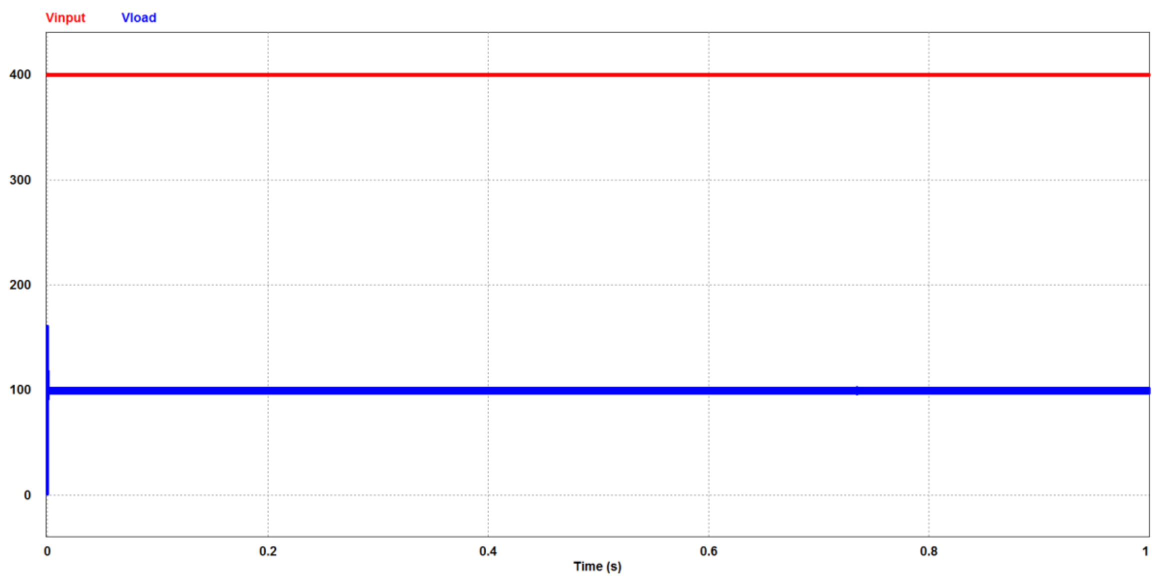


Figure 3.7: Input and output voltage of buck converter

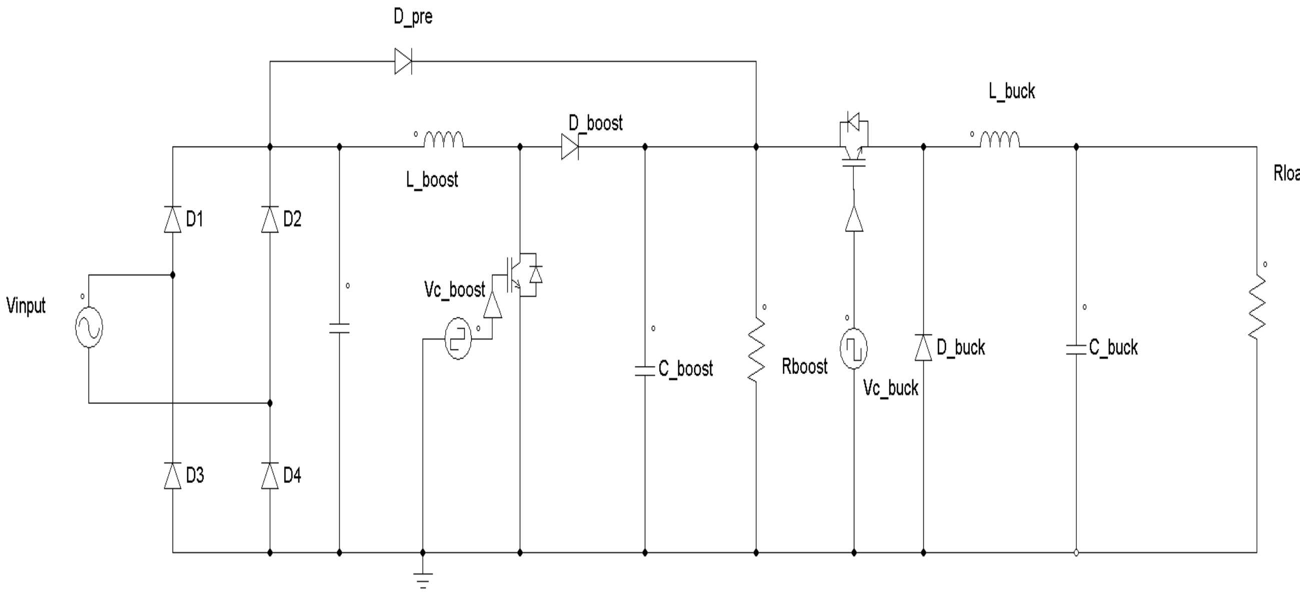


Figure 3.8: Smart Power Factor Correction Unit

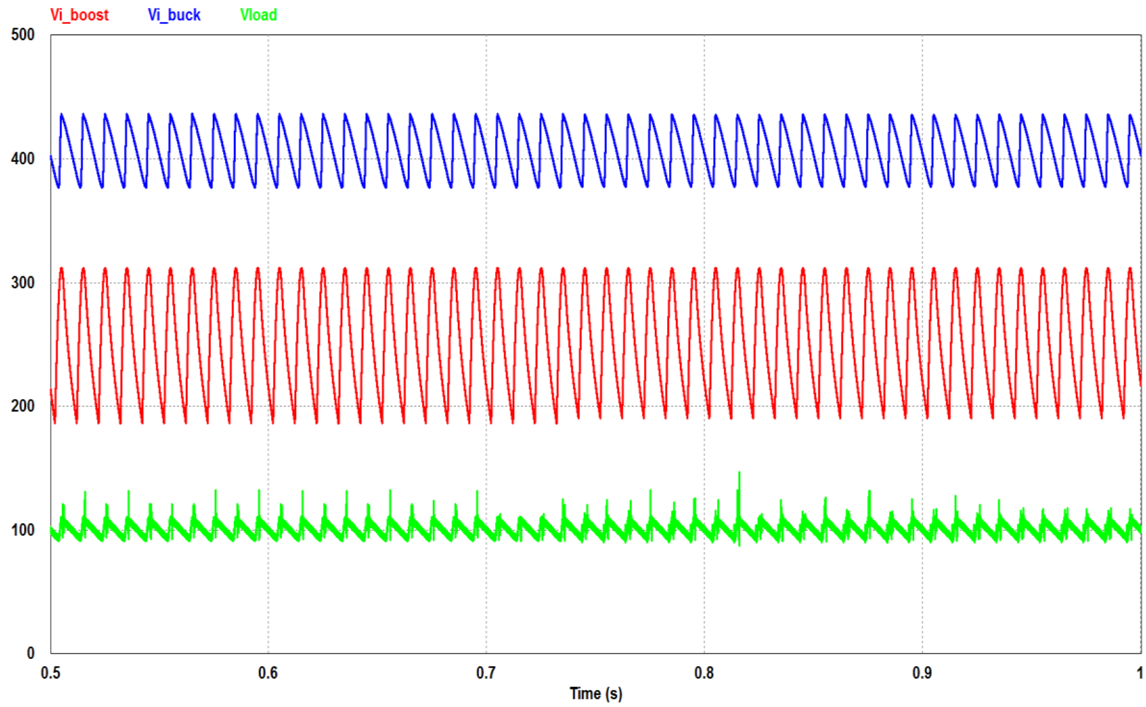


Figure 3.9: Various Voltage levels in PFC system

Load and the switching frequency effects the output voltage. For that reason, control system or microcontrollers are applied which generates the gate voltage of semiconductor switches. In **figure 3.8** there are two DC/DC converters a one AC/DC converters working together. So, we had to adjust the duty cycle of the boost controller according to the output voltage we need. The hundred volt output we get in **figure 3.9** the duty cycle of the boost system needed to be decreased to match the required configuration.

3.6 Limitations

If we consider the stability of the system, we need to take account of the gain and the phase margin. Type III compensator will surely boost the phase margin by 180 degrees. But for designing purpose it is mandatory to take appropriate design register and capacitor values. So, without proper margins the system will not become stable. Again we know that increasing margins will cost some extra time in settling time.

In the system, the switching devices IGBT will heat up. We need to have a proper cooling system in order to make the system work perfectly. Heat will cause power loss and lower efficiency. So, air cooling via small DC motor fan will be needed.

Load used outside of the limit will cause the system fail to provide hundred volts DC output. We need to be very careful of the load resistance we use. This problem can be overcome by designing another control system for Buck DC/DC converter.

3.7 Conclusion

With fixed duty cycle, it is not very effective to correct power factor. Moreover, this system can become less if any fault current or change in load occurs. It is not viable to change duty cycle when the system if working. For this reason, control system is must.

Chapter 4

Modeling of Controller Circuit

4.1 Control system:

Any control system consists of at least two basic components, the plant, which describes the mathematically modeled behavior of the system, and the output which is our desirable goal.

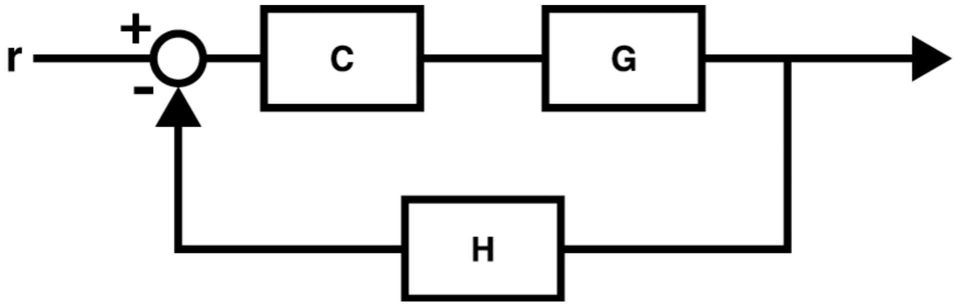


Figure 4.1: Block diagram of control system

Here r is the input signal, and G is the plant, while H is the feedback the controller unit C gets. This is the basic block representation for any control system.

The input: **r** having direct correlation with the system's output. This can be a voltage/power source, or a setting or switch that will connect a voltage/power source to the system. In our case, it is a DC source.

The controller: **C** in our case is a PI controller that we will design. It is positioned before the plant that we need to adjust for a constant voltage output.

The Plant: **G** is the subsystems mathematically expressed as a transfer function. The plant in our case is a boost converter circuit. The input will cause the plant to react in a way that will supply an output value that is ideally close to our input.

The output: **y** is the actual system's response to our desired response (the input) which has passed through our plant and the output to the input is compared with a certain error tolerance range, considered acceptable.

Feedback **H**: In a system's equivalent block diagram introduces the output of the system into the input, and the error between the input and output is what is introduced to the controller. Our system's error is then equal to: input. If the system has a unitary feedback (H = 1), then our error is simply input minus the output.

Further simplifying into just one block with a single input and single output by the use of the closed loop transfer function:

$$\mathrm{Closed-Loop}(s) = \frac{C(s)\,G(s)}{1+C(s)\,G(s)\,H(s)}$$

4.2 State Space Analysis of Boost Converter

The idea of the state of a dynamic system refers to a minimum set of variables, known as state variables that completely describe the system and its response to any given set of inputs Specifically a state-determined system model has the characteristic that:

A mathematical description of the system in terms of a minimum set of variables xi(t), i = 1, . . . , n, together with information of those variables at an initial time t0 and the system inputs for time t ≥ t0, are sufficient to predict the future system state and outputs for all time t > t0.

The definition of State Space denotes that the dynamic behavior of a state-determined system is completely characterized by the response of the set of n variables Xi(t), where n is the order of the system [7].

Vast classes of engineering, biological, social and economic systems may be represented by state-determined system models. System models built with e pure and ideal (linear) one-port elements (such as mass, spring and damper elements) are state-determined system models. For such systems the quantity of state variables, n, is equal to the quantity of free energy storage elements in the system. The estimations of the state variables at any time t indicate the energy of each energy storage element within the system and therefore the total system energy and the time derivatives of the state variables determine the rate of change of the system energy. Furthermore, the values of the system state variables at any time t provide sufficient information to determine the values of all other variables in the system at that time.

There is no one of a kind arrangement of state variables that describe any given system. [15] A wide range of sets of variables might be chosen to yield a complete system description. Notwithstanding, for a given system the order n is unique, and is independent of the particular set of state variables chosen. State variable descriptions of systems may be formulated in terms of physical and measurable variables, or in terms of variables that are not specifically quantifiable. It is possible to mathematically transform one set of state variables to another; the important point is that any set of state variables must provide a complete description of the system. In this note we concentrate on a particular set of state variables that are based on energy storage variables in physical systems [13].

- **Procedure of State Space Averaging:**

1. Draw the linear switched circuit model for each state of the switching converter.
2. Write state equations for each switched circuit model using Kirchhoff's voltage and current laws
3. Averaging the State- space Equation using the duty ratio.
4. Perturb the averaged state equation to yield steady-state (DC) and dynamic (AC) terms and eliminate the product of any AC terms
5. Transform the AC equations into S- domain to solve for Transfer Function.

- **Different modes of operation:**

a) A dc-dc converter is said to be operating in CCM, if inductor current never reaches to zero.

b) A dc-dc converter is said to be operating in DCM, if inductor current reaches zero and remains there for certain period of time.

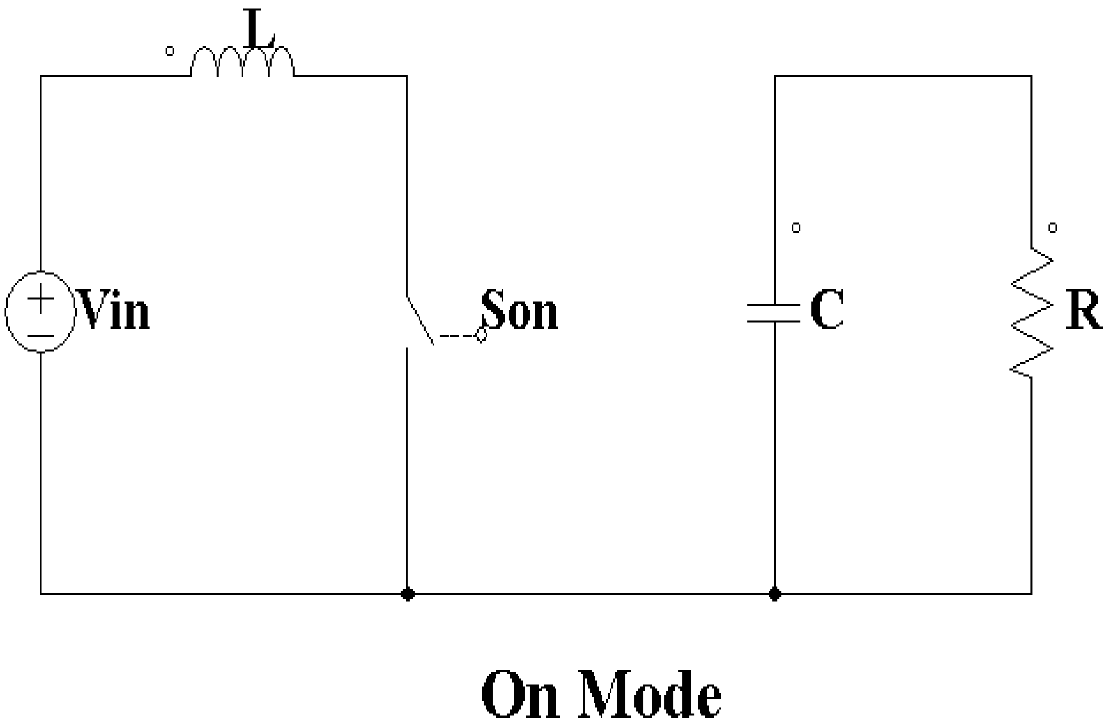


Figure 4.2(a): Boost converter during on mode

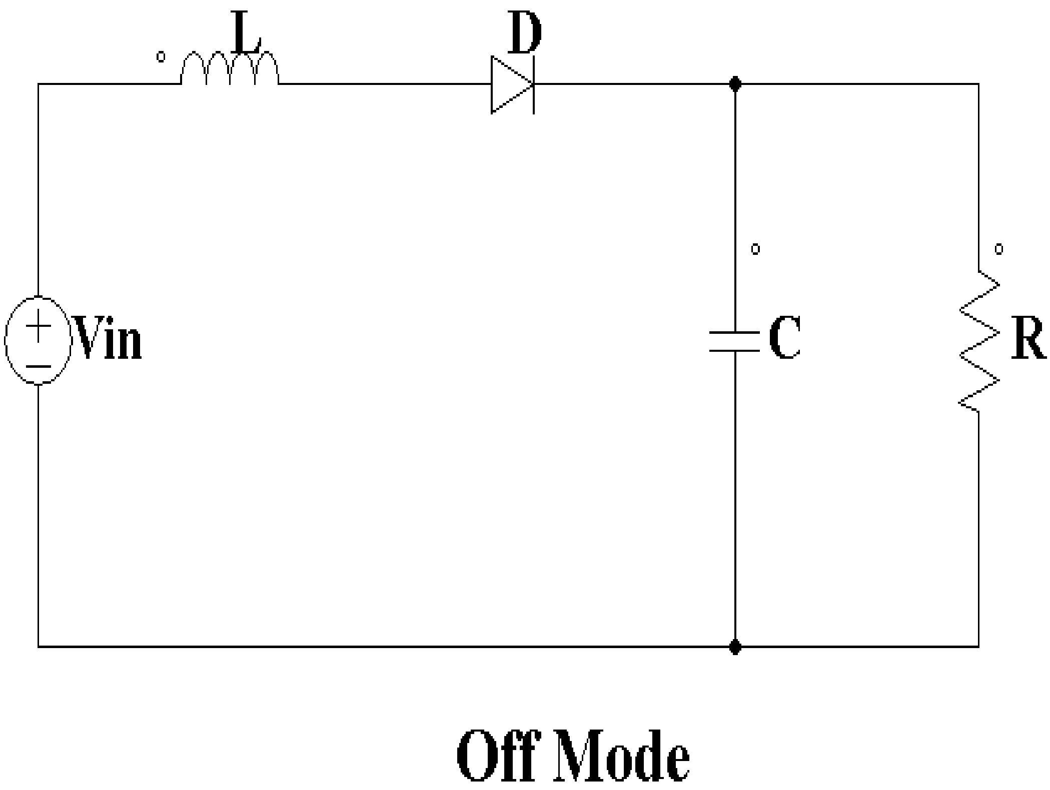


Figure 4.2(b): Boost converter during off mode

- Boost converter during on mode shown **in figure 4.2(a)**:

$$\text{From KVL : } V_{In} - L\frac{di_L}{dt} = 0$$

$$\text{From KCL: } \quad \frac{V_c}{R} + c\frac{dV_c}{dt} = 0$$

In State Space:

$$\begin{bmatrix} \frac{di_L}{dt} \\ \frac{dV_c}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_L \\ V_c \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_{In}$$

$$V_o = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} i_L \\ V_c \end{bmatrix}$$

- Boost converter during off mode shown **in figure 4.2(b)**:

$$\text{From KVL : } V_{In} - V_C - L\frac{di_L}{dt} = 0$$

$$\text{From KCL: } \quad i_L - \frac{V_c}{R} - c\frac{dV_c}{dt} = 0$$

In State Space:

$$\begin{bmatrix} \frac{di_L}{dt} \\ \frac{dV_c}{dt} \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_L \\ V_c \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_{In}$$

$$V_o = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} i_L \\ V_c \end{bmatrix}$$

During Discontinuous Conduction Mode:

$$\text{From KVL : } \frac{di_L}{dt} = 0$$

$$\text{From KCL: } \quad \frac{V_c}{R} + c\frac{dV_c}{dt} = 0$$

In State Space:

$$\begin{bmatrix} \frac{di_L}{dt} \\ \frac{dV_c}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_L \\ V_c \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} V_{In}$$

$$V_o = \begin{bmatrix} 0 & 0 \end{bmatrix} \begin{bmatrix} i_L \\ V_c \end{bmatrix}$$

- The state space averaged model:

$$A_1 = \begin{bmatrix} 0 & 0 \\ 0 & -\frac{1}{RC} \end{bmatrix}, A_2 = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix}, A_3 = \begin{bmatrix} 0 & 0 \\ 0 & -\frac{1}{RC} \end{bmatrix}$$

$$B_1 = \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix}, B_2 = \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix}, B_3 = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

As only one inductor is present and X is having dimension of two, so the modified matrix k is

$$K = \begin{bmatrix} \frac{1}{d1 + d2} & 0 \\ 0 & 1 \end{bmatrix}$$

So modified averaged model of boost converter is:

$$\frac{d}{dt} \begin{bmatrix} i_L{}' \\ V_c{}' \end{bmatrix} = \begin{bmatrix} 0 & -\frac{d2}{L} \\ \frac{d2}{C} & -\frac{1}{RC} \end{bmatrix} K \begin{bmatrix} i_L{}' \\ V_c{}' \end{bmatrix} + \begin{bmatrix} \frac{d1+d2}{L} \\ 0 \end{bmatrix} V_{In}$$

$$= \begin{bmatrix} 0 & -\frac{d2}{L} \\ \frac{d2}{C(d1+d2)} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_L{}' \\ V_c{}' \end{bmatrix} + \begin{bmatrix} \frac{d1+d2}{L} \\ 0 \end{bmatrix} V_{In}$$

Here,

$$\frac{dI_L{}'}{dt} = 0$$

$$\frac{dV_c{}'}{dt} = \frac{Vin}{Vc} \frac{I_L{}'}{C} - \frac{V_c{}'}{RC}$$

Reduced Order Averaged Model for Boost Converter:

Apply standard linearization technique and apply perturbations

$$i_L' = I_L + i_L\sim$$

$$V_c' = V_c + V_c^{\sim}$$

$$V_{In} = V_{In} + V_{In}{}^{\sim}$$

$$d = D + d\sim$$

$$\frac{d(V_c + V_c^{\sim})}{dt} = \frac{V_{In} + V_{In}^{\sim}}{2LC}\frac{(D+d)^2 T_s}{(V_c + V_c^{\sim} - V_{In} - V_{In}^{\sim})} - \frac{V_c + V_c^{\sim}}{Rc}$$

$$2RLC(V_c - V_{In})\frac{d+V_c^{\sim}}{dt} = R\left(V_{In}^2 + 2V_{In}V_{In}^{\sim}\right)(D^2 + 2Dd)T_s - 2L(V_c + V_c^{\sim})(V_c + V_c^{\sim} - V_{In} - V_{In}^{\sim})$$

Separating $i_L\sim, V_c^{\sim}, V_{In}^{\sim}, d\sim$ and converting it to state space form[14]

$$\begin{bmatrix} i_L' \\ V_c' \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & -\frac{1}{RC}\left(\frac{2m-1}{M-1}\right) \end{bmatrix}\begin{bmatrix} i_L\sim \\ V_c\sim \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ \frac{D^2T_S}{LC(M-1)} + \frac{M}{RC(M-1)} & \frac{DT_SV_{In}}{LC(M-1)} \end{bmatrix}\begin{bmatrix} V_{In}^{\sim} \\ d\sim \end{bmatrix}$$

Then,

$$\begin{bmatrix} i_L\sim \\ V_c\sim \end{bmatrix} = X^{\sim}(s) = (S' - A)^{-1}B\,U(s)$$

Where, $$(S' - A)^{-1} = \left\{\begin{bmatrix} s & 0 \\ 0 & s \end{bmatrix} - \begin{bmatrix} 0 & 0 \\ 0 & -\frac{1}{RC}\left(\frac{2M-1}{M-1}\right) \end{bmatrix}\right\}^{-1}$$

$$= \frac{1}{\Delta}\begin{bmatrix} s + \frac{1}{RC}\left(\frac{2M-1}{M-1}\right) & 0 \\ 0 & s \end{bmatrix} \text{ where, } \frac{1}{\Delta} = \frac{1}{S^2 + S\left[\frac{1}{RC}\left(\frac{2M-1}{M-1}\right)\right]}$$

$$\begin{bmatrix} i_L\sim \\ V_c\sim \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ s\left(\frac{D^2T_S}{LC(M-1)} + \frac{M}{RC(M-1)}\right) & s\left(\frac{DT_SV_{In}}{LC(M-1)}\right) \end{bmatrix}\begin{bmatrix} V_{In}(s) \\ d(s) \end{bmatrix}\frac{1}{\Delta}$$

Thus the transfer functions are:

$$\frac{V_c^{\sim}(s)}{V_{In}^{\sim}(s)} = \frac{S\left(\frac{D^2T_S}{LC(M-1)} + \frac{M}{RC(M-1)}\right)}{\Delta}$$

$$\frac{V_c^{\sim}(s)}{d(s)} = \frac{s\left(\frac{DT_SV_{In}}{LC(M-1)}\right)}{\Delta}$$

- Small Signal Model:

$$\frac{d}{dt}\begin{bmatrix} i_L\sim \\ V_c\sim \end{bmatrix} = A\begin{bmatrix} i_L\sim \\ V_c\sim \end{bmatrix} + B\begin{bmatrix} V_{In}^{\sim} \\ d\sim \end{bmatrix}$$

Where,

$$A=\begin{bmatrix}\frac{2(1-M)}{DT_S} & \frac{-D}{L(M-1)}\\ \frac{1}{C} & -\frac{1}{RC}\end{bmatrix},\ B=\begin{bmatrix}\frac{DM^2}{L(M-1)} & \frac{2MV_{In}}{L}\\ \frac{-D^2T_S}{2LC} & \frac{-DT_SV_{In}}{LC}\end{bmatrix}$$

Then,

$$\begin{bmatrix}i_L\sim\\ V_c\sim\end{bmatrix}=X^{\sim}(s)=(S'-A)^{-1}B\,U(s)$$

$$(S'-A)^{-1}=\{\begin{bmatrix}s & 0\\ 0 & s\end{bmatrix}-\begin{bmatrix}\frac{2(1-M)}{DT_S} & \frac{-D}{l(M-1)}\\ \frac{1}{c} & -\frac{1}{RC}\end{bmatrix}\}^{-1}$$

$$\frac{1}{\Delta}\begin{bmatrix}s+\frac{1}{RC} & \frac{-D}{L(M-1)}\\ \frac{1}{C} & s-\frac{2(1-M)}{DT_S}\end{bmatrix}\text{ where, }\frac{1}{\Delta}=\frac{1}{S^2+S\left[\frac{1}{RC}\left(\frac{2(M-1)}{DT_S}\right)\right]+\frac{2}{RC}\left(\frac{2(M-1)}{DT_S}\right)}$$

$$\begin{bmatrix}i_L\sim\\ V_c\sim\end{bmatrix}=\begin{bmatrix}\frac{sM^2}{L(M-1)}+\frac{M^2}{RLC(M-1)}+\frac{MD}{RLC} & \frac{s(2MV_{In})}{L}+\frac{2MV_{In}}{RLC}+\frac{2MV_{In}}{RLC}\\ \frac{M^2}{LC(M-1)}+\frac{D(1-M)}{LC}+\frac{s(-D^2T_S)}{2LC} & \frac{s(-DT_SV_{In})}{LC}+\frac{2MV_{In}}{LC}+\frac{2(1-M)V_{In}}{LC}\end{bmatrix}\begin{bmatrix}V_{In}{}^{\sim}(s)\\ d\sim(s)\end{bmatrix}\frac{1}{\Delta}$$

- Transfer functions

So, transfer functions can be formulated from small signal model to below equations:

$$\frac{i_L\sim(s)}{V_{In}{}^{\sim}(s)}=[\frac{sM^2}{L(M-1)}+\frac{M^2}{RLC(M-1)}+\frac{MD}{RLC}]\frac{1}{\Delta}$$

$$\frac{i_L\sim(s)}{d^{\sim}(s)}=[\frac{s(2MV_{In})}{L}+\frac{2MV_{In}}{RLC}+\frac{2MV_{In}}{RLC}]\frac{1}{\Delta}$$

$$\frac{V_c\sim(s)}{V_{In}{}^{\sim}(s)}=[\frac{M^2}{LC(M-1)}+\frac{D(1-M)}{LC}+\frac{s(-D^2T_s)}{2LC}]\frac{1}{\Delta}$$

$$\frac{V_c\sim(s)}{d^{\sim}(s)}=[\frac{s(-DT_sV_{In})}{LC}+\frac{2MV_{In}}{LC}+\frac{2(1-M)V_{In}}{LC}]\frac{1}{\Delta}$$

MATLAB Approach:

We can also use MATLAB to Find the transfer function and the root locus of the circuit.

```
clc;
clear all;
close all;
Vg=220.68109;%input volatge
D=0.45;%Duty ratio
L=68.92e-6;%Inductance
C=400e-6;%capacitance
R=100;%load resistance
%stedy state model%
%As, Bs, Cs, Ds %
As=[0 -(1-D)/L; (1-D)/C -1/(R*C)];
Bs=[1/L 0 0; 0 -1/C 0];
Cs=[0 1; 1 0];
Ds=[0 0 0;0 0 0];

V0=-Cs(1,:)*inv(As)*Bs(:,1)*Vg
Ig=-Cs(2,:)*inv(As)*Bs(:,1)*Vg
% small signal mode;%
a=[0 -(1-D)/L;(1-D)/C -1/R/C];
b=[1/L 0 V0/L; 0 -1/C -Ig/C];
c=[0 1];
d=[0 0 0];
ulabels=['vg iz d'];
ylabels=['vo ig'];
xlabels=['il vc'];
printsys(As,Bs,Cs,Ds,ulabels,ylabels,xlabels)
printsys(a,b,c,d,ulabels,ylabels,xlabels)
disp(['transfer function in s domain'])
disp(['V0/d(s)'])
Tfb=zpk(tf(ss(a,b(:,3),c,[0])))
rlocus(Tfb)
bode(Tfb)
```

MATLAB Result:

Transfer Function (Tfb):

transfer function in s domain V0/d(s)

$$Tfb = \frac{-18238(s-4.389^5)}{s^2 + 25s + 1.087^7}$$

Continuous-time zero/pole/gain model.

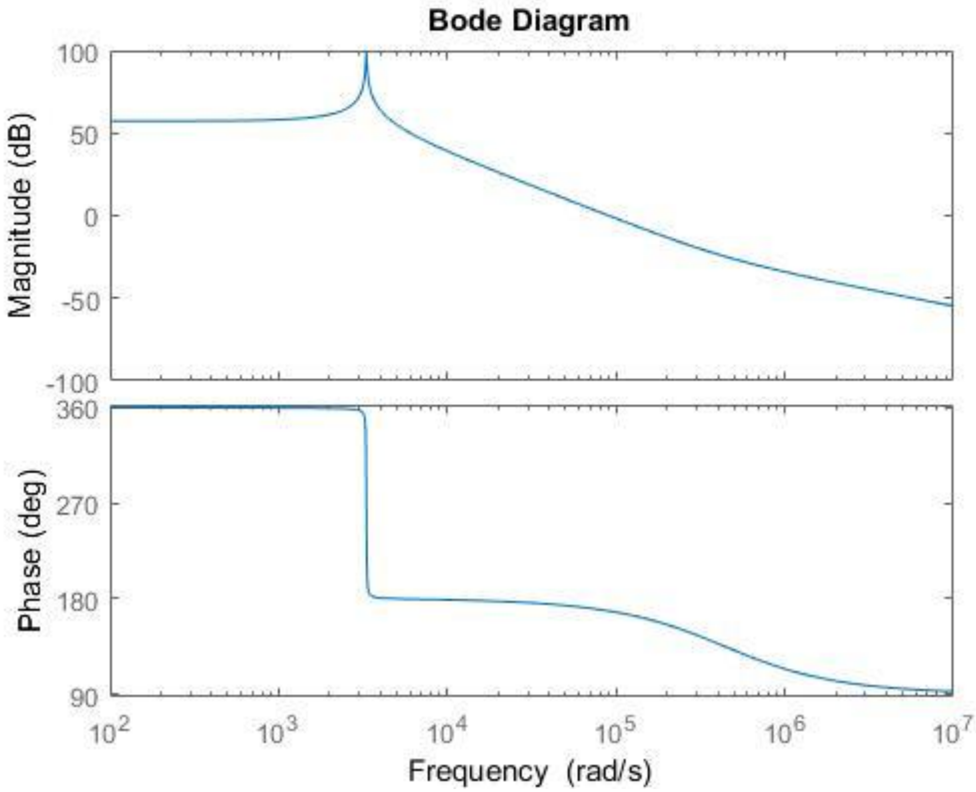


Figure 4.3: Bode plot

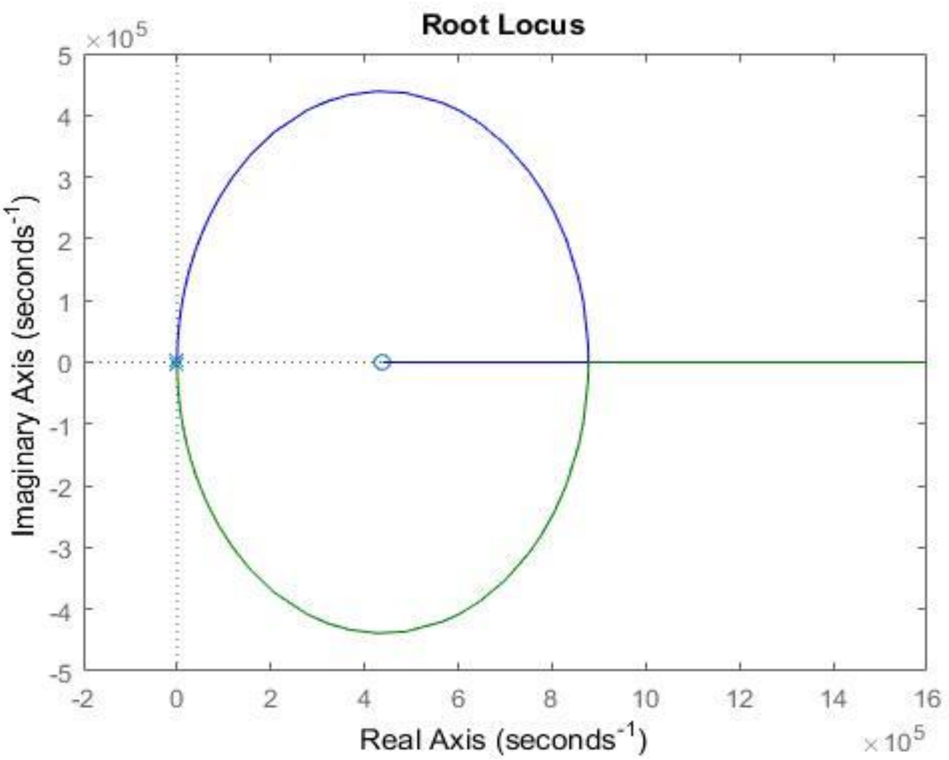


Figure 4.4: Root Locus

4.3 Generating PWM:

One of the major parts of the converter circuit is switch control circuit (controller). The control method chosen to maintain the output voltage of the circuit is voltage mode control. Voltage mode has a single voltage feedback path with pulse width modulation (PWM) perform by measuring voltage error with a ramp waveform. The control element driven by the difference between two voltages and adjust the output voltage to a desire voltage level. This is known as output voltage regulation. **Figure 4.5** show a general approach to use the comparator circuit.

The switch control signal (PWM) controls the two states of the circuit, the on state and the off state. The idea is to control the duty cycle of the switch so that a load gets a controllable average voltage. To achieve this switching frequency (frequency for PWM signal) is set high enough so that the load cannot follow the individual switching [12].

Switching power supplies depends on the negative feedback to maintain the desire output voltage. To achieve this, a differential amplifier is used to sense the difference between an ideal voltage and the actual output voltage.

The PWM signal with a constant frequency is generated by comparing a single level control voltage with a repetitive wave from. The frequency of the repetitive wave from with a constant peak is the saw tooth, which establishes the switching frequency. This has a constant frequency and chosen to be in kilohertz (KHz) range. With the amplified error signal that varies slowly with time relative to the switching frequency is greater than the saw tooth wave from the switch control signal becomes high a turn on the switch. Otherwise the switch is off. Thus the output voltage also changes. **Figure 4.6 and figure 4.7** is the PWM circuit and the voltage levels that can do the switching procedure described here.

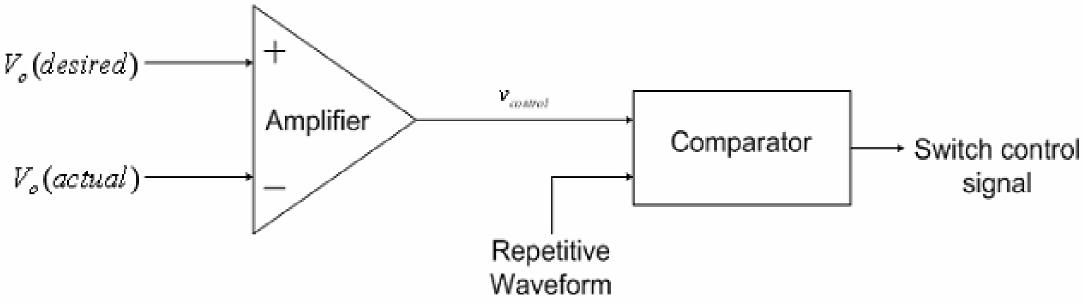


Figure 4.5: Voltage Comparator

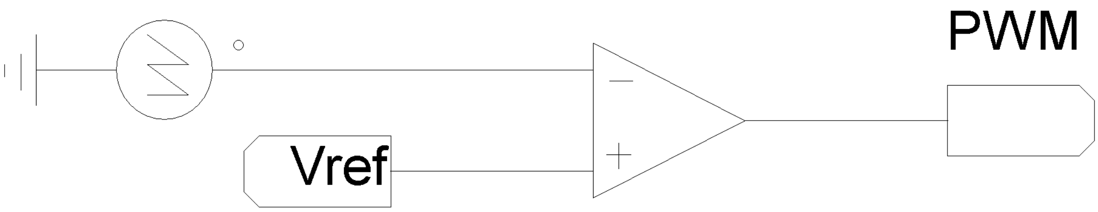


Figure 4.6: Pulse Width Modulation(PWM) circuit

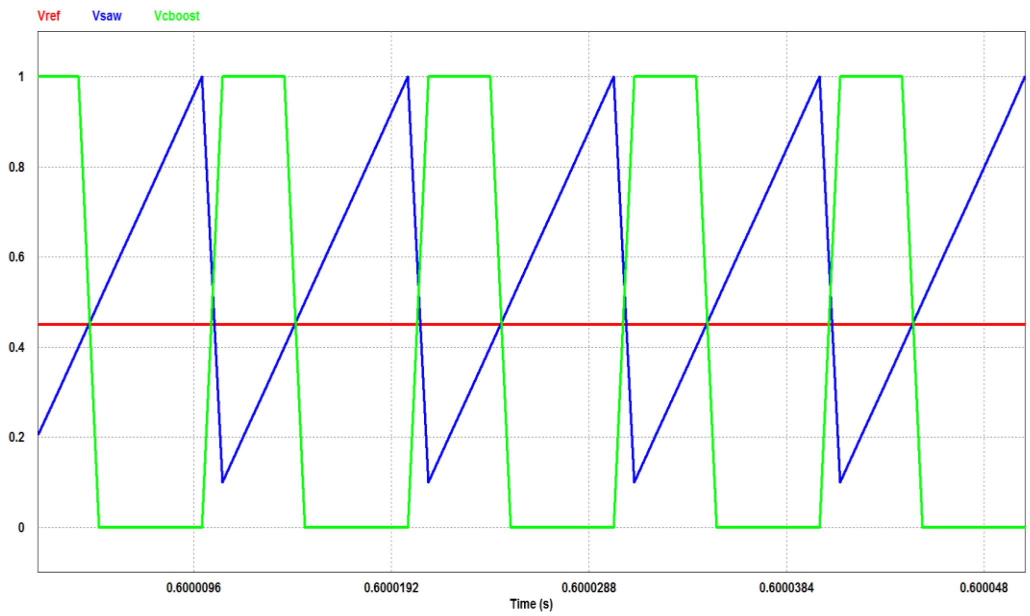


Figure 4.7 PWM Comparator Signals

4.4 Types of compensator:

The compensator is the feedback controller for the converter circuit. It also improves the phase margin. There are three types of compensator circuits [2]. They are:

1. Type I compensator
2. Type II compensator
3. Type III compensator

1. Type I compensator

Type I compensator is referred as the single pole compensator. This type of compensation is used for converter tropology. This includes forward mode voltage regulations such as boost, buck, half wave and full wave bridge rectifier either using voltage or current mode control. This converter gives a relative poor response time because the gain cross over frequency occurs at a low frequency. But its load regulation is good enough, because DC gain is high. **Figure 4.8(a)** shows the circuit configuration of type one compensator.

The transfer function of this compensator is:

$$K(s) = -\frac{Vout(s)}{Vin(s)} = \frac{R2}{R1(1 + R2\,C1\,S)}$$

Generally this type of compensator is not used if a rapid transient load response time is desired.

2. Type II compensator

Type II compensator helps to shape the gain with respect to the frequency and also boost the phase by 90°. This boost is essential to counteract the effects of the resonant output filter at the double pole. **Figure 4.8(b)** shows the circuit configuration of type two compensator.

The transfer function of this compensator is:

$$K(s) = \frac{1 + sR2C1}{sR1(C1 + C2)(1 + sR2(\frac{C1C2}{C1+C2}))}$$

3. Type III compensator

Also the type III compensator shapes the gain with respect to frequency like type II compensator. But two zeros give a phase boost of 180°. This boost is essential to counteract the effects of an under damped resonance of the output filter at the double pole. It has two poles and two zeros and a pole at its origin which gives a better DC accuracy. **Figure 4.8(c)** shows the circuit configuration of type three compensator.

The transfer function of this compensator is:

$$K(s) = \frac{R1 + R3}{R1 * R3 * C1} \frac{(S + \frac{1}{R2*C2})(S + \frac{1}{(R1+R3)C3})}{S(S\frac{C1+C2}{R2*C1*C2})(S + \frac{1}{R3*C3})}$$

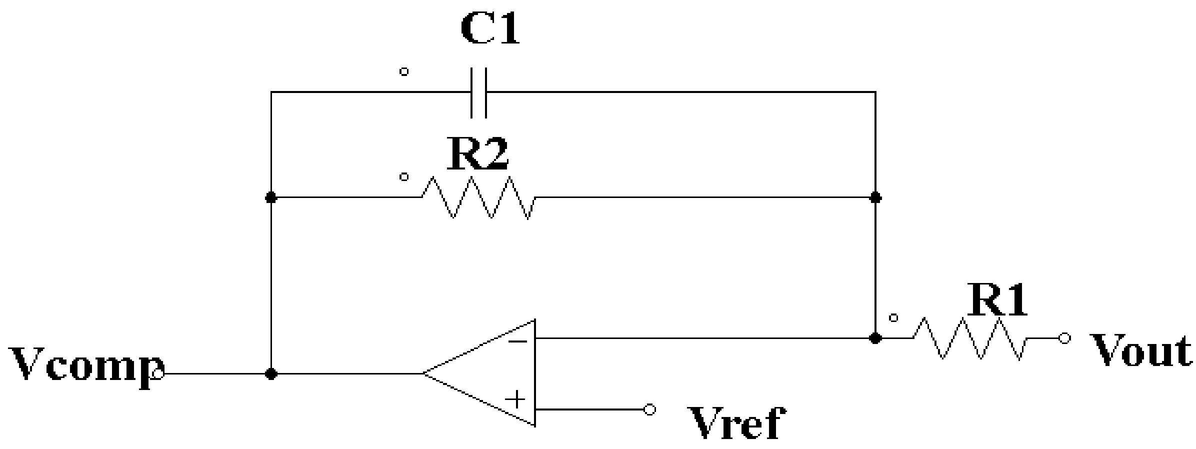


Figure 4.8 (a): Type I compensator

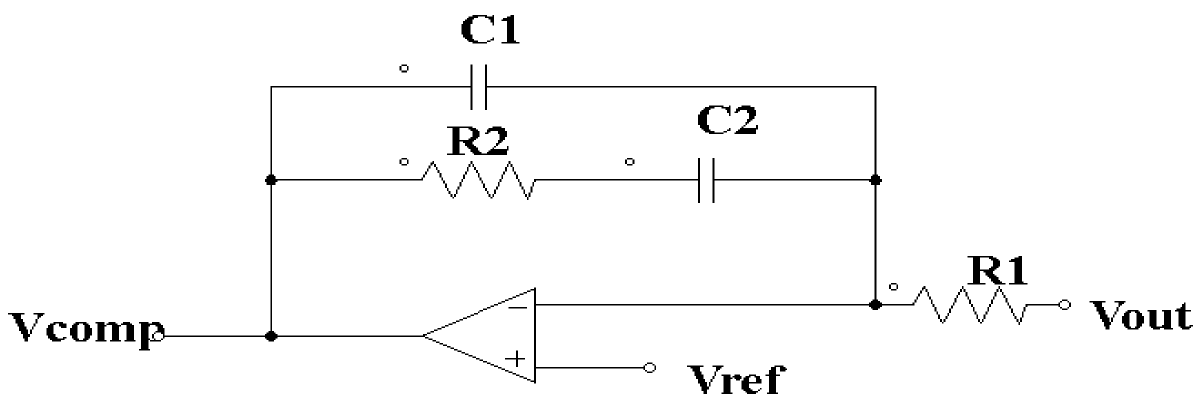


Figure 4.8 (b): Type II compensator

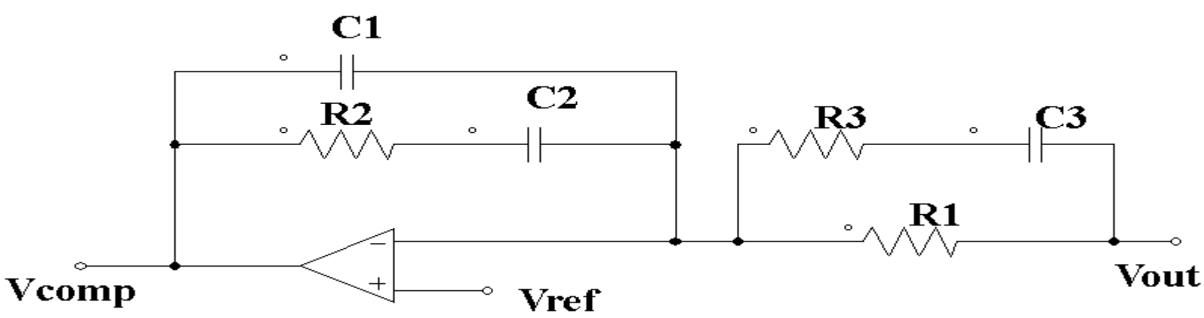


Figure 4.8 (c): Type III compensator

4.5 Designing of Controller

The design methods are broadly classified as follows:

1. Transfer Function Based Controller Design Methods (TFBCD): System displayed here is Linear time invariant (LTI) as well as Single-input and Single-output (SISO).
2. State Space Controller Design Methods (SSCD): System modeled here is Multiple-input and multiple-output system (MIMO).

The adopted method to design controller is TFBCD since assuming system to be LTI and SISO therefore classical techniques available are as:

- Root locus.
- Bode diagram.
- Nyquist Diagram.
- Inverse Polar plot.
- Nicholas chart.

The classical methods above are well suited methods but root locus is enough for predicting the results for lower order as well as higher order systems, Bode diagram is also popular technique among designers but it fails for the non-minimum phase systems.

4.6 Close Loop Analysis of the Boost Converter System

For a boost AC-DC converter a feedback control is shown in Fig. 4.9. Different part of the circuit is error amplifier, PI controller and Comparator as shown in Fig. 4.10. The wave shapes of the circuit of Fig. 4.9 for different reference voltage is shown in Fig. 4.11. It can be observe that changing the reference voltage the output voltage changes accordingly.

The shape of the input current is yet to be achieving by connecting a current control loop which is not done in this report.

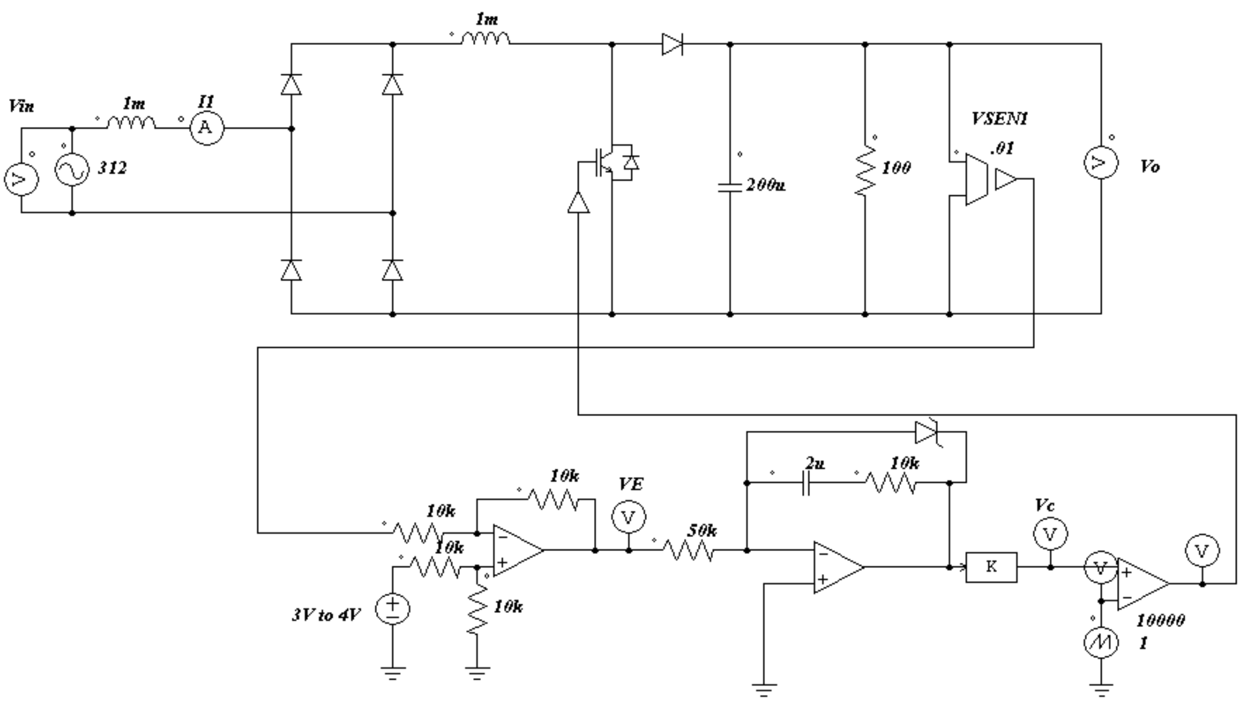


Figure 4.9: Close loop system of boost converter.

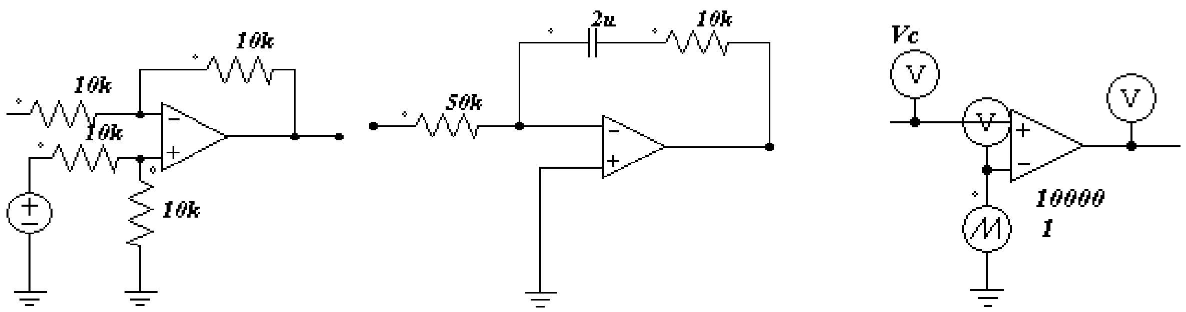


Fig. 4.10 Error amplifier, PI Controller and Comparator

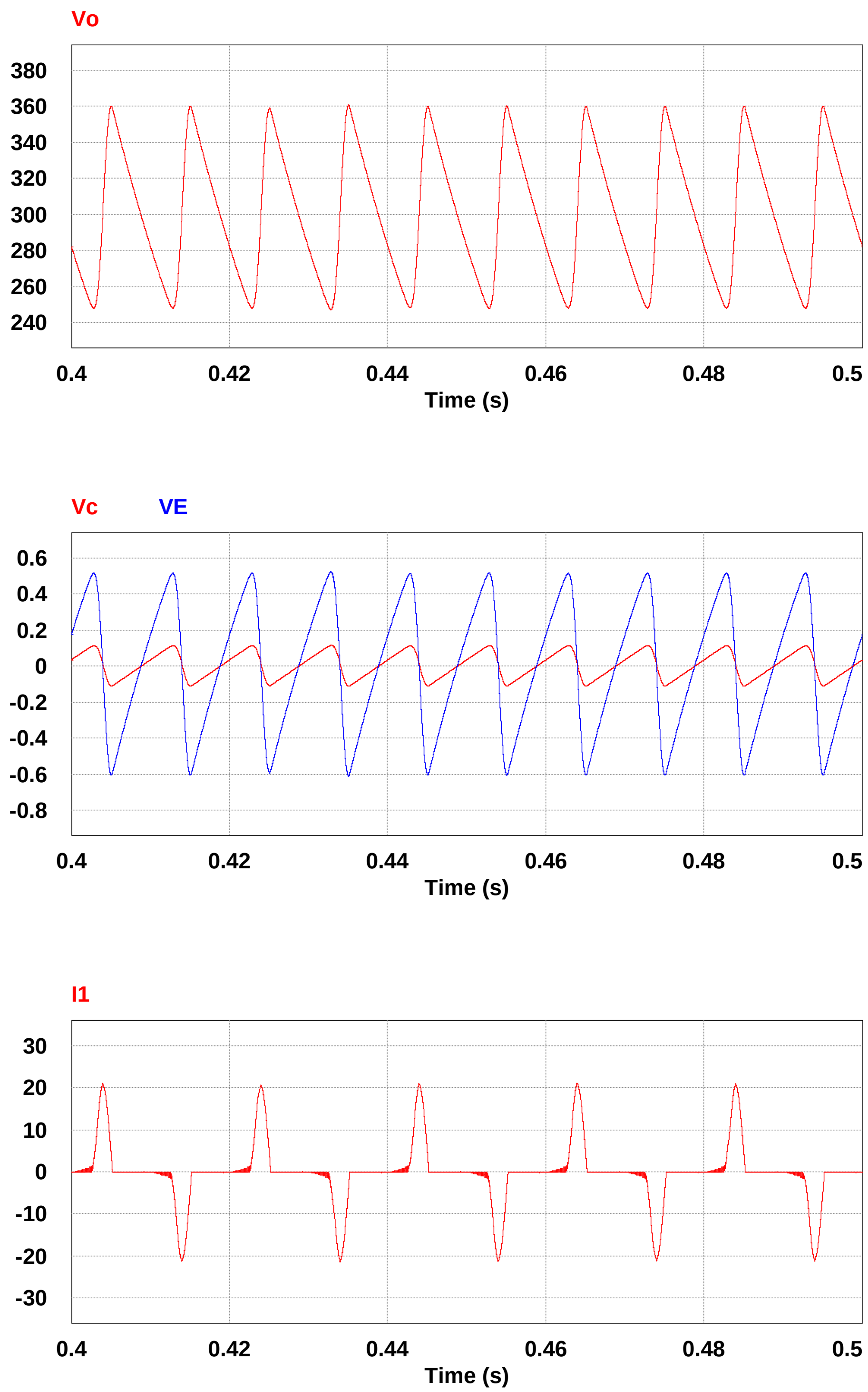


Fig.4.11 (a): Wave shapes for Vref=3V

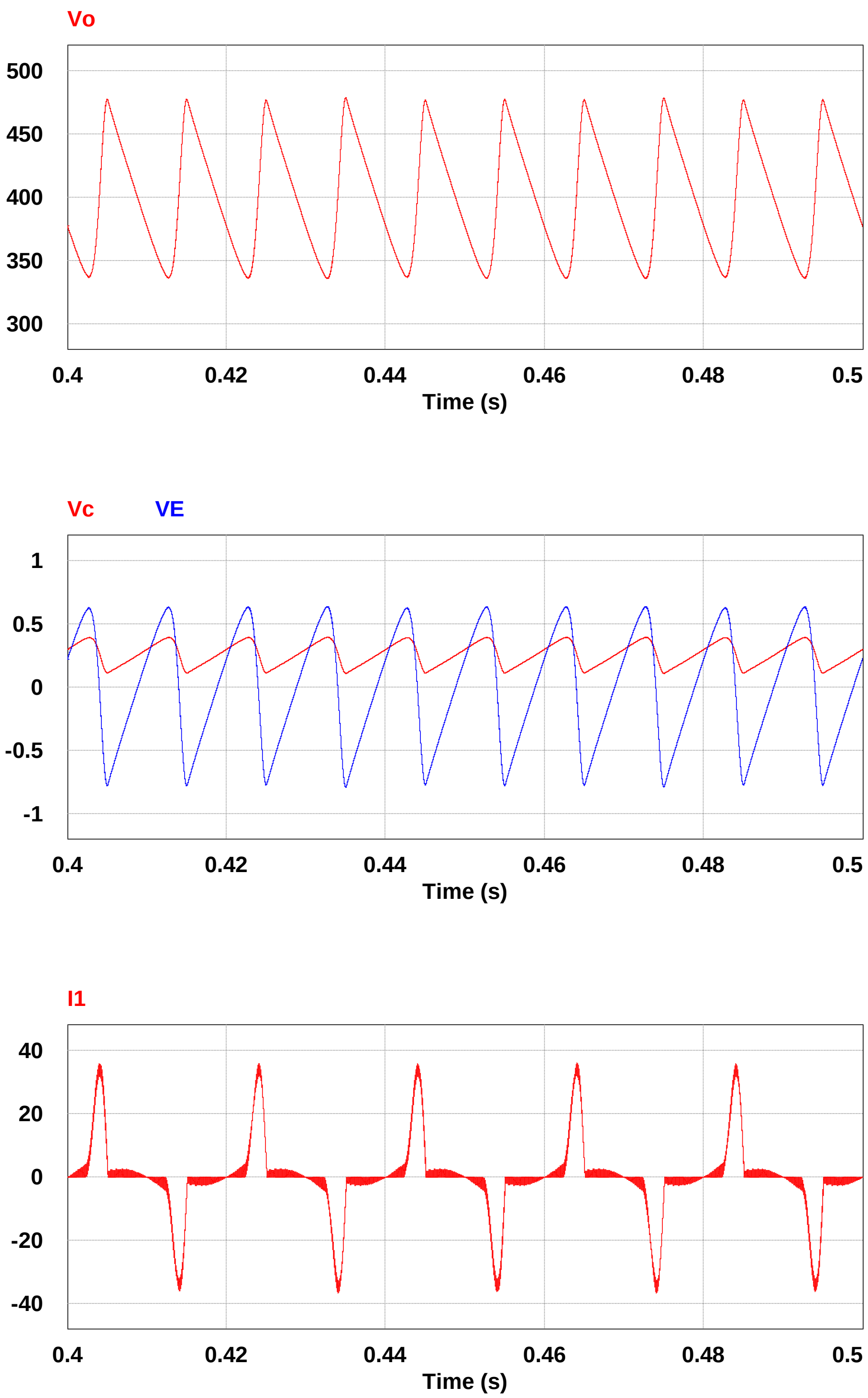


Fig. 4.11 (b): Wave shapes for Vref=4V

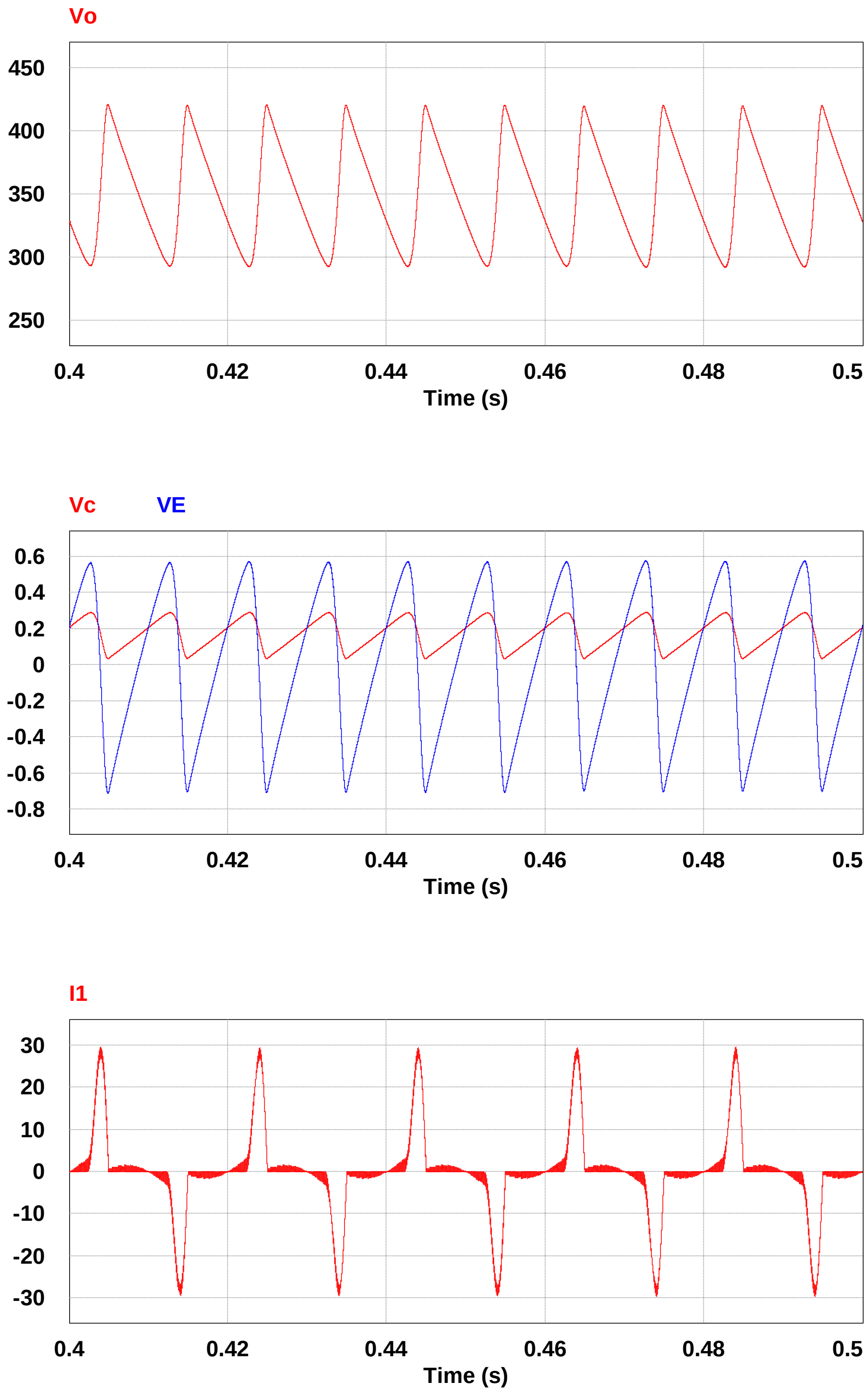


Fig. 4.11 (c): Wave shapes for Vref=3.5V

4.7 Arduino as Feedback Control in buck converter

Arduino is used to generate the control voltage of the buck circuit in our project. As we mentioned before the initial idea was to improve the power factor and total harmonic distortion by the boost DC/DC converter and for fixed DC output beside the change in output load in a limit via Buck DC/DC converter. For Boost DC/DC converter PI controller is used to generate the controlling voltage of IGBT. Same method could be applied the buck circuit. But if we have a fixed range we can easily solve the problem just by using numerical method for a fixed range or load. For variable load the duty cycle of the control voltage is needed to be fixed. The difference is not that great in a small range. But if we consider upper limit lie one kilo ohm load and 10-ohm load, there is a clear difference in output voltage. So, solving this problem is a must in order to get a constant output voltage.

Firstly, we have to determine a range of register. In our circuit we used the range 100 ohm to 250 ohms.
Then in X axis we need to put the variable we can control which is the load register. In Y axis we put the result of the independent variable duty cycle which is the duty cycle. We take different data points and form a curve. From regression analysis or using any interpolation method equation we can easily figure out the relationship between X and Y.

Then we need to use a sensor that can sense the output load and. Therefore, with that output load Arduino will solve the equation and produce the duty cycle required. According to demand. Arduino will be generating the control signal required to produce the constant output voltage. Like Boost DC/DC converter the switching frequency used will be one hundred kilo hertz. Same switching frequency over the whole system causes a synchronous change in each and every step of converter. **Figure 4.9** show the configuration how ARDIUNO will be implemented over the buck DC/DC converter.

Arduino can also be used instead of PI controller we used but PI controller is simple to use in the boost DC/DC converter. For this reason, we have decided to use PI controller instead of a microcontroller. Also, this option is more cost effective which can produce the same result.

From the output we measured voltage with Arduino and as we added a very small resistance in series with the load resistance we find the value of current flow in the load resistance. With the function we created for the duty cycle we were able to create a PWM signal of 100k.

Load Resistance(R)	Duty Cycle (D)
100	0.25
130	0.239
150	0.234
180	0.213
200	0.202
230	0.188
250	0.18

Figure 4.10 shows the change of duty cycle in respect of load. Using **2rd order Lagrange method of interpolation**, a second order equation is derived to describe the relation between R and D. Using R/10 for the calculation,

we can define D as:

$$D = (145.6667)(10)^{-6}R^2 + 0.0004667R + 0.26$$

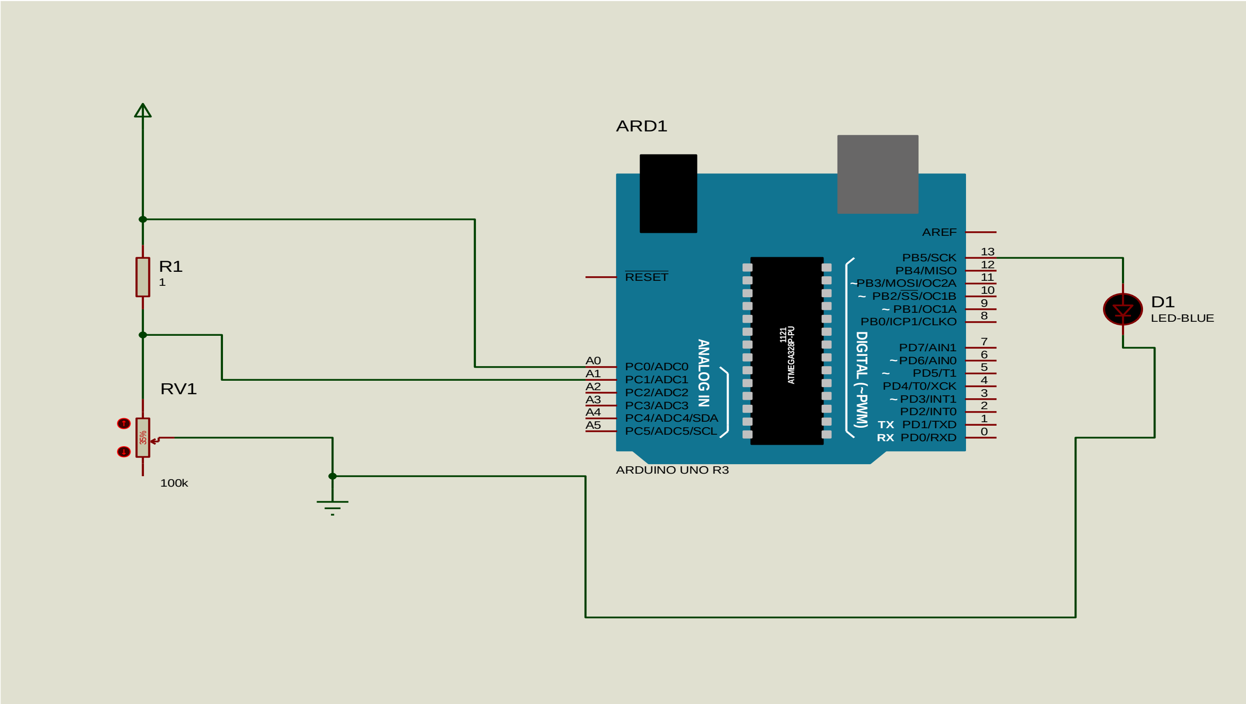


Figure 4.12: circuit diagram for testing Arduino

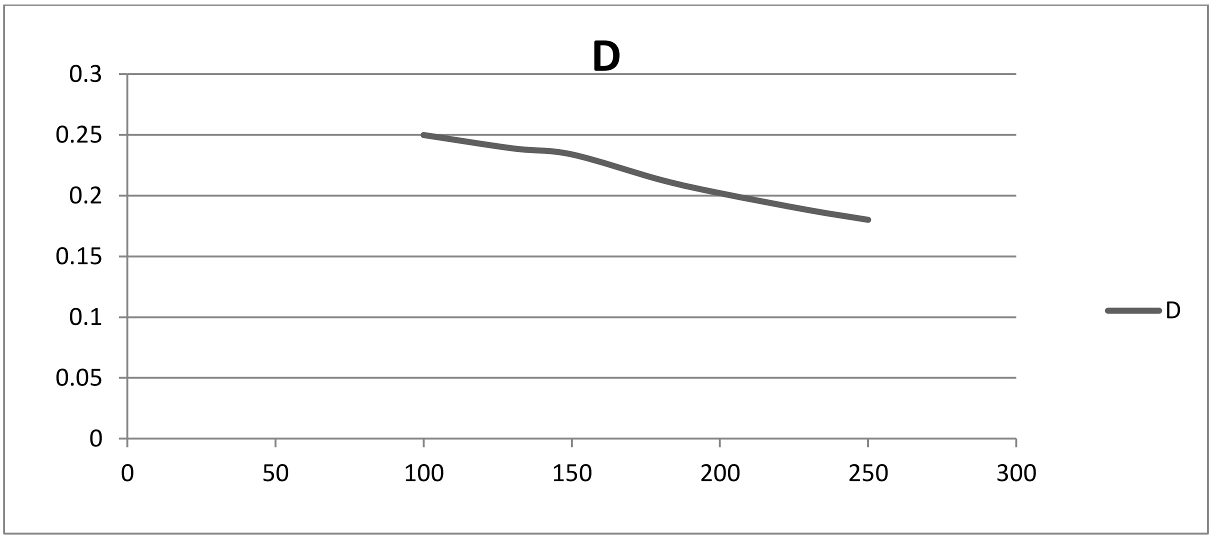


Figure 4.13: Relation between resistance(X-axis) and duty cycle(Y-axis)

Code for Arduino:

```
float R = 1.00;
void setup()
{
  pinMode(13, OUTPUT);   //DUTY CYCLE PIN
  Serial.begin(9600);
}
void loop()
{
  float  v0 = analogRead(0);
  float v1 = analogRead(1);
  float v_r = v0 - v1;
  float i_r = v_r / R;
  float I = i_r;
  float Rl = v_r / I;
  float  D = (pow(Rl,2))* (145.6667) * pow(10, -6)   -( 0.0004667*Rl)+ 0.26);
  //pwm
  digitalWrite(13, HIGH);
  delayMicroseconds(D); // Approximately 10% duty cycle @ 1KHz
  digitalWrite(13, LOW);
  delayMicroseconds(1000 - D);
}
```

4.8 Conclusion

This chapter was all about the compensator types, pros and cons and the methods used to represent our system as a mathematical model in order to design and implement a controller for the system.

For the controller system an Arduino was used and therefore we got an idea about how an Arduino works and how to apply it to build a feedback system for our circuit, and we now have successfully designed a controller for our boost circuit that will do the power factor correction while the load changes.

Chapter 5

Summary

5.1 Developments:

The power factor correction unit we analyzed was analog and works on continuous conduction mode(CCM). Now a day, with use of microcontroller and analog to digital converters, digital power factor correction unit is made. Digital power factor correction unit has more functions than analog one. Furthermore, the control also has fully programmable firmware so that it is possible to program the power factor correction unit according to the need.

With improvement in advanced semiconductor device the power factor correction unit can be improved. Fast switching capability switches and new generation diodes can rapidly decrease the heat loss in the system. Cooling system can be installed to keep the system heat minimum.

Fabrication technology allows us to reduce the circuit size. With recent developments it is possible to integrate digital power factor correction unit and DC/DC converter in one small integrated circuit(IC) [3].

5.2 Conclusion:

During this thesis project we have studied about different types of rectifiers and converter circuits.

We have analyzed half and full wave rectifiers with different combinations of load and observed the outcomes through simulations. We also studied about various types and applications of DC-DC and AC-DC converters, keeping our major focus on buck and boost converter circuits.

We gained vast knowledge about PSIM and MATLAB software during the project, where we carried out all our simulations and codes respectively.

Topics we have covered in order to design the controller circuit for the rectifiers include close loop and open loop transfer function and stability of a system, state space analysis, Nyquist criteria and bode plots are some of them.

We also focused on the different types of compensators, I.e. we used PI controller for our design, to get the most efficient results considering its pros and cons respectively.

For the controller we have used an Arduino to provide the feedback system for a certain range of load by varying the duty cycle.

At the end, we successfully designed a smart power factor correction circuit with can correct power factor. From this thesis we were able to get better knowledge on advanced semiconductor switches, AC/DC, DC/DC converters and control system.

This design can be implemented in order to get higher efficiency for any system given a certain range of load.

Reference

[1] Sam Abdel-Rahman, Franz Stückler, Ken Siu “PFC boost converter design guide”, Infineon Technologies AG, February 2016.

[2] SW Lee “Demystifying Type II and Type III Compensators Using OpAmp and OTA for DC/DC Converters”; Texas Instruments, July 2014.

[3] “Power factor correction (PFC) controller – Texas Instrumentals” - http://www.ti.com/lsds/ti/power-management/power-factor-correction-overview.page.

[4] K. Kit Sum, “Improved Valley-Fill Passive Current Shaper” Power System World. Year - 1997.

[5] Muhammad H. Rashid “Power Electronics Circuits, Devices and Applications” 3rd edition, Pearson Education India.

[6] Fang Lin Luo, Hong Ye “Power Electronic Advanced Conversion Technologies” CRC Press and Taylor & Francis Group.

[7] Ned Mohan “Power Electronic and Drives”, MNPERE.

[8] Ned Mohan, Tore M. Undeland, William P. Robbins “Power Electronics” 2nd edition, John Wiley & Sons, INC.

[9] Ned Mohan “Power Electronics a First Course”; John Wiley & Sons, INC.

[10] Daniel W. Hart “Power Electronics”; McGraw-Hill .

[11] Rosario Costanzo, Gianluca Messina, Antonino Gaito “Fishbone diagram for power factor correction”; STMicroelectronics Press, March 2014.

[12] SW Lee “Practical Feedback Loop Analysis for Voltage-Mode Boost Converter”;

Texas Instruments, January 2014.

[13] Derek Rowell “State-Space Representation of LTI Systems” MIT Publications, October 2002.

[14] Prof. S. Samanta “State-space average Modeling of DC-DC Converters with parasitic in Discontinuous Conduction Mode (DCM). Department of Electrical Engineering. National Institute of Technology, May 2010.

[15] Minyoung Kim, Vladimir Pavlovic “Conditional State Space Models”.; Rutgers Publication 2007.