Design of a Single Phase Switch Mode AC-DC Converter

A Thesis
Submitted to the Department of Electrical and Electronics
Of
BRAC University
By

Md. Rafiur Rahman Surjo- 09221105
Md. Afsarul Amin- 09221180

Supervised by
Mrs. Amina Hasan Abedin

In Partial Fulfilment of the Requirements for the degree of Bachelor of Science in Electrical and Electronics Engineering

Fall 2011
BRAC University, Dhaka

DECLARATION

We hereby declare that this thesis is based on the results we found in our pre-thesis and thesis-I session. Contents of work found by other researchers are mentioned by reference. This thesis has never been previously submitted for any degree neither in whole nor in part.

Signature of Supervisor	Signature of Author
……………..	……………
Amina Hasan Abedin	Md. Rafiur Rahman
	……………
	Md. Afsarul Amin

ACKNOWLEDGEMENT

Firstly, we would like to thank our supervisor Mrs. Amina Hasan Abedin for giving us the opportunity to work on this project under her supervision and also for her support and guidance throughout the thesis. Under her supervision, we have learned a lot.

Chapter

LIST OF FIGURES

LIST OF TABLES

OBJECTIVE

The basic objective of the thesis is to construct a circuit that can give flexible control over the speed of a DC motor. In the pre-thesis session, the concept for the design for a rectifier circuit to convert AC power into DC was presented along with simulation results. The focus of the thesis session to construct a CUK rectifier circuit that can cut the voltage down below input and can also boost the output voltage to a higher value and thus establish flexible control over the speed of a motor.

PROJECT OVERVIEW

In the pre-thesis session, the concept for the speed control of a DC motor has been presented. Study of the AC-DC converter and simulations were the prime target. In the thesis-I session an appropriate pulse width modulator was designed constructed along with a prototype that implemented the basic idea of the speed control via means of input voltage control of a motor. In the thesis-II the circuit for the speed control has been designed, constructed and implemented for a 24V DC motor with effective results.

Page left blank on purpose

Chapter 1
INTRODUCTION

1.1 Introduction

The use of rectifiers in industrial applications started at the era of mercury converters with the electromechanical contact converter. DC machines are common in day to day use. But the supply that we get from power companies is AC. To use those machines AC supply has to be turned into DC supply by the use of a rectifier.

A rectifier is an electrical device that converts the incoming AC (alternating current) from a transformer or any other ac power source to pulsating DC (direct current). Rectifier may be made of diodes, solid states, vacuum tube, mercury arc valves and other components. All rectifier circuits may be classified into one of two categories, i) half wave rectifiers and ii) full wave rectifier. Rectifiers are also used for 3-phase inputs.

Rectifiers can further be classified into two categories i. e. controlled and uncontrolled rectifier. The dc output always remain constant if ac input voltage is constant in an uncontrolled rectifier whereas the output voltage can be controlled in a controlled rectifier. Rectifiers are widely used in non linear loads which are connected with distribution systems which plays an important role in power system network (ex: UPS, discharge lamp, television, computer, fax machines, ferromagnetic devices, arc furnaces, energy savers etc).

A further application of the rectifier is driving a DC motor. Speed control in DC motor is an important issue. With time the need of flexible speed control for motor is becoming essential. One way to control the speed of the motor is by varying its input voltage. Thus this project aims on designing a rectifier circuit that can supply a voltage as required and can be adjusted if necessary even after the operation starts.

1.2 Background studies

With very few exceptions, distribution of electric power is in AC format. With the advancement of technology ac to dc converters are enjoying widespread applications. As a result ac-dc converter has formed an active area of research in recent decades. The need for DC power may be supplementary, such as use in electronic controls, or crucial, such as the DC link of a motor drive. At the same time regulatory agencies are enforcing strict harmonics regulations such as IEC 1000, Std 500 etc. This is due to the high power factor and low line current harmonic distortion requirements. In addition to the high power factor, the advantages of high frequency switching are also being utilized for realizing ac-dc converter. These include high efficiency, smaller reactive components, easier filtering, reduced volume etc.

To convert line frequency ac to dc, a line frequency diode bridge rectifier is used. A large filter capacitor is used at the rectifier output to reduce the ripple in the output voltage. But current drawn by this converter is peaky in nature for the large capacitor. This input current is rich in low order harmonics and due to the presence of these harmonics, the total harmonic distortion is high and the input power factor is deprived. Problems associated with these low power factors and harmonics, utilities will enforce harmonic standards and guidelines which will limit the amount of current distortion allowed into the utility. It is highly require to achieving rectification at close to utility power factor and low input current distortion.

In modern systems most of the conversions are performed with semiconductor switching devices such as diodes, thyristor and transistors. An AC to DC converter is the most commonly used power electronics devices found in many consumer electronics device (e.g. television, computer, battery chargers etc). Power electronics devices are characterized being either a short circuit or an open circuit. As the switching capability combined with efficiency and performance making power electronics a fast growing area in electrical engineering. At the same time it is desirable because of relatively small power loss in the device. An AC to DC converter enables integrated circuits to operate from a 50/60 Hz AC line voltage by converting the AC signal to a DC signal of the suitable voltage. Therefore, this project is assigned to design a single phase switch mode AC to DC converter.

1.3 Applications

With the wide spread of electronics and technology the necessary of DC power has increased as the used of DC electronics has increased over the decades. Here comes an AC-DC converter in play. With the wide spread of DC power needs, the application of AC-DC converter has covered a range from milli-watts to megawatts. Some applications of AC-DC converter is given below.

1. Use in detection of amplitude modulated radio signal
2. Use to supply polarized voltage for welding
3. Use in Uninterruptible power supplies
4. Use in Induction heating
5. Use in HVDC power transmission
6. Use in Variable-frequency drives
7. Use in Electric vehicle drive Application
8. Use in vacuum cleaners
9. Use in Air conditioning
10. Use in cordless telephone
11. Use in DC motor control
12. Use in rice cookers
13. Use in electric carpets
14. Use in washing basket
15. Use in washing machine
16. Use in air cleaner

Chapter 2
RECTIFIERS

2.1 Study of Rectifiers

Classification of Rectifiers

I) Single phase

   a) Half-wave : i) Controlled ii) Uncontrolled

   b) Full-wave : i) Controlled ii) Uncontrolled

II) Three Phase

   a) Half-wave : i) Controlled ii) Uncontrolled

   b) Full-wave : i) Controlled ii) Uncontrolled

2.2 Single phase rectifier

(a) Half-Wave Rectifier: In half-wave rectifier, half of the ac cycle (either positive or negative) pass, while during the other half cycle the diode blocks the current from flowing. Basic half-wave rectifier circuit may be constructed with a single diode in a one-phase supply, or three diodes with a three-phase supply. Such circuits are known as half-wave rectifier as they only work on half of the incoming ac wave.

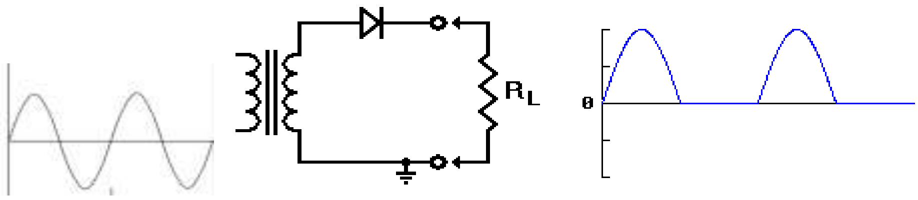


Fig. 2.1: Half Wave Rectifier

(b) Full-Wave Rectifier: A full-wave rectifier converts the whole incoming ac wave so that both halves are used to cause the output current to flow in same direction (either positive or negative). Full-wave rectification is more efficient because it converts both polarities of input waveform to DC. A full-wave rectifier circuit requires four diodes instead of one needed for half-wave rectification. For the arrangement of four diodes the circuit is called a diode bridge or bridge rectifier.

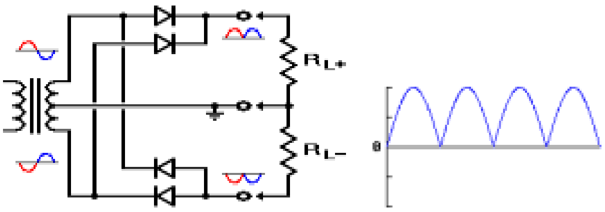


Fig. 2.2: Full Wave Rectifier

2.3 Three-phase half wave rectifier

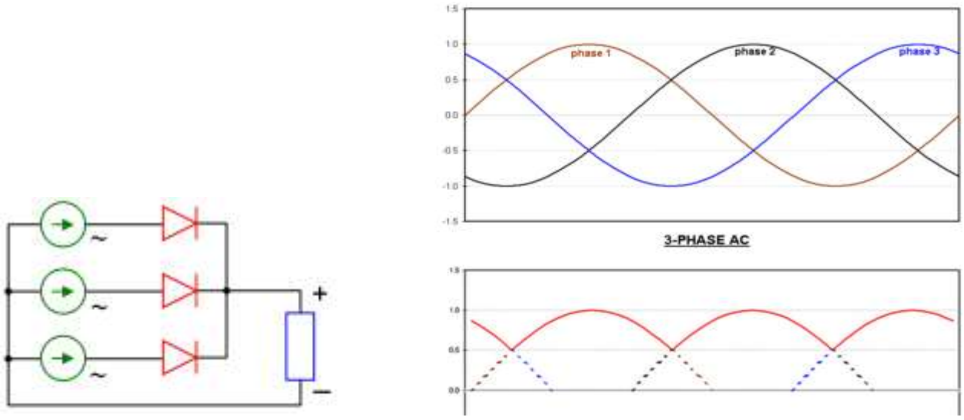
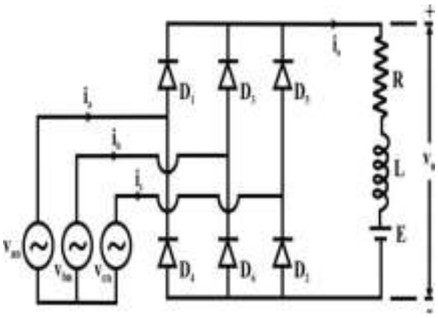


Fig. 2.3: phase half wave rectifier

The operation theory is like a single phase half wave rectifier. As each of the phases reach 0.7V the diode of the respective phase start conducting. The resultant current flows through the load.



Highest line-line voltage	Conducting diode pair
V_{ab}	D1 and D6
V_{ac}	D1 and D2
V_{bc}	D2 and D3
V_{ba}	D3 and D4
V_{ca}	D4 and D5
V_{cb}	D5 and D6

Fig. 2.4: 3-phase full wave rectifier

Table 2.1: Conduction modes of diodes

The conducting pair is those that have the highest line-line voltage at that particular instant. The conduction modes are listed in table 2.1.

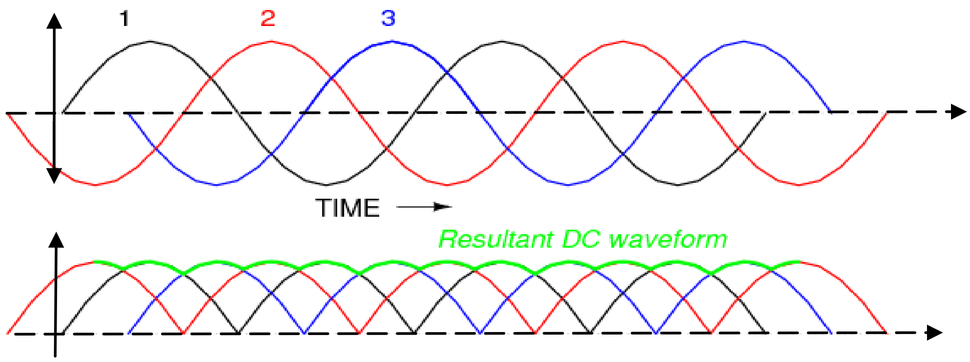


Fig. 2.5: Input and output voltage waveform for 3 phase full wave rectifier

2.4 Study of single phase rectifier

When capacitor is added to the load side of the circuit, to eliminate the ripples (pulses), the output voltage and current wave become more dc but the input currents give rise to huge amount of harmonics.

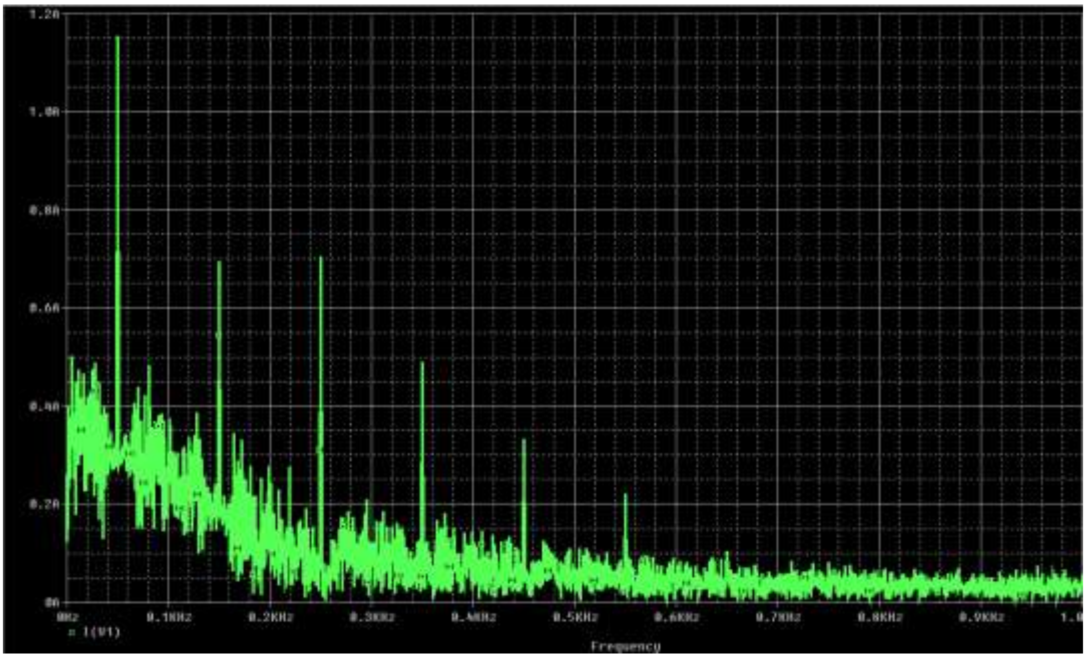


Fig. 2.6: Fourier series of the output of a bridge rectifier with a capacitor on the load side

Harmonics	**Values(mA)**	**Harmonics**	**Values(mA)**
I_1(50Hz)	1956.9	I_{11} (550Hz)	311.775
I_2(100Hz)	1038.1	I_{12} (600Hz)	172.471
I_3 (150Hz)	444.444	I_{13}(650Hz)	112.770
I_4 (200Hz)	500.829	I_{14}(700Hz)	76.285
I_5(250Hz)	805.970	I_{15}(750Hz)	199.005
I_6 (300Hz)	182.421	I_{16}(800Hz)	116.086
I_7 (350Hz)	497.512	I_{17}(850Hz)	53.068
I_8 (400Hz)	268.657	I_{18}(900Hz)	89.552
I_9 (450Hz)	348.259	I_{19}(950Hz)	175.788
I_{10}(500Hz)	86.236	I_{20}(1000Hz)	92.869

THD= 83.6%

Table 2.2: Harmonics component for fig. 2.6

Adding another capacitor to the circuit on the input side (fig 2.7) helps reducing the harmonic frequencies. The capacitor acts as a filter eliminating the higher frequency components. But in order to get rid of all or most of the harmonics (bring down THD to about less than 5%) huge capacitors are needed (in the range of milli-farads). Although the capacitor filters off a huge portion of the harmonics, it causes the circuit to draw too much current from the system.

Introducing passive filters to the circuit can prevent harmonics. The harmonic distortion can almost be reduced to less than 5%. But they do not allow the regulation of the output voltage and also decreases the output voltage levels in comparison with the unfiltered rectifiers. In order to get such low harmonic content the value of the inductor and the capacitor has to be huge too (e.g. 100mH and 100uF). A single phase diagram of a rectifier with passive filter is given below.

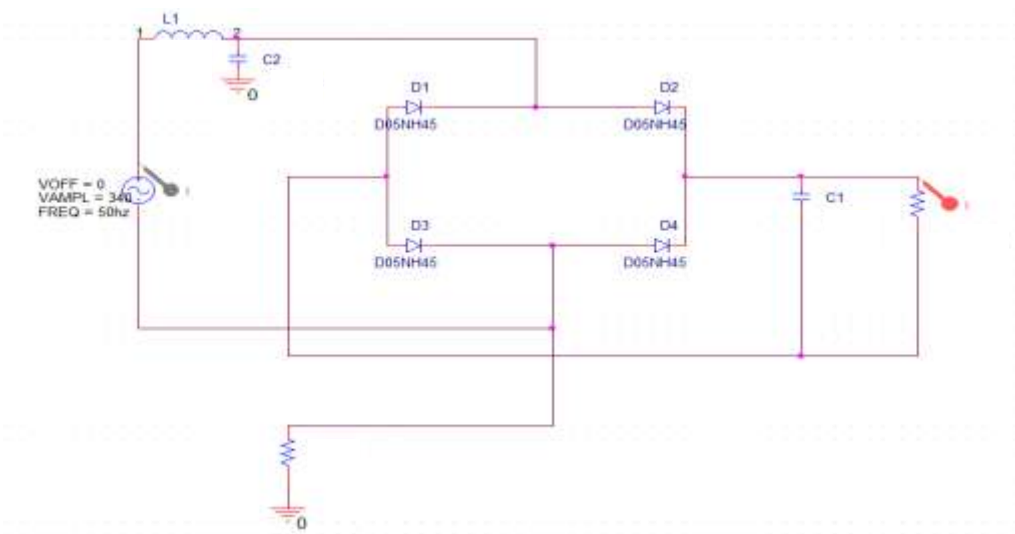


Fig. 2.7: Rectifier circuit with passive

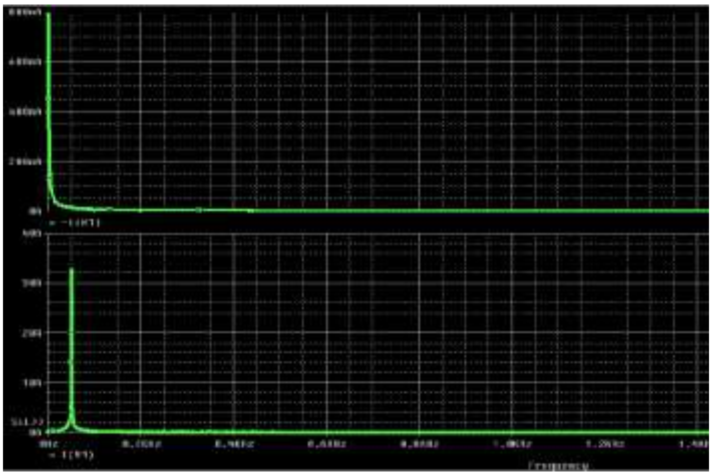


Fig. 2.8: Fourier series of the output of a rectifier with passive filter

As can be seen in the graph the harmonic content has been eliminated almost completely by the use of the passive filter.

2.5 Controlled rectifier

Control over the output voltage and thus power can be established using several different techniques, e.g linear mode regulator or transformer-based rectifier. Switched mode control method has been selected for application in this project. This mode uses a switch to connect and disconnect the source to the load a regular intervals and thus controlling the amount of power to be transferred. Switched mode rectifiers can be made to be highly efficient. The advantages of the switched mode regulator over a linear mode regulator or a transformer based regulator are listed below.

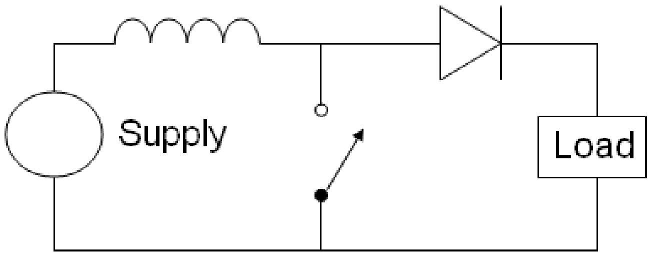


Fig. 2.9: Switched mode rectifier

2.6 Advantages of switching power over linear power supply

	Linear power supply	Switching power supply
Size and weight	Heat-sinks for high power linear regulators add size and weight. Transformers, if used, are large due to low operating frequency	Smaller transformer (if used; else inductor) due to higher operating frequency (typically 50 kHz – 1 MHz). Size and weight of adequate RF shielding may be significant.
Output voltage	If transformer is used the achievable voltage is restricted by the transformers capability but the output voltage caries greatly with load.	Any voltages available, limited only by transistor breakdown voltages in many circuits. Voltage varies little with load. A SMPS can usually cope with wider variation of input before the output voltage changes.
Efficiency, heat, and power dissipation	If regulated: efficiency largely depends on voltage difference between input and output; output voltage is regulated by dissipating excess power as heat resulting in a typical efficiency of 30–40%.	Output is regulated using duty cycle control; the transistors are switched fully on or fully off, so very little resistive losses between input and the load. The only heat generated is in the non-ideal aspects of the components.
Complexity	The circuits used are simpler to design and construct.	Consists of a controller IC, one or several power transistors and diodes as well as a power transformer, inductors, and filter capacitors. Some design complexities present (reducing noise/interference; extra limitations on maximum ratings of transistors at high switching speeds) not found in linear regulator circuits.
Radio frequency interference	Mild high-frequency interference may be generated by AC rectifier diodes under heavy current loading, while most other supply types produce no high-frequency interference.	EMI/RFI produced due to the current being switched on and off sharply. Therefore, EMI filters and RF shielding are needed to reduce the disruptive interference.
Electronic noise at the input terminals	Causes harmonic distortion to the input AC, but relatively little or no high frequency noise.	Very low cost SMPS may couple electrical switching noise back onto the mains power line, causing interference with A/V equipment connected to the same phase. Non power-factor-corrected SMPSs also cause harmonic distortion.
Acoustic noise	Faint, usually inaudible mains hum, usually due to vibration of windings in the transformer and/or magnetostriction.	Usually inaudible to most humans, unless they have a fan or are unloaded/malfunctioning, or use a switching frequency within the audio range or the laminations of the coil vibrate at a sub harmonic of the operating frequency.
Power factor	Low for a regulated supply because current is drawn from the mains at the peaks of the voltage sinusoid, unless a choke-input or resistor-input circuit follows the rectifier.	Ranging from very low to medium since a simple SMPS without PFC draws current spikes at the peaks of the AC sinusoid.

Table 2.3: Comparison of switched mode and linear regulator

2.7 Consideration of Harmonics in rectifier Circuits

The output of a rectifier circuit is non-linear as the resulting voltage is DC. Drawing non linear power from a source causes harmonic current (current that have frequency that are multiple of the fundamental) to arise in the circuit.

In an electrical distribution system harmonics create:

1) Large load currents in the neutral wires of a 3 phase system. Theoretically the neutral current can be up to the sum of all 3 phases therefore causing overheating of the neutral wires. Since only the phase wires are protected by circuit breakers of fuses, this can result in a potential fire hazard.
2) Overheating of standard electrical supply transformers which shortens the life of a transformer and will eventually destroy it. When a transformer fails, the cost of lost productivity during the emergency repair far exceeds the replacement cost of the transformer itself.
3) High voltage distortion exceeding IEEE Standard
4) High current distortion and excessive current draw on branch circuits
5) High neutral-to-ground voltage often greater than 2 volts
6) High voltage and current distortions exceeding IEEE Standard
7) Poor power factor conditions that result in monthly utility penalty fees for major users (factories, manufacturing, and industrial) with a power factor less than 0.9.
8) Resonance that produces over-current surges. This results in destroyed capacitors and their fuses and damaged surge suppressors which will cause an electrical system shutdown.
9) False tripping of branch circuit breakers.

A non-sinusoidal current waveform is rich in harmonics. This is most apparent from noting the Fourier series. Any alternating waveform can be represented by the summation of a fundamental frequency and its harmonics.

$i = I_0 + I_1\sin(wt + \alpha) + I_{2\sin}(2wt + \alpha) +..+ I_n\sin(nwt + \alpha)$

The term I is the instantaneous value at any time. The I terms are the maximum amplitude for each of the harmonic frequencies. The angular frequency w is 2πf. The phase shift angle represents the time delay between the reference voltage waveform and the current. The n subscript and coefficient of frequency indicates the harmonic number.

The harmonic factor (HF) is used to describe the total harmonic distortion (THD) on the waveform. Harmonic factor is the ratio of the RMS value of all the harmonics(For example, if the fundamental power frequency is 50 Hz, then the 2^{nd} harmonic is 100 Hz, the 3^{rd} is 150 Hz, etc.) to the RMS value of the fundamental.

$$THD\% = \frac{\sqrt{\sum_{h=2}^{h=\infty}(M_h)^2}}{M_1} \times 100\%$$

Where M_h is the magnitude of either voltage or current harmonic component and M_1 is the magnitude of either the fundamental voltage or current.

In today’s environment, all computer systems use converted utility AC voltage to regulated low voltage DC for internal electronics. These non-linear power supplies draw current in high amplitude short pulses. These current pulses create significant distortion in the electrical current and voltage wave shape. This is referred to as a harmonic distortion and is measured in Total Harmonic Distortion (THD). The distortion travels back into the power source and can affect other equipment connected to the same source.

Chapter 3
CONVERTERS

The output voltage coming from full wave the full bridge rectifier is unregulated. That is the output voltage cannot be controlled. The output of rectifier is fed into a converter for regulation.

There are four different types of converter available. A brief study of the kinds are presented below.

Before proceeding further the following assumptions are made: that all the elements in the circuit are considered ideal, i.e. the inductor and capacitor absorbs no energy, the average voltage drop across the inductor and the average capacitor current is zero, the net change in inductor current and the net change in the capacitor voltage at the end of a commutation cycle is zero and the circuit is operating in steady state.

There are four basic types of converter, the buck, the boost, the buck-boost and the cuk. All these converters have some basic common aspects. All these converters use an energy storing element to transfer energy from the source to the load. They all use electronic switches like MOSFET, transistors, etc to control the power flow.

All these converters have two modes of conduction 1) continuous mode and 2) discontinuous mode. In the continuous mode the current through the inductors of the converters are never zero and thus the inductor never discharges totally whereas in discontinuous mode the inductor current falls back to zero showing total discharge of inductor energy.

3.1 The buck

The buck converter is used to step an input voltage down from a higher potential to a lower potential. The input and output power ideally remains the same. The circuit usually consists of an inductor to store energy and a switch to control the power flow.

Operating principle

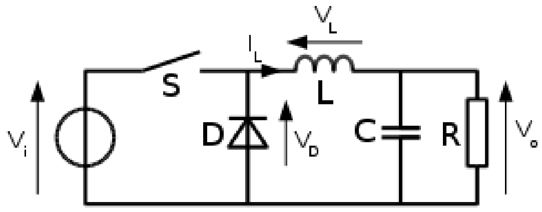


Fig. 3.1: buck converter

The circuit has two stages of operation

On state: when the switch is on the diode is open and the inductor and the load side is connected to the input and the inductor stores energy.

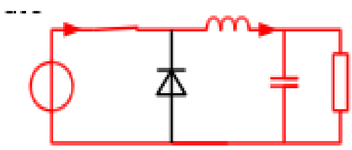


Fig. 3.2: on state

Off state: the switch opens to isolate the source from the rest of the circuit, the diode becomes positive biased as the inductor changes polarity and the inductor discharges to provide energy to the load.

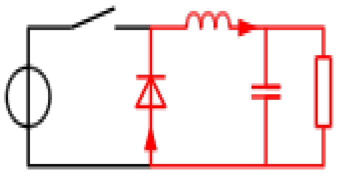


Fig. 3.3: off state

Continuous mode

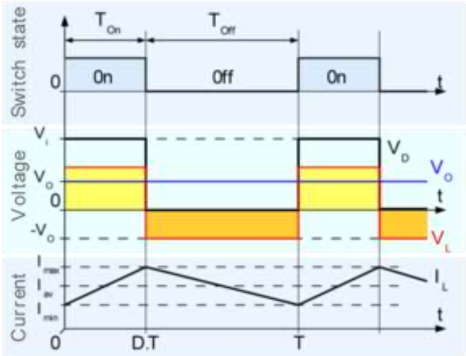


Fig. 3.4: wave shapes of continuous mode

The rate of change of I_L can be calculated from:

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

With V_L equal to $V_i - V_o$ during the On-state and to $-V_o$ during the Off-state. Therefore, the increase in current during the On-state is given by:

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

Identically, the decrease in current during the Off-state is given by:

$$\Delta I_{L_{off}} = \int_{t_{on}}^{t_{off}} \frac{V_L}{L}\,dt = -\frac{V_o}{L}t_{off}$$, t{off}= T

If the circuit operates in steady state then ideally the current at the start of a cycle would be equal to current in the end of the cycle. That is, the net change in current is zero.

So we can write from the above equations:

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

Replacing t_{on}=DT and t_{off}= (1-D)T we get

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

Or,

$$\boldsymbol{V_0 = D.V_i}$$

From this equation, it can be seen that the output voltage of the converter varies linearly with the duty cycle for a given input voltage. As the duty cycle D is equal to the ratio between t_{On} and the period T, it cannot be more than 1. Therefore, $V_o \leq V_i$. This is why this converter is referred to as *step-down converter*.

So, for example, stepping 12 V down to 3 V (output voltage equal to a fourth of the input voltage) would require a duty cycle of 25%, in our theoretically ideal circuit.

Discontinuous mode

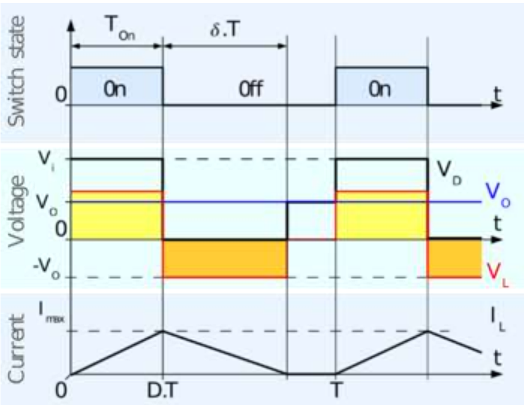


Fig. 3.5: wave shapes of discontinuous mode

The energy in the inductor is the same at the beginning and at the end of the cycle (in the case of discontinuous mode, it is zero). This means that the average value of the inductor voltage (V_L) is zero; i.e., that the area of the yellow and orange rectangles in figure 3.5 are the same. This yield:

$$(V_i - V_o)\,DT - V_o\delta T = 0$$

So the value of δ is:

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

The output current delivered to the load (I_o) is constant; as we consider that the output capacitor is large enough to maintain a constant voltage across its terminals during a commutation cycle. This implies that the current flowing through the capacitor has a zero average value. Therefore, we have:

$$\bar{I}_L = I_o$$

Where $\bar{I_L}$ is the average value of the inductor current. As can be seen in figure 3.5, the inductor current waveform has a triangular shape. Therefore, the average value of I_L can be sorted out geometrically as follow:

$$\begin{aligned}\bar{I_L} &= \left(\frac{1}{2}I_{L_{max}}DT + \frac{1}{2}I_{L_{max}}\delta T\right)\frac{1}{T} \\ &= \frac{I_{L_{max}}\left(D+\delta\right)}{2} \\ &= I_o\end{aligned}$$

The inductor current is zero at the beginning and rises during t_{on} up to I_{Lmax}. That means that I_{Lmax} is equal to:

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

Substituting the value of I_{Lmax} in the previous equation leads to:

$$I_o = \frac{\left(V_i - V_o\right)DT\left(D+\delta\right)}{2L}$$

And substituting δ by the expression given above yields:

$$I_o = \frac{\left(V_i - V_o\right)DT\left(D + \frac{V_i - V_o}{V_o}D\right)}{2L}$$

The previous expression can be rewritten as:

$$V_o = V_i\frac{1}{\frac{2LI_o}{D^2V_iT}+1}$$

It can be seen that the output voltage of a buck converter operating in discontinuous mode is much more complicated than its counterpart of the continuous mode. Furthermore, the output voltage is now a function not only of the input voltage (V_i) and the duty cycle D, but also of the inductor value (L), the commutation period (T) and the output current (I_o).

3.2 The boost

The boost converter is used to step a voltage up from a lower value. Again the circuit uses an inductor to store and transfer energy to the load from the input. The circuit topology is thus

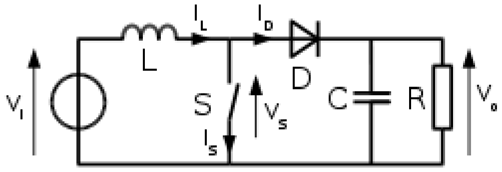


Fig. 3.6: boost converter

Operating principle

An inductor always has a tendency to resist changes in current. When being charged, it acts as a load and absorbs energy; when being discharged it acts as an energy source. The voltage it produces during the discharge phase is proportional to the rate of change of current, and not to the original charging voltage, thus allowing different input and output voltages.

The basic principle of a Boost converter consists of 2 distinct states

On-state: the switch S is closed, resulting in an increase in the inductor current.

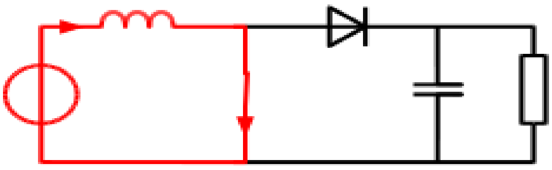


Fig. 3.7: On state

Off-state: the switch is open and the only path offered to inductor current is through the fly back diode D, the capacitor C and the load R. This result in transferring the energy accumulated during the On-state into the capacitor.

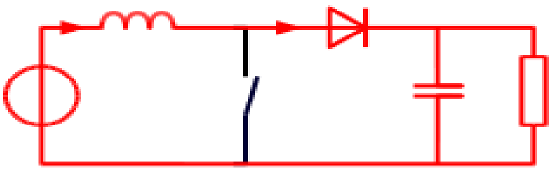


Fig. 3.8: off state

Continuous mode

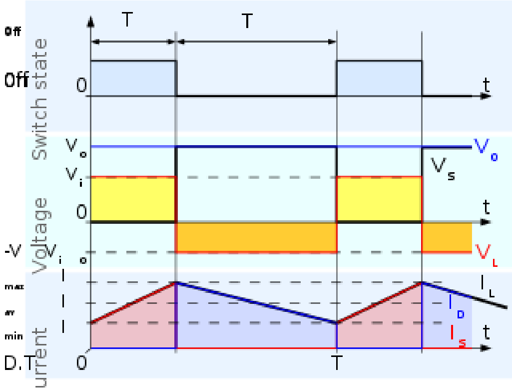


Fig. 3.9: wave shapes of continuous mode

The current through the inductor (I_L) never falls to zero. The typical waveforms of currents and voltages in a converter operating in this mode are shown in the graph above. The output voltage can be calculated as follows:

In the on-state, the switch S is closed, which makes the input voltage (V_i) appear across the inductor, which causes a change in current (I_L) flowing through the inductor during a time period (t) by the formula:

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

At the end of the On-state, the increase of I_L is therefore:

$$\Delta I_{L_{On}} = \frac{1}{L}\int_0^{DT} V_i dt = \frac{DT}{L} V_i$$

During the off-state, the switch S opens, so the inductor current flows through the load. If we consider zero voltage drops in the diode, and a capacitor large enough for its voltage to remain constant, the evolution of I_L is:

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

Therefore, the variation of I_L during the Off-period is:

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

For steady state the inductor current has to be the same at the start and end of the commutation cycle. This means the overall change in the current (the sum of the changes) is zero:

$$\Delta I_{L_{On}} + \Delta I_{L_{Off}} = 0$$

Substituting $\Delta I_{L_{On}}$ and $\Delta I_{L_{Off}}$ by their expressions yields:

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

This can be written as:

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

Or,

$V_0 = V_i/(1\text{-}D)$

From the above expression it can be seen that the output voltage is always higher than the input voltage (as the duty cycle goes from 0 to 1), and that it increases with D, theoretically to infinity as D approaches 1. This is why this converter is sometimes referred to as a *step-up* converter.

Discontinuous mode

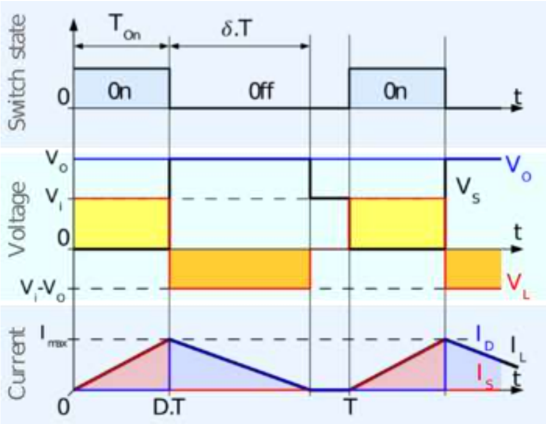


Fig. 3.10: wave shapes of discontinuous mode

As the inductor current at the beginning of the cycle is zero, its maximum value $I_{L_{Max}}$(at *t* = *DT*) is

$$I_{L_{Max}} = \frac{V_i D T}{L}$$

During the off-period, I_L falls to zero after δT:

$$I_{L_{Max}} + \frac{(V_i - V_o)\,\delta T}{L} = 0$$

Using the two previous equations, δ is:

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

The load current I_o is equal to the average diode current (I_D). As can be seen on, the diode current is equal to the inductor current during the off-state. Therefore the output current can be written as:

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

Replacing I_{Lmax} and δ by their respective expressions yields:

$$I_o = \frac{V_i DT}{2L} \cdot \frac{V_i D}{V_o - V_i} = \frac{V_i^2 D^2 T}{2L\left(V_o - V_i\right)}$$

Therefore, the output voltage gain can be written as follows:

$$\frac{V_o}{V_i} = 1 + \frac{V_i D^2 T}{2LI_o}$$

Compared to the expression of the output voltage for the continuous mode, this expression is much more complicated. Furthermore, in discontinuous operation, the output voltage gain not only depends on the duty cycle, but also on the inductor value, the input voltage, the switching frequency, and the output current.

3.3 The buck-boost

The buck-boost is a DC-DC converter that can be regulated to give an output voltage that is higher or lower than the input voltage. During normal operation of the buck-boost power stage, the switch is repeatedly turned on and off. This switching action gives rise to a train of pulses at the junction of the switch, diode and the inductor. Although the inductor, L, is connected to the output capacitor, C, only when the diode conducts, an effective L/C output filter is formed. It filters the train of pulses to produce a DC output voltage. There are two different topologies of the concept.

A buck followed by a boost converter

The output is in the same polarity of the input and can be regulated to be higher or lower than the input. Such a non-inverting buck-boost converter may use a single inductor that is used as both the buck inductor and the boost inductor.

The inverting topology

The output is negative in polarity. The duty cycle again determines the output voltage. For duty cycle less than 0.5 the circuit acts as a buck converter and for duty cycle greater than 0.5 the circuit acts as a boost converter.

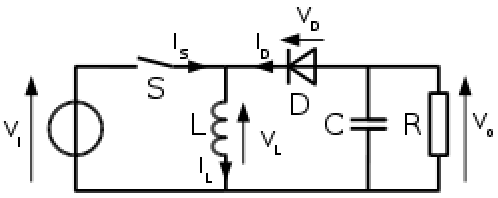


Fig. 3.11: buck–boost converter

As the inverted topology is more common to all we emphasize on the inverted topology. The operating principles are as follows:

There are two stages in which the circuit works

On state: when the switch is on the input and the inductor are isolated from the load side and the inductor is charged. The load receives energy from the capacitor that it accumulates during the off state.

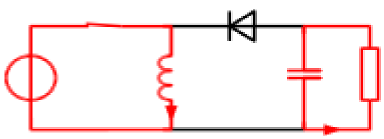


Fig. 3.12: On stage

Off state: the input is isolated from the whole system and the inductor supplies energy to the output filter capacitor and the load resistor.

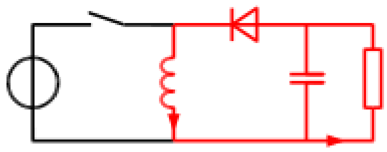


Fig. 3.13: Off stage

Continuous mode

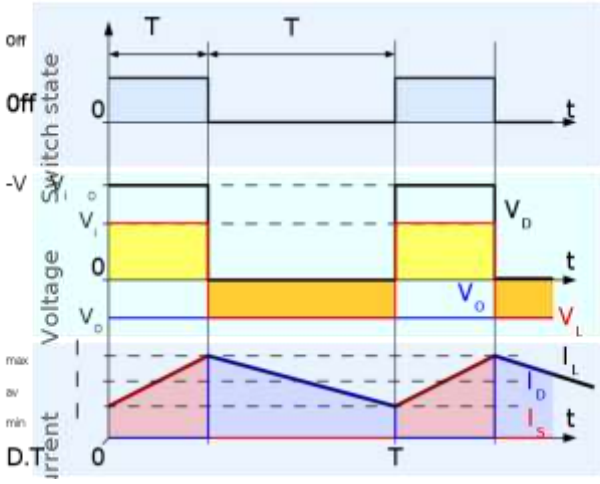


Fig. 3.14: wave shapes of continuous mode

In this mode the inductor current never reaches zero. During the on stage the rate of change in the inductor current (I_L) is

$$\frac{\mathrm{d}\,I_{\mathrm{L}}}{\mathrm{d}\,t}=\frac{V_i}{L}$$

At the end of the On-stage the change in inductor current is

$$\Delta I_{\mathrm{L_{On}}}=\int_0^{DT}\mathrm{d}\,I_{\mathrm{L}}=\int_0^{DT}\frac{V_i}{L}\,\mathrm{d}\,t=\frac{V_i\,D\,T}{L}$$

D= duty cycle=Ton/T

$T_{on}=DT$

During the Off-state the switch is open effectively disconnecting the source from the inductor and the load side. The energy stored in the inductor discharges into the capacitor and the load. During this time the inductor current is

$$\frac{\mathrm{d}\,I_{\mathrm{L}}}{\mathrm{d}\,t}=\frac{V_o}{L}$$

The change in the inductor current during the off stage is:

$$\Delta I_{\mathrm{L_{Off}}}=\int_0^{(1-D)T}\mathrm{d}\,I_{\mathrm{L}}=\int_0^{(1-D)T}\frac{V_o\,\mathrm{d}\,t}{L}=\frac{V_o\,(1-D)\,T}{L}$$

The source current during the on stage is equal to the inductor current and equal to zero when the switch is off.
The energy in an inductor is given by:

$$E=\frac{1}{2}L\,I_{\mathrm{L}}^2$$

At the end of a cycle the inductor current is the same as the beginning of the cycle. Thus the summation of the current is therefore zero.

$$\Delta I_{\mathrm{L_{On}}} + \Delta I_{\mathrm{L_{Off}}} = 0$$

Substituting $\Delta I_{\mathrm{L_{On}}}$and $\Delta I_{\mathrm{L_{Off}}}$by their expressions yields:

$$\Delta I_{\mathrm{L_{On}}} + \Delta I_{\mathrm{L_{Off}}} = \frac{V_i\,D\,T}{L} + \frac{V_o\,(1-D)\,T}{L} = 0$$

Rearranging:

$$\frac{V_o}{V_i} = \left(\frac{-D}{1-D}\right)$$

Or:

V_0= -Vs.D/(1-D)

The output of the circuit is in reverse polarity to the input. Output voltage is lower than input when D<5 and higher than input when 5<D<1. Theoretically, the output voltage should reach infinity when duty cycle is set to 1.

Discontinuous mode

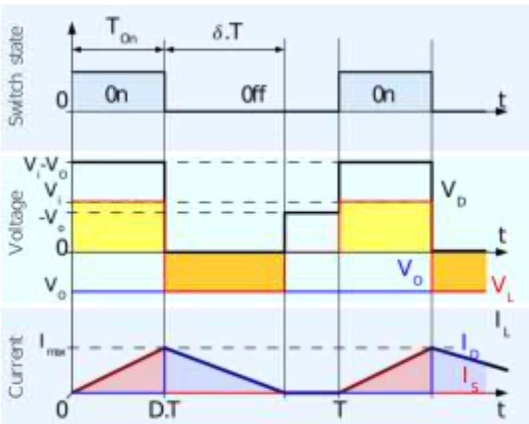


Fig. 3.15: wave shapes of discontinuous mode

As the inductor current at the beginning of the cycle is zero, its maximum value $I_{L_{\max}}$ (at$t = D\,T$) is

$$I_{L_{\max}} = \frac{V_i\,D\,T}{L}$$ ………….1

During the off-stage, I_L falls to zero after δ.T:

$$I_{L_{\max}} + \frac{V_o\,\delta\,T}{L} = 0$$ ……..2

Putting equations 1 and 2 together:

$$\delta = -\frac{V_i\, D}{V_o}$$

The load current I_o is equal to the average diode current (I_D) which is equal to the inductor current during the off-stage. Therefore, the output current can be written as:

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

Replacing $I_{L_{\max}}$and δ by their respective expressions:

$$I_o = -\frac{V_i\, D\, T}{2L}\frac{V_i\, D}{V_o} = -\frac{V_i^2\, D^2\, T}{2L\, V_o}$$

Therefore, the output voltage gain can be written as:

$$\frac{V_o}{V_i} = -\frac{V_i\, D^2\, T}{2L\, I_o}$$

The output voltage in negative in polarity and increases with duty cycle from zero. In discontinuous operation, the output voltage not only depends on the duty cycle, but also on the inductor value, the input voltage and the output current.

3.4 The cuk

The circuit setup is like a combination of the buck and boost converters. Like the buck-boost circuit it delivers an inverted output. Virtually all of the output current passes through C1, and as ripple current. So C1 is usually a large electrolytic with a high ripple current rating and low ESR (equivalent series resistance), to minimize losses. The main difference between the cuk and the other converters is that the cuk used a capacitor as the energy storing element.

Operating Principle

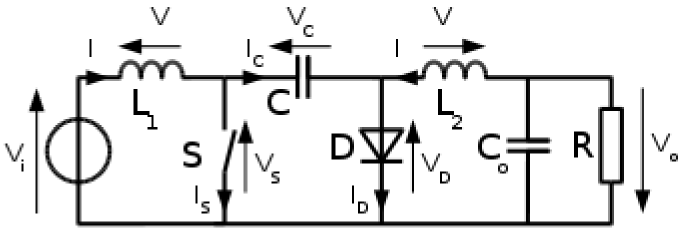


Fig. 3.16: a non-isolated Cuk converter

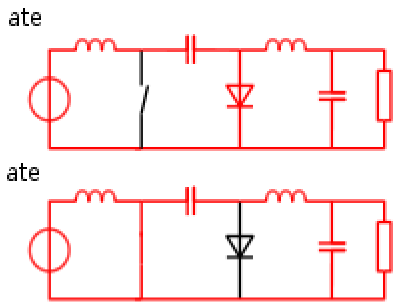


Fig. 3.17: on & off state

When S is turned on, current flows from the input source through L1 and S, storing energy in L1's magnetic field. Then when S is turned off, the voltage across L1 reverses to maintain current flow. As in the boost converter current then flows from the input source, through L1 and D1, charging up C1 to a voltage somewhat higher than Vin and transferring to it some of the energy that was stored in L1. When S is turned on again, C1 discharges through via L2 into the load, with L2 and C2 acting as a smoothing filter. Meanwhile energy is being stored again in L1, ready for the next cycle.

As with other converters (buck converter, boost converter, buck-boost converter) the Cuk converter can operate in two modes 1) continuous 2) discontinuous current mode. However, unlike these converters, it can also operate in discontinuous voltage mode (i.e., the voltage across the capacitor drops to zero during the commutation cycle).

Continuous mode

The current through the inductors has to be the same at the beginning and the end of the commutation cycle. As the evolution of the current through an inductor is related to the voltage across it:

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

it can be seen that the average value of the inductor voltages over a commutation period have to be zero to satisfy the steady-state requirements.
If we consider that the capacitors C and C_o are large enough for the voltage ripple across them to be negligible, the inductor voltages become:

in the off-state, inductor L_1 is connected in series with V_i and C. Therefore $V_{L1} = V_i - V_C$. As the diode D is forward biased (we consider zero voltage drop), L_2 is directly connected to the output capacitor. Therefore $V_{L2} = V_o$

in the on-state, inductor L_1 is directly connected to the input source. Therefore $V_{L1} = V_i$. Inductor L_2 is connected in series with C and the output capacitor, so $V_{L2} = V_o + V_C$

The converter operates in on-state from t=0 to t=D·T (D is the duty cycle), and in off state from D·T to T (that is, during a period equal to (1-D)·T). The average values of V_{L1} and V_{L2} are therefore:

$$\bar{V}_{L1} = D\cdot V_i + (1-D)\cdot(V_i - V_C) = (V_i - (1-D)\cdot V_C)$$

$$\bar{V}_{L2} = D\left(V_o + V_C\right) + (1-D)\cdot -V_o = (V_o + D\cdot V_C)$$

As both average voltage have to be zero to satisfy the steady-state conditions we can write, using the last equation:

$$V_C = \frac{V_o}{D}$$

So the average voltage across L_1 becomes:

$$\bar{V}_{L1} = \left(V_i + (1-D)\cdot\frac{V_o}{D}\right) = 0$$

This can be written as:

$V_o = -V_i.D/(1-D)$

As with the buck-boost converter, the ratio between the output voltage and the input voltage is Vout/Vin = -D/(1-D) = -Ton/Toff. The output voltage is in negative polarity. The output voltage can either be stepped up or down, depending on the switching duty cycle. The main difference between buck-boost and cuk converter is that because of the series inductors at both input and output, the Cuk converter has much lower current ripple in both circuits. By careful adjustment of the inductor values, the ripple in either input or output can be nulled completely.

Discontinuous mode

Like all DC-DC converters Cuk converters rely on the ability of the inductors in the circuit to provide continuous current, in much the same way a capacitor in a rectifier filter provides continuous voltage. If this inductor is too small or below the "critical inductance", then the current will be discontinuous.
The minimum inductance is given by:

$$L_1 min = \frac{(1-D)^2 R}{2 D f_s}$$

Where f_s is the switching frequency.
Filters are used on the input and the output side of the converters to maintain constant output and input voltage and current. The filters also eliminate the switching harmonics (EMI). A capacitor is used in a filter to reduce ripple in voltage. Since switched power regulators are usually used in high current, high-performance power supplies, the capacitor should be chosen for minimum loss.

3.5 Efficiency factors

Conduction losses that depend on load:
Resistance when the transistor or MOSFET switch is conducting.
Diode forward voltage drop (usually 0.7 V or 0.4 V for schottky diode)
Inductor winding resistance and capacitor equivalent series resistance.

Switching losses:
Voltage-Ampere overlaps loss
$Frequency_{switch} * CV^2$ loss
Reverse latency loss
Losses due driving MOSFET gate and controller consumption
Transistor leakage current losses and controller standby consumption.

3.6 Impedance matching

A buck converter can be used to maximize the power transfer through the use of impedance matching. An application of this is in a "maximum power point tracker" commonly used in photovoltaic systems.
By the equation for electric power:

$$V_o I_o = \eta V_i I_i$$

Where:
V_o is the output voltage
I_o is the output current
η is the power efficiency (ranging from 0 to 1)
V_i is the input voltage
I_i is the input current

By Ohm's Law:

$$I_o = V_o / Z_o$$

$$I_i = V_i / Z_i$$

Where:
Z_o is the output impedance
Z_i is the input impedance
Substituting these expressions for I_o and I_i into the power equation yields:

$$V_o^2 / Z_o = \eta V_i^2 / Z_i$$

As was previously shown for the continuous mode, (where $I_L > 0$):

$$V_o = D V_i$$

where: D is the duty cycle
Substituting this equation for V_o into the previous equation, yields:

$$(D V_i)^2 / Z_o = \eta V_i^2 / Z_i$$

which reduces to:

$$D^2 / Z_o = \eta / Z_i$$

$$D = \sqrt{\eta Z_o / Z_i}$$

This shows that it is possible to adjust the impedance ratio by adjusting the duty cycle.

3.7 Why CUK?

Cuk converters can boost an input voltage to a higher voltage level than the input and can also cut the voltage down to any required level whereas the buck and the boost can step down and step up the voltage respectively only. Although a buck-boost circuit can do the same thing, a Cuk converter is less complex than a buck-boost converter in terms of practical implementation. For constructing a buck-boost converter the switch has to be placed in series with the source. Placing the switch in series adds the complexity of proper grounding. And thus the use of separate opto-coupler circuit to isolate the ground of the PWM and converter, which makes the overall circuit much more complicated. Whereas the switch position in Cuk converter is simple as the ground position of the source and the switch are same. The output filter inductor is smaller for the Cuk converter though it requires two inductors. The first inductor is basically for input current filtering.

Chapter 4
CIRCUIT DESIGN

4.1 Circuit Design

A switch mode AC-DC converter has been implemented in the laboratory. A block diagram of the circuit is given in Figure 24.

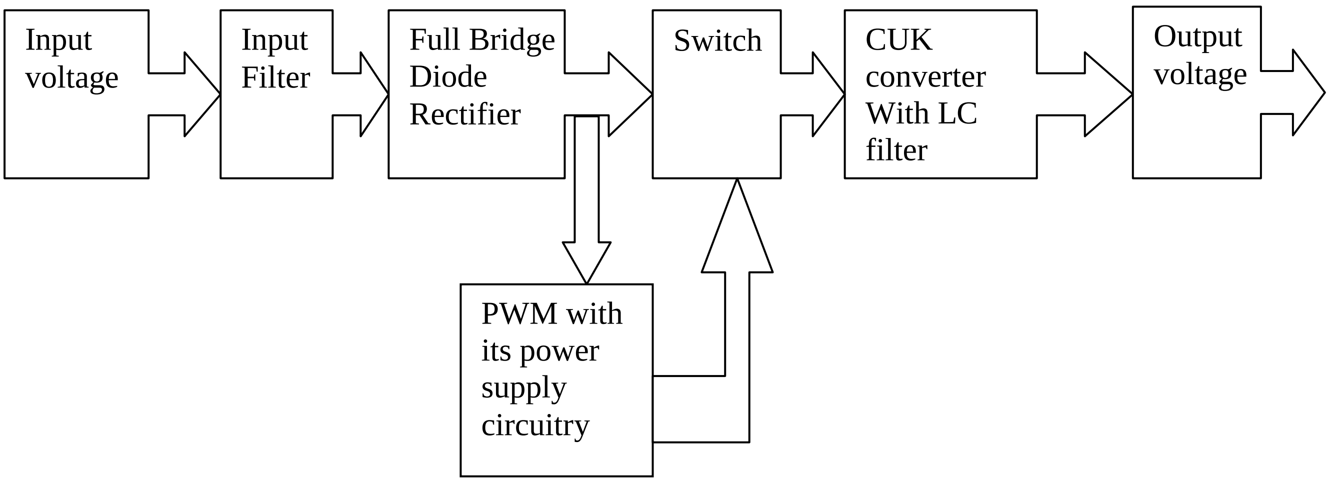


Fig. 4.1: functional diagram of the constructed circuit

At present a transformer is used to step the 220v input down to 30v rms. The full wave diode-bridge rectifier rectifies the alternating voltage into a pulsating DC voltage of an average of approximately 30V (voltage drop across the diodes accounts for the loss).

The PWM constructed using the SG3524 IC draws its power from the pulsating DC at node 3 converted into 12V dc. The used switching frequency is 20 kHz. The switch, IRFP 240 is driven by the PWM, turns off and on and thus controlling the current flow and the power transferred to the load.

The following parameters were set for use in the PWM circuit:

V_{in}= 12V
I_{in}= 0.130A
R_t= 10Kohms
C_t= 0.01uF
Duty cycle control= 0%-100%
$F_{switching}$=20 kHz

4.2 Design of the switch mode rectifier using CUK converter

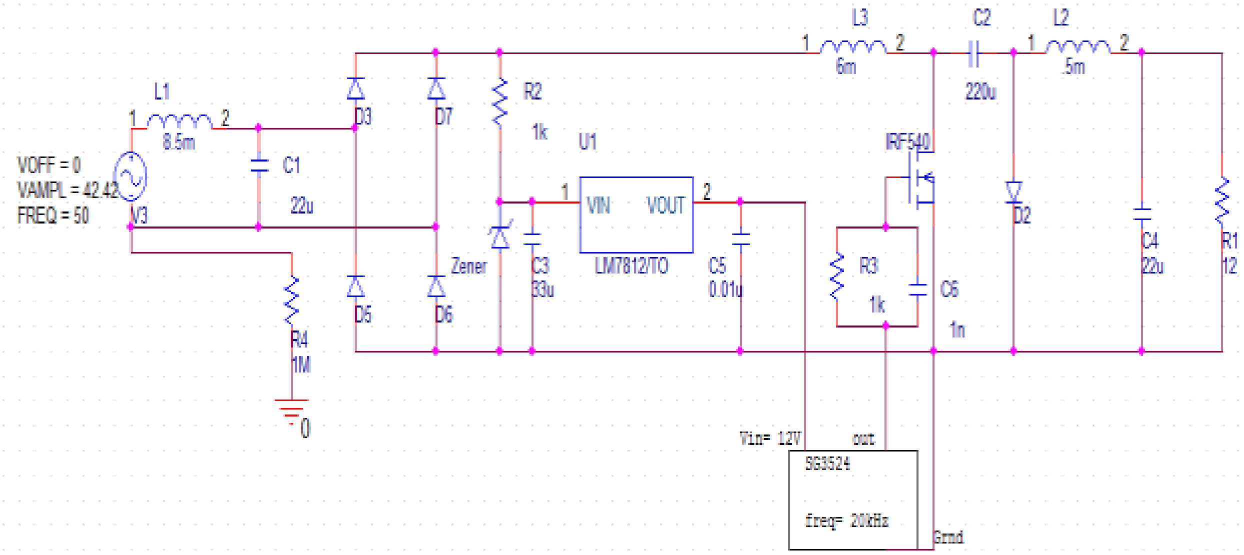


Fig. 4.2: circuit diagram of the constructed circuit

Theoretical calculation of the circuit is as follows:

Vo= -D*Vs/(1-D)

The input voltage was 28.5 volts rms from the transformer. The calculated output voltage is over the range of the duty cycle 0%-100% is tabulated below

Duty cycle	Output voltage in V	Duty cycle	Output voltage in V
0.0	0.00	0.6	-42.75
0.1	-3.16	0.7	-66.50
0.2	-7.125	0.8	-114.00
0.3	-12.214	0.9	-256.50
0.4	-19.00	1.0	Infinity
0.5	-28.50		

Table 4.1: calculated values of output voltage

The ripple voltage across the capacitor can be used to calculate the value of the capacitor. The target ripple voltage is 1%. Using the highest value of the calculated output voltage and the corresponding duty cycle

ΔVc1= (Vin-Vout)* % ripple
(30+66.50)* 0.01
0.965V

C1> V0.D/RfΔVc1
66.50*0.7/12*10000*0.965
> 200.99uf

L1> R (1-D) ^2)/2f
12(1-0.1) ^2)/ (2*20,000)
>2.43mH

To ensure the continuous mode 25% larger inductance is used.
So, L_1= 3.0mH

L_2> (1-D) R/2f
0.9(12)/ (2*20000)
> 0.27mH
Again taking an inductor that is bigger, L2=0.33mH

For the input filter
X_l=X_c
2*pi*f*L=1/ (2*pi*f*C)
L= 1/ (4*(pi) ^2*(f^2)*C)
L= 8.12mH

The circuit was constructed using the parameters calculated above.

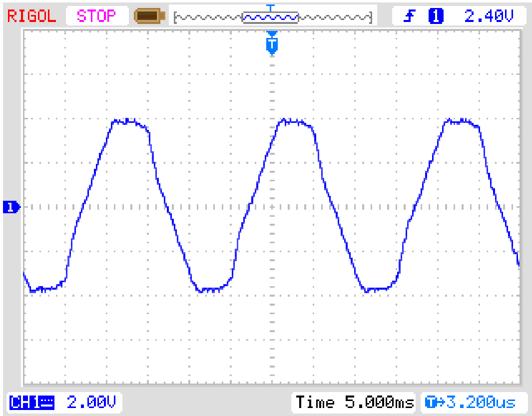
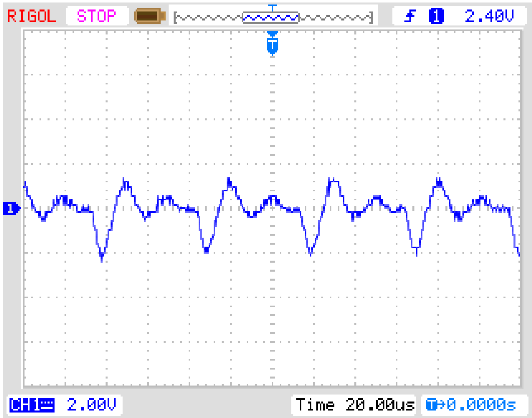
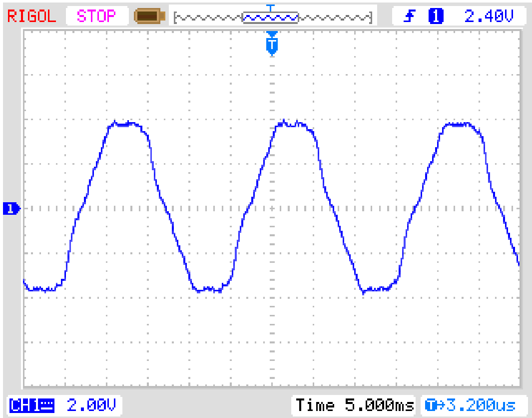
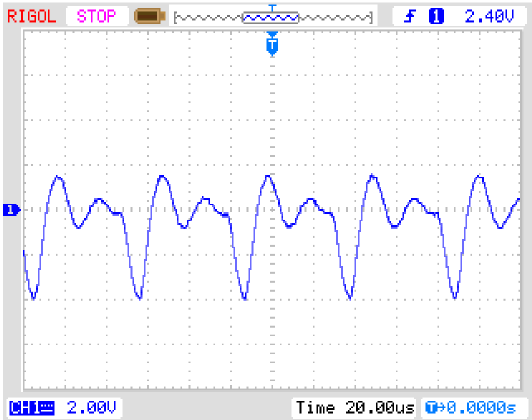
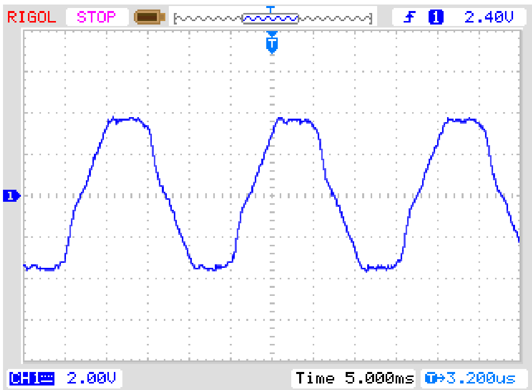
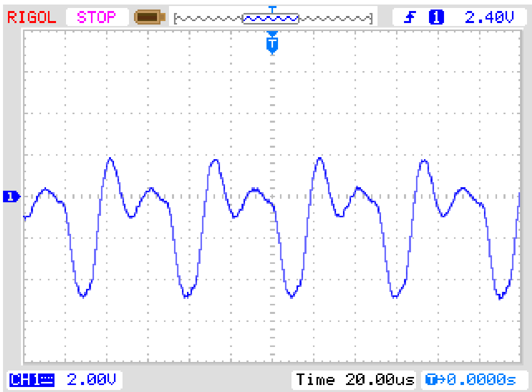
4.3 Results from the constructed circuit

Input Voltage = 28.5 V_{rms}

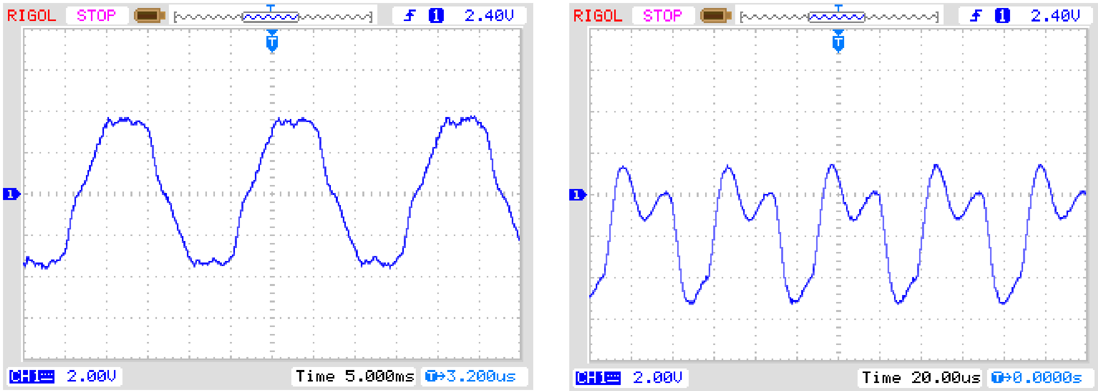
Duty cycle	RMS Current (input)	Input power(W)	RMS Voltage (output)	RMS Current (output)	Output power	Motor speed (rpm)	Efficiency
0.1	0.048	1.386	-1.91	0.117	0338	304	0.24
0.2	0.087	2.481	-6.8	0.152	1.033	1384	0.41
0.3	0.157	4.474	-13.4	0.179	2.398	3255	0.53
0.4	0.237	6.745	-19.4	0.198	3.841	5406	0.57
0.5	0.388	9.633	-26.3	0.222	5.838	8433	0.61
0.6	0.707	20.149	-39.3	0.267	10.493	10352	0.52
0.7	1.068	30.438	-46.6	0.278	12.954	12700	0.43
0.8	1.423	40.555	-43.8	0.235	10.235	13203	0.27

Table 4.4: practical results

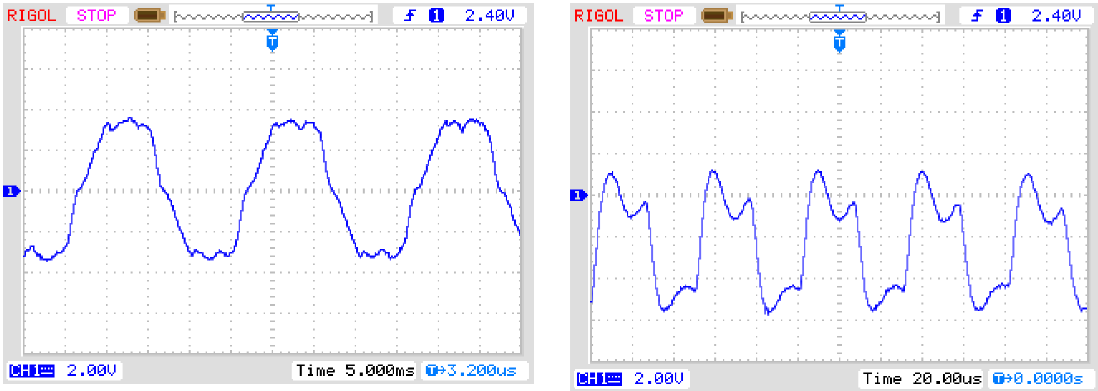
4.4 The wave shapes of the input and output voltages of the constructed circuit are shown below

Input	Output
D=0.1	
 	
D= 0.2	
 	
D=0.3	
 	

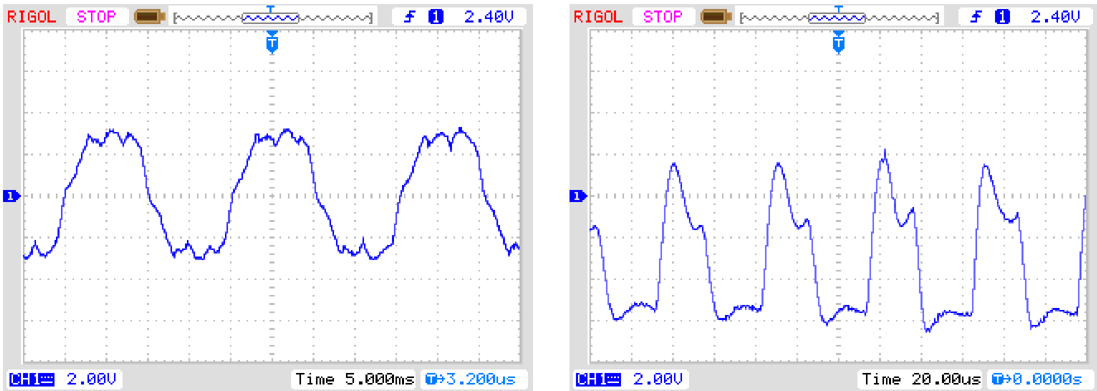
D= 0.4



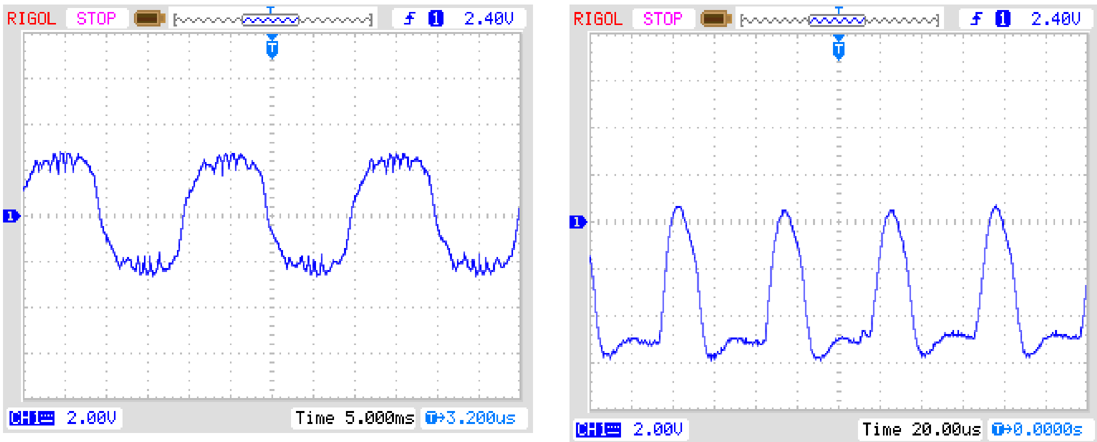
D=0.5



D=0.6



D=0.7



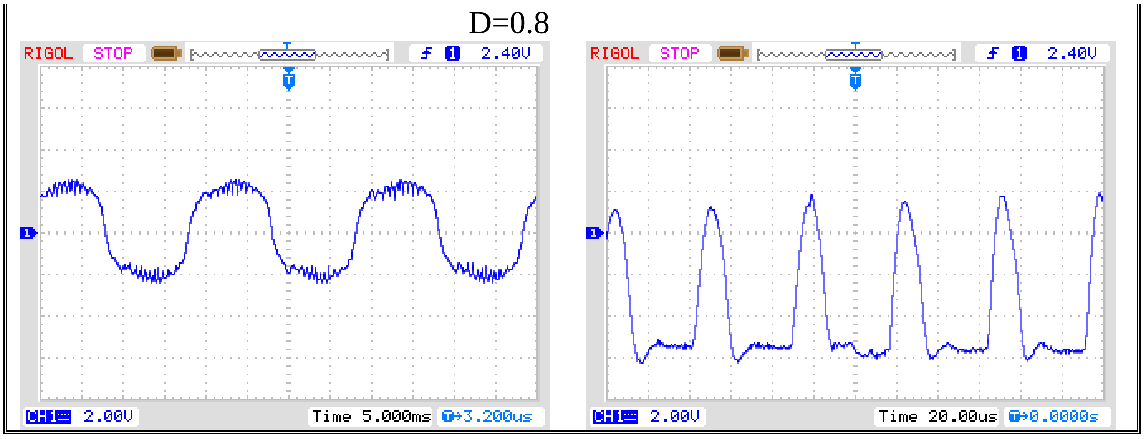


Fig. 4.3: wave shapes of the input and output voltage constructed circuit.(the wave shapes are ten times smaller)

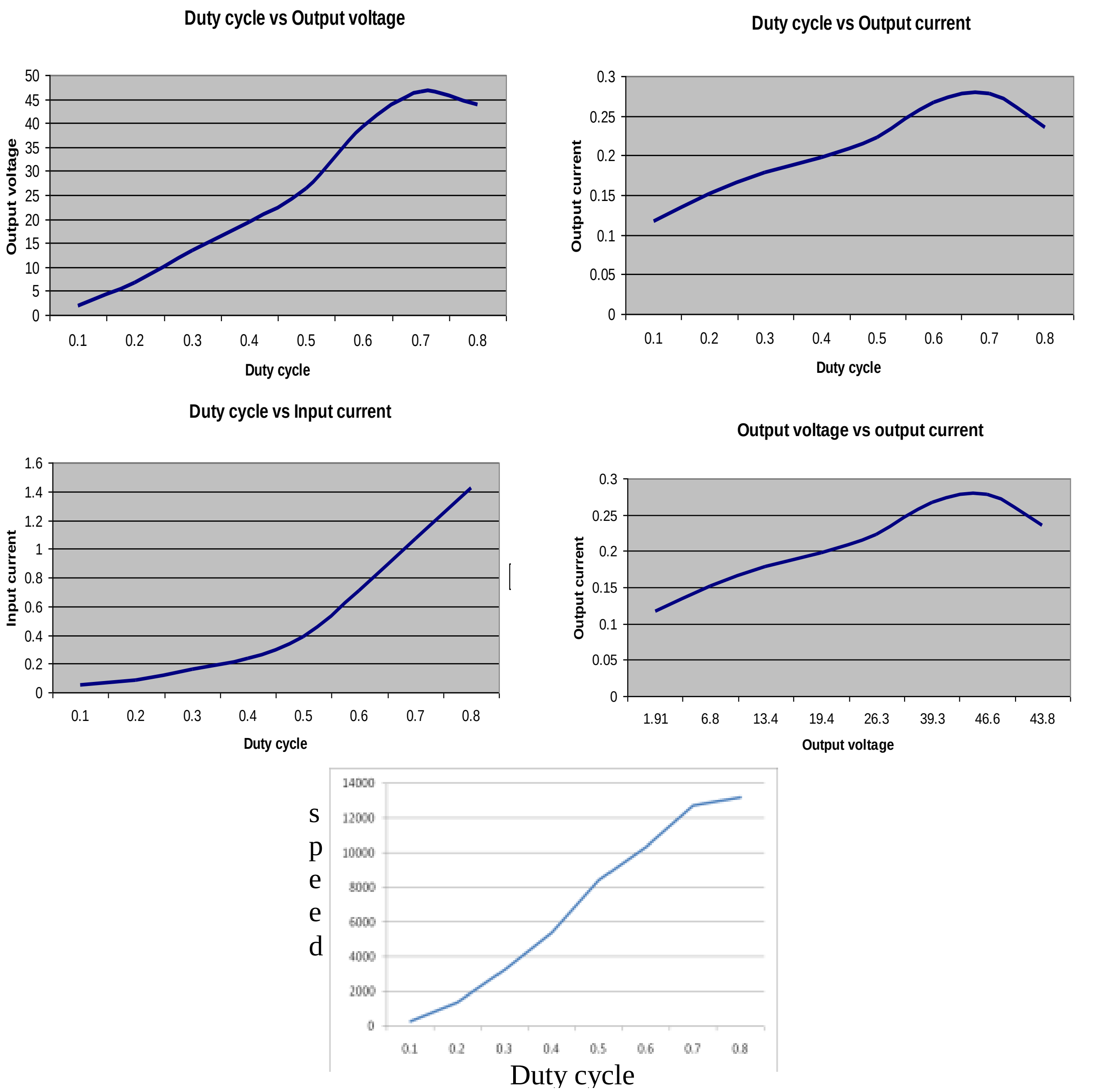


Fig. 4.4: a) duty cycle vs output voltage b) duty cycle vs output current c) duty cycle vs input current d) output voltage vs output current e) duty cycle vs speed control

4.5 Conclusion

The objective of the thesis has been achieving speed control over a DC motor by implementing a full wave AC-DC CUK converter. The objective has been achieved with a few lacking in the circuit. As seen in the data the speed of the motor can be varied from 0 r.p.m to 13,000 r.p.m almost linearly. the input voltage to the motor can be varied from 0V to 40V. A power in the range of 0W to 10W can be transferred to the motor with flexible control.

A lot of time was needed to construct the appropriate PWM circuit for the converter and thus the total designing of the converter remains incomplete. Although control over the speed of the motor has been achieved the efficiency of the circuit needs to be worked on. The efficiency of the circuit seems varying with the duty cycle. The appropriate filters for input and output need to be designed.

4.6 Problems faced

1) None of our laboratories are grounded properly. Thus while taking data from the oscilloscope the voltage generator would lose half the cycle through the oscilloscope.
2) The inductors needed to be handmade and thus were inaccurate in values which may cause disturbances in the circuit.

Chapter 5

5.1 Future works

The target design for the input filter was an active filter that would incorporate a bidirectional switch along with inductors and capacitors. The resulting filter would have had a smaller inductance and capacitance in comparison with the present filter. In the constructed circuit the output capacitor filter was left out as it caused the output voltage to drop unexpectedly and thus that too needs proper designing. The efficiency of the circuit can be brought up by careful design of the mentioned filters.

A feedback system, e.g a second order servo system can be established that could determine any fluctuations or regulations on the input or output side of the converter and thus react to it by increasing or decreasing the duty cycle to correct the error voltage and thus speed.

5.2 Reference

1) N. Mohan, T. M. Undeland, and W. P. Robbins, *Power Electronics: Converters, Applications and Design*, John Wiley & Sons, 2nd Edition, 1995.
2) J. Schaefer, *Rectifier Circuits: Theory and Design*, John Wiley & Sons, 1965.
3) J. A. M. Bleijs, “Continuous conduction mode operation of three-phase diode bridge rectifier with constant load voltage,” *IEE Proceedings - Electric Power Applications*, Vol. 152, No. 2, March 2005, pp. 59-368.
4) Daniel Hart, *Introduction to Power Electronics*
5) Wikipedia.

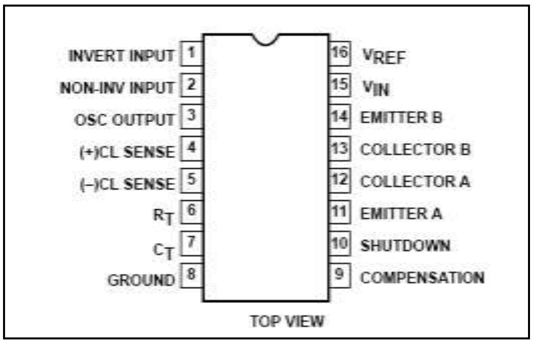
Chapter 6
APPENDIX

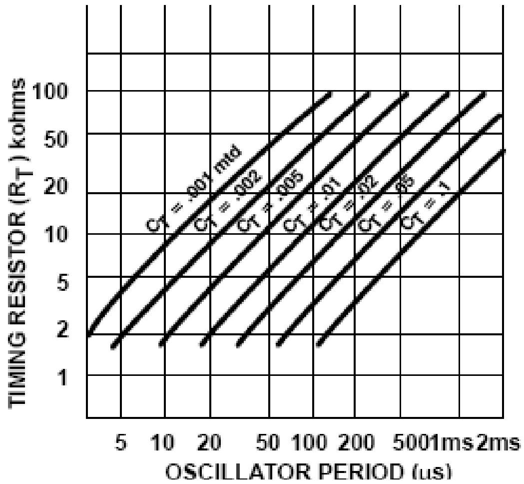
IC description

In our circuit we have used the ICs:

SG3524 for PWM
IRFP240 as switch.
LM7812 as voltage regulator for PWM power supply

6.1 SG3524





Absolute maximum ratings

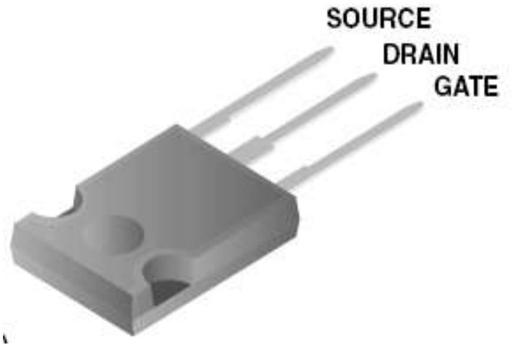
Vcc= 40V
Iout= 100mA
Pdissipation=1W
Fmax=300kHz

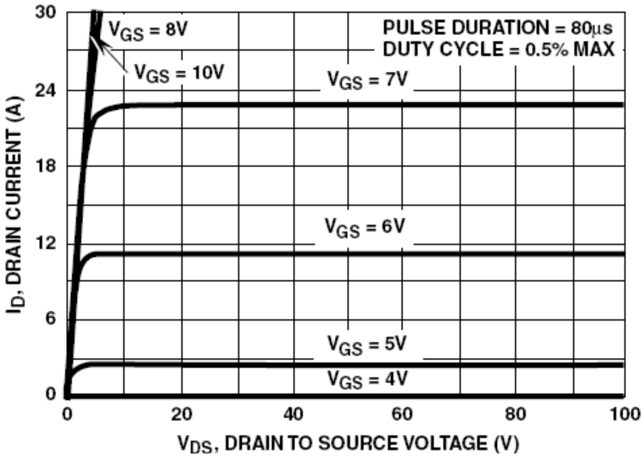
This is a 16 pin dual-in-line package IC. It has the necessary circuitry for switching regulator and regulating power supply inverter. The IC contains voltage reference, error amplifier, oscillator, PWM, pulse steering flip-flop. In our project we are using it as a switching regulator.

The timing capacitor Ct and the timing resistor Rt is used to supply a near linear ramp reference voltage to the internal comparator of the SG3524. The charging current is equal to 3.6V/Rt and should be kept within the approximate range of 30mA to 2mA and thus Rt should be within the range 1.8k<RT<100k.

The range of values for Ct also has limits as the discharge time of Ct determines the pulse-width of the oscillator output pulse. Practical values of Ct fall between 0.001 and 0.1 mF. The oscillator period is approximately t = RtCt where t is in microseconds when Rt = ohms and CT = uF. The two outputs can be shorted together for 0-90% duty cycle modulation and the frequency of the oscillator is the switching frequency used.

6.2 IRFP240



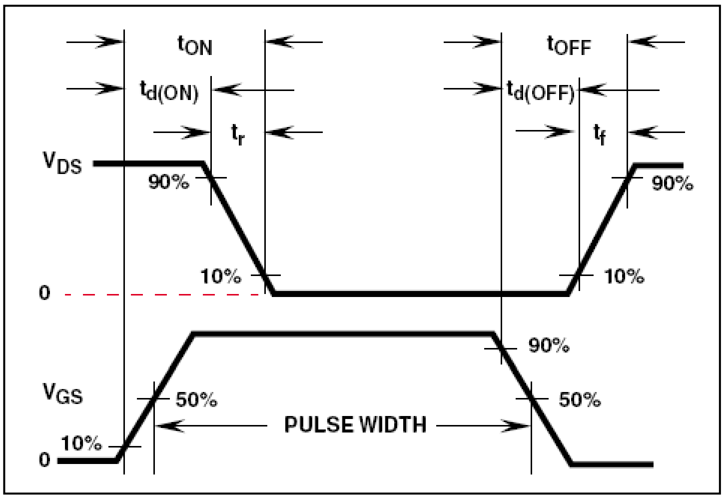


The IRFP240 is a high power MOSFET that is being used as the switch. Its small on-state resistance (0.18ohms) and its low turn on and turn off time (21ns and 68ns respectively) makes it an appropriate choice for the switch. The low turn on voltage (5V) also makes it an ideal choice.

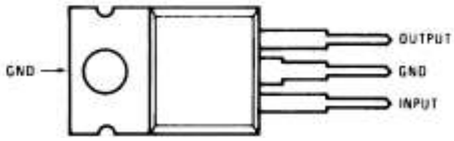
At first use of the MOSFET 2SK2677 as the switch was considered, but its high on-state resistance (1.4ohms) and its high turn on and turn off time(140 ns and 440 ns respectively) caused considerable power loss and drain to source voltage drop and thus we switched to IRFP240.

Absolute Maximum Ratings

Drain to Source Voltage = 200 V
Drain to Gate Voltage = 200 V
Continuous Drain Current = 20 A
Gate to Source Voltage = 20 V
Maximum Power Dissipation = 150 W
Turn on delay time (ton) = 21 ns
Turn off delay time (toff) = 68ns
On state resistance = 0.18 ohms
Gate to source resistance = 20kohm
Reverse recovery time = 530ns



6.3 LM7812



The LM7812 is a three terminal IC that is used as a voltage regulator. The regulator takes in pulse of a high DC voltage to give a steady lower DC voltage. This lower DC voltage is fed to the SG3524 for its power.

Absolute Maximum ratings

Output voltage	5V	12V	15V
Quiescent current	8mA	8mA	8mA
Input voltage	10V	19V	23V
Line regulation	50mV	120mV	150mV
Load regulation	50mV	120mV	150mV
Input voltage required to maintain load regulation	7.5V	14.6V	17.7V