



NEAR EAST UNIVERSITY

Faculty of Engineering

**Department of Electrical and Electronic
Engineering**

**SIMULATION OF SOME POWER
ELECTRONIC CIRCUITS**

**Graduation Project
EE-400**

Student: Jihad Jabarin (970717)

Supervisor: Mr.Özgür C. Özerdem

Lefkoşa-2001

3.8 Sumarry	39
4. A SINGLE SCR CIRCUIT	40
4.1 Overview	40
4.2 Circuit Operation	40
4.3 Mathematical Analysis	41
4.4 Simulation	42
4.5 Pspice Simulation	44
4.6 Matlab Simulation	47
4.7 Mathcad Simulation	51
4.8 Summary	55
5. A TWO-QUADRANT DC DRIVE	56
5.1 Performance Characteristics	56
5.2 Block Diagram	60
5.3 Closed-Loop Control	63
5.4 Simulation	64
5.5 Summary	65
6. STEP-DOWN SMPS/BUCK CONVERTER	
6.1 Introduction	66
6.2 Basic Circuit Operation	71
6.3 Effect Of Ripple In Input Voltage	81
6.4 Effect Of Step Change In Load	82
6.5 Summary	83
CONCLUSION	84
REFERENCES	85

ACKNOWLEDGMENT

First of all I should thanks God Almighty who gave me the strength to complete this thesis.

Then, I would like to thank Mr.Özgür C.Özerdem to be my supervisor. Under his guidance, I successfully overcome many difficulties and learn a lot about simulation of power electronics and in the technical writing theses. In each discussion, he explained my questions patiently, and I felt my quick progress from his advises. He always helps me a lot either in my study or my life. Mr.Özgür, thanks for your continual support.

I would like to thank all our teachers in Near East University, Student Advisors and all the stuff of the Electrical and Electronic Engineering Faculty for giving us the opportunity to experience this remarkable Institute that have showed us preliminary steps toward our professional carrier.

A special thanks to all my friends in Near East University. Being with them make my 4 years in NEU full of fun.

Finally I want to thank my family, especially my parents. Without their endless support and love for me, I would never achieve my current position. I wish my mother lives happily always, and my father in the heaven be proud of me.

ABSTRACT

The use of simulation has always been a powerful tool for the technology in power electronics and all its various fields of application. A fundamental knowledge about simulation technology has been gained by the use of analog simulation methods.

The introduction of digital computers, and the tremendous increase of their calculation speed has brought the possibility to apply the numerical simulation technology to ever increasing systems. Especially from an economical point of view, it appears to be profitable.

Basic mistakes in a system design can be recognized fast and by this fail investments are avoided. The euphony which accompanies such a description must be handled with care. A broad range of simulation program packages is offered to the engineer.

Behind each of these programs hide different simulation techniques and topologies. It can therefore often appear as if the results from different numerical simulation techniques applied to the same test are strongly different. In the field of Power Electronics, this phenomenon is often observed.

An engineer will therefore feel uncomfortable and sooner fall back on his laboratory experience as to rely on his simulated results.

The aim of this work is therefore to show the importance of the field power electronics and in which field of application, which kind of simulation methods can be used and how a system has to be modeled for an appropriate simulation.

INTRODUCTION

Ever since the discovery of the "miracle force" of electricity more than 200 years ago, engineers have been creating new inventions to perform work and to process information for the benefit of mankind. All these inventions require electric power in order to operate, but the required characteristics of the power source are often different from those which are available.

therefore, power conversion and control are required. Such power conversion and control functions form the basis of what has come to be known as the field of power electronics. In essence, the power electronics engineer must match the characteristics of the source of electrical energy to the requirements of the electrical/electronic devices which it will power. The ability to accomplish these functions satisfactorily is dependent on two key elements; a complete understanding of the characteristics of available power components, and the creative application of these components in circuits and systems.

On other hand, the use of a circuit simulator is more and more necessary in electrical engineering or power electronics, this technique makes it possible to obtain results when the hardware is missing, for example to know how the circuit can be simulated using Pspice, MathCad and Matlab programs.

The Thesis consist of introduction, six chapters and conclusion. The first chapter represent the definition of power electronics, the typical application for a switch-mode power supply, conversions, and the history of power electronics. Chapter 2 has described the circuit of a half-wave rectifier and its operation by using a different simulation. Chapter 3 has also described the circuit of a half-wave rectifier with a free-wheeling diode and its operation by using a different software packages. Chapter 4 described a circuit with a single SCR, it is similar to the single diode circuit, but SCR is used in the place of a diode, the same simulation are will be used. Chapter 5 described how the separately-excited dc motor can be controlled by varying the armature voltage and the rated voltage of the field winding, also the chapter explained how the simulation can be carried out. Chapter 6 has described some of the operation of a switch mode step-down power supply circuit.

The conclusion presents important results obtained in this thesis and practical realization by using different kind of simulation on power electronics.

CHAPTER 1

INTRODUCTION TO POWER ELECTRONICS

1.1 Definition

Power electronics refers to control and conversion of electrical power by power semiconductor devices wherein these devices operate as switches. Advent of silicon-controlled rectifiers, abbreviated as SCRs, led to the development of a new area of application called the power electronics. Prior to the introduction of SCRs, mercury-arc rectifiers were used for controlling electrical power, but such rectifier circuits were part of industrial electronics and the scope for applications of mercury-arc rectifiers was limited. Once the SCRs were available, the application area spread to many fields such as drives, power supplies, aviation electronics, high frequency inverters and power electronics originated.

1.2 History of Power Electronics

The history of power electronics began with the introduction of the mercury arc rectifier in 1900. then the metal tank rectifier, Most of today's advanced electronics technologies are traceable to that invention.

Modern microelectronics evolved over the years grid-controlled vacuum –tube rectifier, ignitron, phanotron, and thyatron were introduced gradually. These devices were applied for power control until the 1950s.

The first electronics revolution began in 1947 with the invention of the silicon transistor at Bell Telephone Laboratories by Bardeen, Brattian, and Schockley from silicon semiconductors. The next breakthrough, in 1956, was also from Bell Laboratories: the invention of the *PNPN* triggering transistor, which was defined as a thyristor or silicon-controlled rectifier (SCR).

The second electronics revolution began in 1958 with the development of the commercial thyristor by the General Electric company. That was the beginning of a new area of power electronics then. Many different types of power semiconductor devices and conversion techniques have been introduced.

1.3 MAIN TASK OF POWER ELECTRONICS

Power electronics has applications that span the whole field of electrical power systems, with the power range of these applications extending from a few VA/Watts to several MVA / MW. The main task of power electronics is to control and convert electrical power from one form to another. The four main forms of conversion are:

- Rectification referring to conversion of ac voltage to dc voltage,
- DC-to-AC conversion,
- DC-to DC conversion and
- AC-to-AC conversion.

"Electronic power converter" is the term that is used to refer to a power electronic circuit that converts voltage and current from one form to another. These converters can be classified as:

- Rectifier converting an ac voltage to a dc voltage,
- Inverter converting a dc voltage to an ac voltage,
- Chopper or a switch-mode power supply that converts a dc voltage to another dc voltage, and
- Cycloconverter and cycloinverter converting an ac voltage to another ac voltage.

In addition, SCRs and other power semiconductor devices are used as static switches.

1.4 Rectification

Rectifiers can be classified as uncontrolled and controlled rectifiers, and the controlled rectifiers can be further divided into semi-controlled and fully-controlled rectifiers. Uncontrolled rectifier circuits are built with diodes, and fully-controlled rectifier circuits are built with SCRs. Both diodes and SCRs are used in semi-controlled rectifier circuits.

There are several rectifier circuits rectifier configurations. The popular rectifier configurations are listed below.

- Single-phase semi-controlled bridge rectifier,
- Single-phase fully-controlled bridge rectifier,
- Three-phase three-pulse, star-connected rectifier,

- Double three-phase, three-pulse star-connected rectifiers with inter-phase transformer (IPT),
- Three-phase semi-controlled bridge rectifier,
- Three-phase fully-controlled bridge rectifier and
- Double three-phase fully-controlled bridge rectifiers with IPT.

Apart from the configurations listed above, there are series-connected and 12-pulse rectifiers for delivering high power output.

Power rating of a single-phase rectifier tends to be lower than 10 kW. Three-phase bridge rectifiers are used for delivering higher power output, up to 500 kW at 500 V dc or even more. For low voltage, high current applications, a pair of three-phase, three-pulse rectifiers interconnected by an inter-phase transformer(IPT) is used. For a high current output, rectifiers with IPT are preferred to connecting devices directly in parallel. There are many applications for rectifiers. Some of them are:

- Variable speed dc drives,
- Battery chargers,
- DC power supplies and Power supply for a specific application like electroplating.

1.5 Conversions

1.5.1 DC-To-AC Conversion

The converter that changes a dc voltage to an alternating voltage is called an inverter. Earlier inverters were built with SCRs. Since the circuitry required to turn the SCR off tends to be complex, other power semiconductor devices such as bipolar junction transistors, power MOSFETs, insulated gate bipolar transistors (IGBT) and MOS-controlled thyristors (MCTs) are used nowadays. Currently only the inverters with a high power rating, such as 500 kW or higher, are likely to be built with either SCRs or gate turn-off thyristors(GTOs). There are many inverter circuits and the techniques for controlling an inverter vary in complexity.

Some of the applications of an inverter are listed below:

- Emergency lighting systems
- AC variable speed drives
- Uninterrupted power supplies, and

- Frequency converters.

1.5.2 DC-To-DC Conversion

When the SCR came into use, a dc-to-dc converter circuit was called a chopper. Nowadays, an SCR is rarely used in a dc-to-dc converter. Either a power BJT or a power MOSFET is normally used in such a converter and this converter is called a switch-mode power supply. A switch-mode power supply can be of one of the types listed below:

- Step-down switch-mode power supply
- Step-up chopper
- Fly-back converter and
- Resonant converter.

The typical applications for a switch-mode power supply or a chopper are:

- DC drive
- Battery charger and
- DC power supply.

1.5.3 AC-To-AC Conversion

A cycloconverter or a cycloinverter converts an ac voltage, such as the mains supply, to another ac voltage. The amplitude and the frequency of input voltage to a cycloconverter tend to be fixed values, whereas both the amplitude and the frequency of output voltage of a cycloconverter tend to be variable. On the other hand, the circuit that converts an ac voltage to another ac voltage at the same frequency is known as an ac-chopper.

A typical application of a cycloconverter is to use it for controlling the speed of an ac traction motor and most of these cycloconverters have a high power output, of the order a few megawatts and SCRs are used in these circuits. In contrast, low cost, low power cycloconverters for low power ac motors are also in use and many of these circuit tend to use triacs in place of SCRs. Unlike an SCR which conducts in only one direction, a triac is capable of conducting in either direction and like an SCR, it is also a three terminal device. It may be noted that the use of a cycloconverter is not as common as that of an inverter and a cycloinverter is rarely used.

1.6 Additional Insights Into Power Electronics

There are several striking features of power electronics, the foremost among them being the extensive use of inductors and capacitors. In many applications of power electronics, an inductor may carry a high current at a high frequency. The implications of operating an inductor in this manner are quite a few, such as necessitating the use of litz wire in place of single-stranded or multi-stranded copper wire at frequencies above 50 kHz, using a proper core to limit the losses in the core, and shielding the inductor properly so that the fringing that occurs at the air-gaps in the magnetic path does not lead to electromagnetic interference. Usually the capacitors used in a power electronic application are also stressed. It is typical for a capacitor to be operated at a high frequency with current surges passing through it periodically. This means that the current rating of the capacitor at the operating frequency should be checked before its use. In addition, it may be preferable if the capacitor has self-healing property. Hence an inductor or a capacitor has to be selected or designed with care, taking into account the operating conditions, before its use in a power electronic circuit.

In many power electronic circuits, diodes play a crucial role. A normal power diode is usually designed to be operated at 400 Hz or less. Many of the inverter and switch-mode power supply circuits operate at a much higher frequency and these circuits need diodes that turn ON and OFF fast. In addition, it is also desired that the turning-off process of a diode should not create undesirable electrical transients in the circuit. Since there are several types of diodes available, selection of a proper diode is very important for reliable operation of a circuit.

Analysis of power electronic circuits tends to be quite complicated, because these circuits rarely operate in steady-state. Traditionally steady-state response refers to the state of a circuit characterized by either a dc response or a sinusoidal response. Most of the power electronic circuits have a periodic response, but this response is not usually sinusoidal. Typically, the repetitive or the periodic response contains both a steady-state part due to the forcing function and a transient part due to the poles of the network. Since the responses are none sinusoidal, harmonic analysis is often necessary. In order to obtain the time response, it may be necessary to resort to the use of a computer program.

Power electronics is a subject of interdisciplinary nature. To design and build control circuitry of a power electronic application, one needs knowledge of several areas, which are listed below.

- Design of analogue and digital electronic circuits, to build the control circuitry.
- Microcontrollers and digital signal processors for use in sophisticated applications.
- Many power electronic circuits have an electrical machine as their load. In ac variable speed drive, it may be a reluctance motor, an induction motor or a synchronous motor. In a dc variable speed drive, it is usually a dc shunt motor.
- In a circuit such as an inverter, a transformer may be connected at its output and the transformer may have to operate with a none sinusoidal waveform at its input.
- A pulse transformer with a ferrite core is used commonly to transfer the gate signal to the power semiconductor device. A ferrite-cored transformer with a relatively higher power output is also used in an application such as a high frequency inverter.
- Many power electronic systems are operated with negative feedback. A linear controller such as a PI controller is used in relatively simple applications, where a controller based on digital or state-variable feedback techniques is used in more sophisticated applications.
- Computer simulation is often necessary to optimize the design of a power electronic system. In order to simulate, knowledge of software package such as MATLAB and the know-how to model nonlinear systems may be necessary.

The study of power electronics is an exciting and a challenging experience. The scope for applying power electronics is growing at a fast pace. New devices keep coming into the market, sustaining development work in power electronics.

CHAPTER 2

A SINGLE DIODE CIRCUIT

2.1 Overview

This chapter describes a single diode circuit. Most of the power electronic applications operate at a relative high voltage and in such cases, the voltage drop across the power diode tends to be small. It is quite often justifiable to use the ideal diode model. An ideal diode has zero conduction drop when it is forward-biased and has zero current when it is reverse-biased. The explanation and the analysis presented below is based on the ideal diode model.

2.2 Circuit Operation

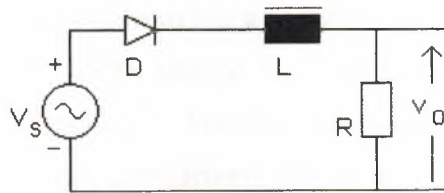


Figure 2.1 A circuit with a single diode and an RL load.

A circuit with a single diode and an RL load is shown in figure 2.1, the source v_s is an alternating sinusoidal source. If $v_s = E \sin(\omega t)$, v_s is positive when $0 < \omega t < \pi$, and v_s is negative when $\pi < \omega t < 2\pi$. When v_s starts becoming positive, the diode starts conducting and the source keeps the diode in conduction till ωt reaches π radians. At that instant defined by $\omega t = \pi$ radians, the current through the circuit is not zero and there is some energy stored in the inductor. The voltage across an inductor is positive when the current through it is increasing and it becomes negative when the current through it tends to fall. When the voltage across the inductor is negative, it is in such a direction as to forward-bias the diode. The polarity of voltage across the inductor is as shown in figures 2.1.a and 2.1.b.

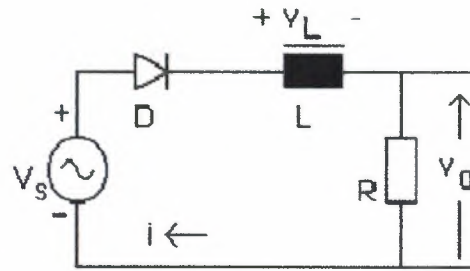


Figure 2.1.a When current is increasing.

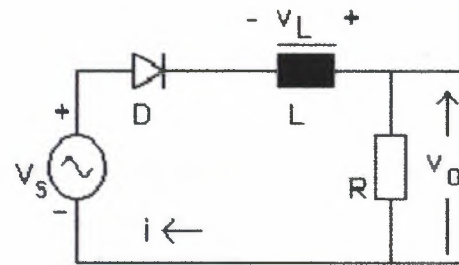


Figure 2.1.b When current is decreasing.

When v_s changes from a positive to a negative value, there is current through the load at the instant $\omega t = \pi$ radians and the diode continues to conduct till the energy stored in the inductor becomes zero. After that the current tends to flow in the reverse direction and the diode blocks conduction. The entire applied voltage now appears across the diode.

2.3 Mathematical Analysis

An expression for the current through the diode can be obtained as shown below. It is assumed that the current flows for $0 < \omega t < \beta$, where $\beta > \pi$. When the diode conducts, the driving function for the differential equation is the sinusoidal function defining the source voltage. During the period defined by $\beta < \omega t < 2\pi$, the diode blocks current and acts as an open switch. For this period, there is no equation defining the behavior of the circuit. For $0 < \omega t < \beta$, the equation (1) defined below applies.

$$L \frac{di}{dt} + R * i = E * \sin(\theta), \text{ where } 0 \leq \theta \leq \beta. \quad (1)$$

$$L \frac{di}{dt} + R * i = 0. \quad (2)$$

$$wL \frac{di}{d\theta} + R * i = 0. \quad (3)$$

$$i(\theta) = A * e^{\frac{-R\theta}{wL}} \quad (4)$$

Given a linear differential equation, the solution is found out in two parts. The homogeneous equation is defined by equation (2). It is preferable to express the equation in terms of the angle θ instead of 't'. Since $\theta = wt$, we get that $d\theta = w \cdot dt$. Then equation (2) then gets converted to equation (3). Equation (4) shown above is the solution to this homogeneous equation and is called the complementary integral. The value of constant A in the complimentary solution is to be evaluated later.

The particular solution is the steady-state response and equation (5) expresses the particular solution. The steady-state response is the current that would flow in steady-state in a circuit that contains only the source, the resistor and the inductor shown in the circuit above, the only element missing being the diode. This response can be obtained using the differential equation or the Laplace transform or the ac sinusoidal circuit analysis. The total solution is the sum of both the complimentary and the particular solution and it is shown as equation (6). The value of A is obtained using the initial condition. Since the diode starts conducting at $wt = 0$ and the current starts building up from zero, $i(0) = 0$. The value of A is expressed by equation (7).

Once the value of A is known, the expression for current is known. After evaluating A, current can be evaluated at different values of wt , starting from $wt = \pi$. As wt increases, the current would keep decreasing. For some value of wt , say β , the current would be zero. If $wt > \beta$, the current would evaluate to a negative value. Since the diode blocks current in the reverse direction, the diode stops conducting when wt reaches β . Then an expression for the average output voltage can be obtained. Since the average voltage across the inductor has to be zero, the average voltage across the

resistor and the average voltage at the cathode of the diode are the same. This average value can be obtained as shown in equation (8).

$$i(\theta) = \left(\frac{E}{Z} \right) * \sin(\omega t - \alpha), \text{ where } \alpha = \tan^{-1} \left(\frac{\omega L}{R} \right) \text{ and } Z^2 = R^2 + (\omega L)^2. \quad (5)$$

$$i(\theta) = A * e^{\left(\frac{-R\theta}{\omega L} \right)} + \frac{E}{Z} * \sin(\theta - \alpha). \quad (6)$$

$$A = \left(\frac{E}{Z} \right) \sin(\alpha). \quad (7)$$

$$V_{OAVG} = \frac{E}{2\pi} \int_0^\beta \sin \theta \, d\theta = \frac{E}{2\pi} [1 - \cos \beta] \quad (8)$$

2.4 Interactive Simulation

The operation of the circuit can be simulated as shown below. In order to simulate, the solution for current is presented in the following form, where $\tau = (\omega L)/R$. Then

$$i(\theta) = \frac{E}{R\sqrt{1+\tau^2}} * \left[\sin(\alpha) * e^{\left(\frac{-R\theta}{\omega L} \right)} + \sin(\theta - \alpha) \right]. \quad (9)$$

Again it is preferable to normalize. Here E is set to unity and E/R is also set to unity. Then

$$v_s = \sin(\omega t).$$

$$v_o = i \text{ for } 0 < \omega t < \beta,$$

$$v_L = v_s - i \text{ for } 0 < \omega t < \beta.$$

To solve the expression, all we need to know is then the ratio τ . The applet shown below simulates this circuit. You have to key-in the ratio τ and then click on the button next to it.

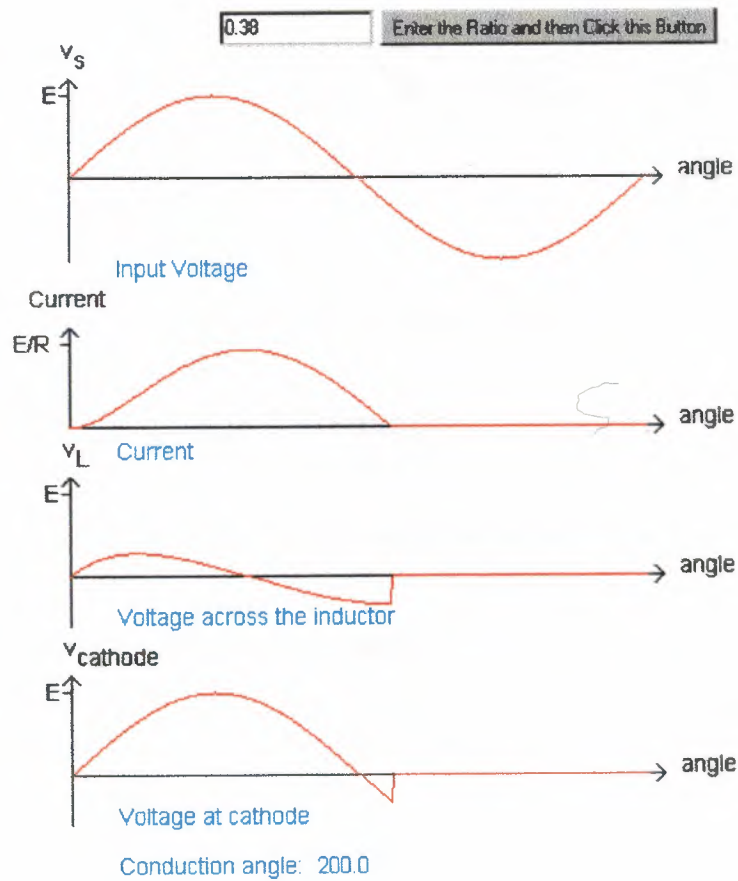
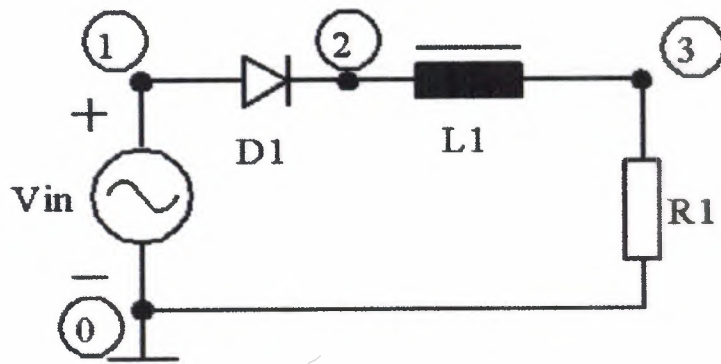


Figure 2.2 The Applet. Shows the Source Voltage, Current, Voltage Across the Inductor and Voltage at Cathode.

2.5 Pspice Simulation

For simulation using Pspice, the circuit used is shown below. Here the nodes are numbered. The ac source is connected between nodes 1 and 0. The diode is connected between nodes 1 and 2 and the inductor links nodes 2 and 3. The resistor is connected from 3 to the reference node, that is, node 0.



For Pspice simulation

Figure 2.3 Circuit Used In Pspice Simulation.

The Pspice program is presented below.

* The Chapter: Half-wave Rectifier with RL Load

* A problem to find the diode current

```
VIN 1 0 SIN(0 340V 50Hz)
```

```
D1 1 2 DNAME
```

```
L1 2 3 31.8MH
```

```
R1 3 0 10
```

```
.MODEL DNAME D(IS=10N N=1 BV=1200 IBV=10E-3 VJ=0.6)
```

```
.TRAN 10US 60.0MS 20.0MS 10US
```

```
.PROBE
```

```
.OPTIONS (ABSTOL=1N RELTOL=.01 VNTOL=1MV)
```

```
.END
```

The diode is described using the MODEL statement. The TRAN statement simulates the transient operation for a period of 60 ms at an interval of 10 μ s.

The OPTIONS statement sets limits for tolerances. The output can be viewed on the screen because of the PROBE statement. A snapshot of output is presented below.

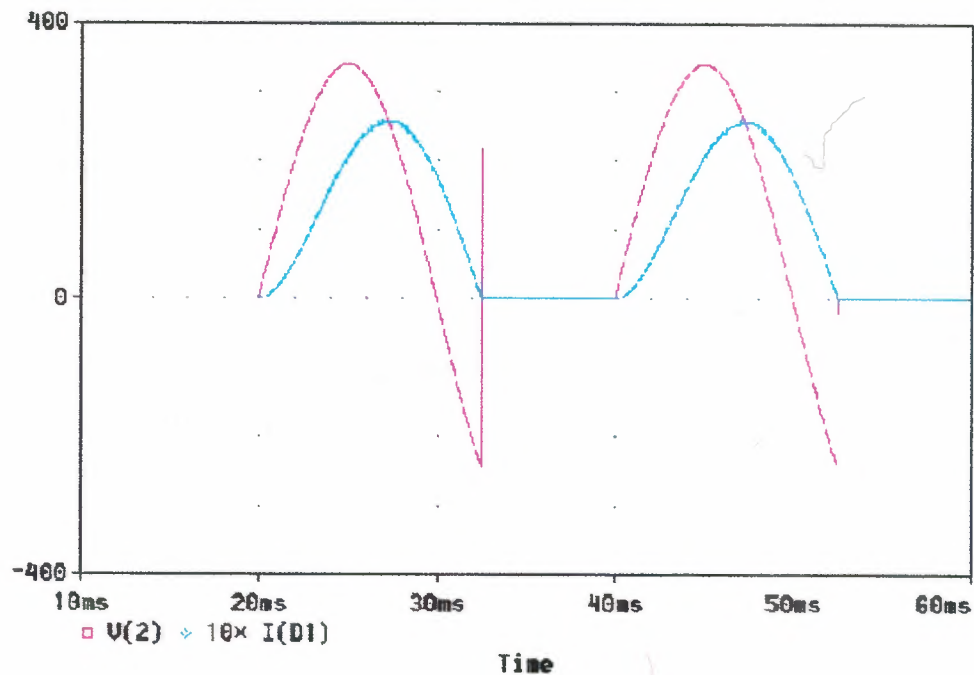


Figure 2.4 A snapshot of output

2.6 Matlab Simulation

The Mat lab program used is re-produced below.

```
% Program to simulate the half-wave rectifier circuit
% Enter the peak voltage, frequency, inductance L in mH and
resistor R
disp('Typical value for peak voltage is 340 V')
peakV=input('Enter Peak voltage in Volts>');
disp('Typical value for line frequency is 50 Hz')
freq=input('Enter line frequency in Hz>');
disp('Typical value for Load inductance is 31.8 mH')
L=input('Enter Load inductance in mH>');
disp('Typical value for Load Resistance is 10.0 Ohms')
R=input('Enter Load Resistance in Ohms>');
w=2.0*pi*freq;
X=w*L/1000.0;
if (X<0.001) X=0.001; end;
Z=sqrt(R*R+X*X);
```

```

loadAng=atan(X/R);
A=peakV/Z*sin(loadAng);
tauInv=R/X;
for n=1:360;
    theta=n/180.0*pi;
    X(n)=n;
    cur=peakV/Z*sin(theta-loadAng)+A*exp(-tauInv*theta);
    if (cur>0.0)
        Vind(n)=peakV*sin(theta)-R*cur;
        iLoad(n)=cur;
        Vout(n)=peakV*sin(theta);
    else
        Vind(n)=0;
        iLoad(n)=0;
        Vout(n)=0;
    end;
end;
plot(X,iLoad)
title('The diode current')
xlabel('degrees')
ylabel('Amps')
grid
pause
plot(X,Vout)
title('Voltage at cathode')
xlabel('degrees')
ylabel('Volts')
grid
pause
plot(X,Vind)
title('Inductor Voltage')
xlabel('degrees')
ylabel('Volts')
grid

```

The plots obtained for the typical values mentioned are shown below.

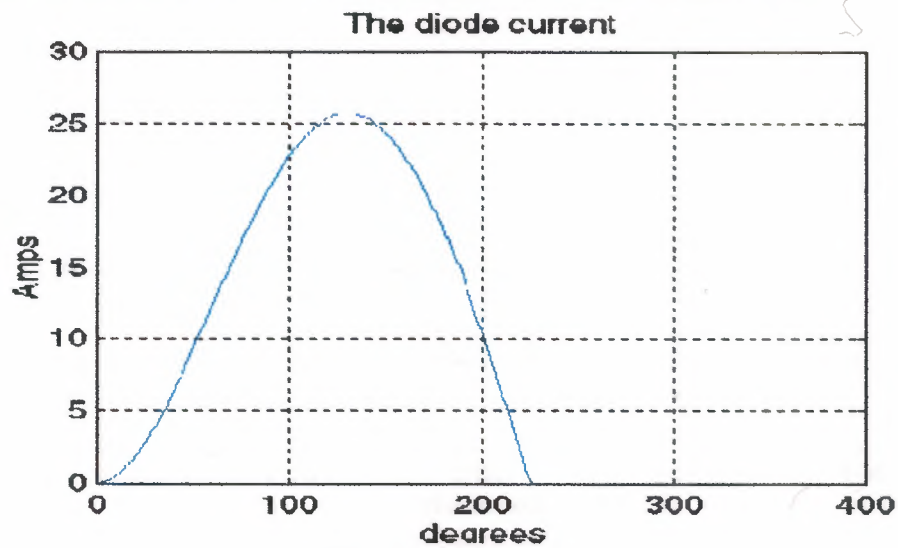


Figure 2.5.a Shows the Diode Current.

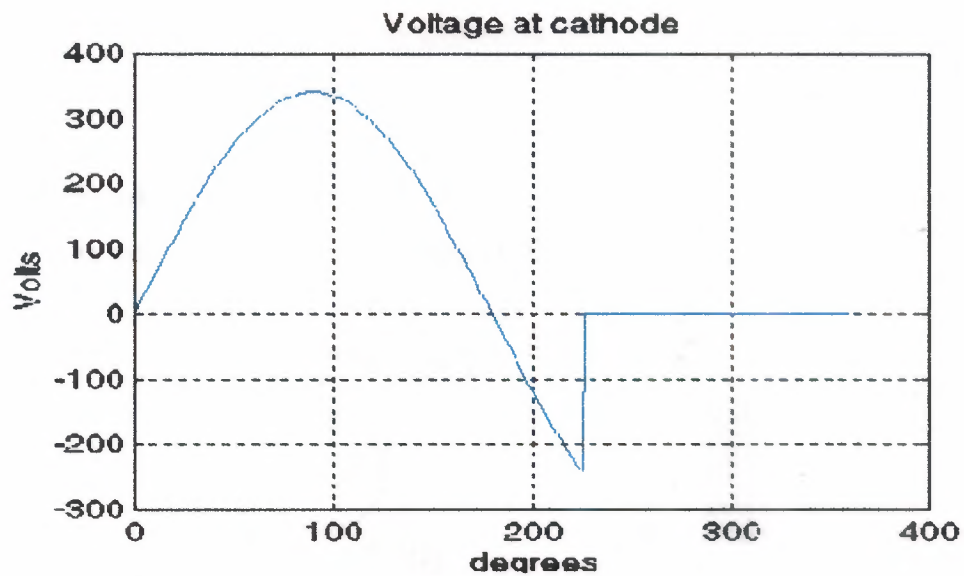


Figure 2.5.b Shows Voltage at Cathode.

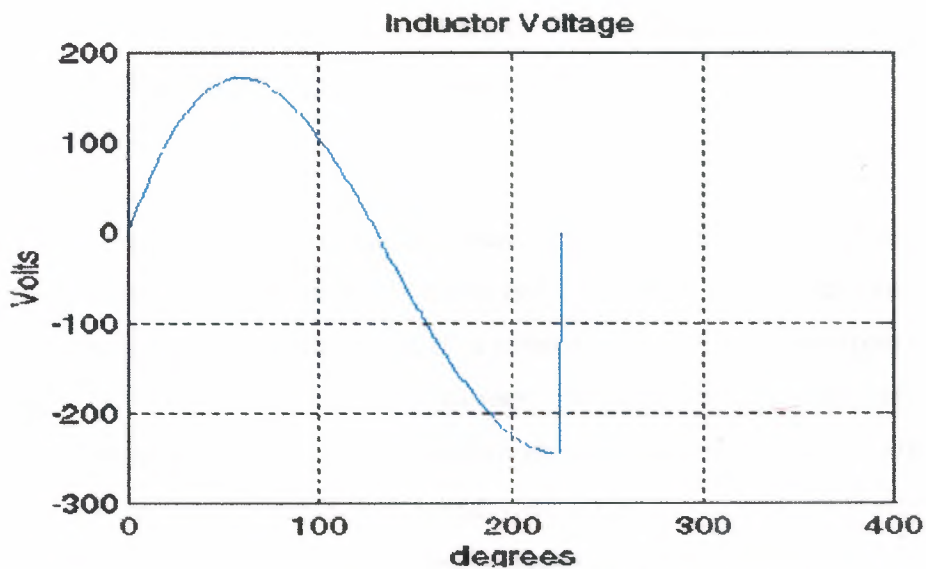


Figure 2.5.c Shows the Inductor Voltage.

It can be seen from the waveform of voltage across the inductor is that the area above the x-axis at 0 V is equal to its area below the x-axis. It can be seen that the mat lab program is relatively simple.

2.7 Mathcad Simulation

Alternatively, we can see the mathcad file in HTML format.

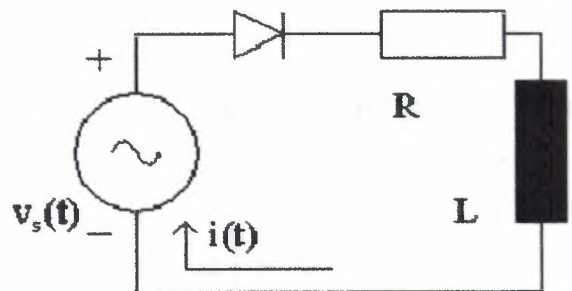


Figure 2.6 Half-Wave Rectifier with RL load.

$$E = 340 \text{ V}$$

$$R = 10 \, \Omega$$

$$\omega L = 2 \times \pi \times 50 \times 31.8 \times 10^{-3} \, \Omega$$

$$\alpha = \text{atan}(\omega L / R)$$

$$\alpha = 0.785 \text{ rad}$$

The value of L is set to be 31.8 mH. The frequency is set to be 50 Hz. The load angle is calculated for the specified values of R, L and f.

$$Z = 14.135 \ \Omega$$

$$A = 17 \text{ Amp}$$

The value of the coefficient A has been computed. Now the plots of the source voltage, the current through the diode and the voltage at the cathode of diode are obtained. A range variable, called θ , is created first and it is varied from 0 deg to 360 deg. At each degree, the current through the diode is computed. The expression for current, Cur_θ , shown above would yield positive values if θ is less than the conduction angle and would yield negative values if θ is higher than the conduction angle. The statement below creates an array called i_θ and it is set equal to Cur_θ , if Cur_θ is positive. If Cur_θ is negative, i_θ is set equal to zero. The expression within the brackets is similar to arithmetic IF operator in C language. Given

$x := \text{if}(\text{expr1}, \text{expr2}, \text{expr3})$, x is assigned the value of expr2, if expr1 evaluates to Boolean TRUE value and x is assigned the value of expr3, if expr1 evaluates to Boolean FALSE value. This arithmetic IF operation is carried out for each value of array i_θ taking into account the corresponding value of Cur_θ . That is, both i_θ and Cur_θ have the same index, θ when evaluation is performed.

$$Z := \sqrt{R^2 + \omega L^2} \quad A := \frac{E}{Z} \cdot \sin(\alpha) \quad \theta := 0..360$$

$$\text{Cur}_\theta := \frac{E}{Z} \cdot \sin\left(\frac{\theta}{180} \cdot \pi - \alpha\right) + A \cdot e^{-\frac{R \cdot \theta \cdot \pi}{180 \cdot \omega L}}$$

$$i_\theta := \text{if}(\text{Cur}_\theta > 0.0, \text{Cur}_\theta, 0.0)$$

$$vR_\theta := R \cdot i_\theta$$

The voltage across the resistor can be computed as shown below. Next the voltage across the inductor is computed. Again the arithmetic IF operation is carried out. When the diode current is positive, the voltage across the inductor is the difference

between the source voltage and the voltage across the resistor. When the diode current is zero, the voltage across the inductor is also zero. Next the conduction angle is determined. MathCad allows a particular construct. Assign a guess value for conduction angle. Here it is called β and is assigned a value of π radians. Next form a block starting with **Given** statement. The equality that should exist is presented below. The program then evaluates the correct value of β for which the equality is true. Then that value of β is assigned to another variable called δ in this program.

$$vL_{\theta} := \text{if}\left(i_{\theta} > 0.0, E \cdot \sin\left(\frac{\theta}{180} \cdot \pi\right) - vR_{\theta}, 0.0\right)$$

$$\beta := \pi$$

Given

$$\frac{E}{Z} \cdot \sin(\beta - \alpha) + A \cdot e^{-\frac{R \cdot \beta}{\omega L}} = 0$$

$$\delta := \text{Find}(\beta)$$

$$\delta = 3.94 \text{ rad}$$

When $\omega t = \delta$, the current through the load becomes zero. The dc value of this current is found out as shown below. Here this current is expressed as a function of x and this function is integrated over the period of conduction.

$$\text{cur}(x) := \frac{E}{Z} \cdot \sin(x - \alpha) + A \cdot e^{-\frac{R \cdot x}{\omega L}}$$

$$I_{DC} := \frac{1}{2 \cdot \pi} \cdot \int_0^{\delta} \text{cur}(x) \, dx$$

$$I_{DC} = 9.187 \text{ Amp.}$$

The ac source shown in Fig. 2.8 has to supply this dc current. An ac source should not normally be required to supply a dc current. The mains ac supply is distributed using transformers and a transformer is not designed to supply a dc current. It is preferable to avoid using half-wave rectifier circuits.

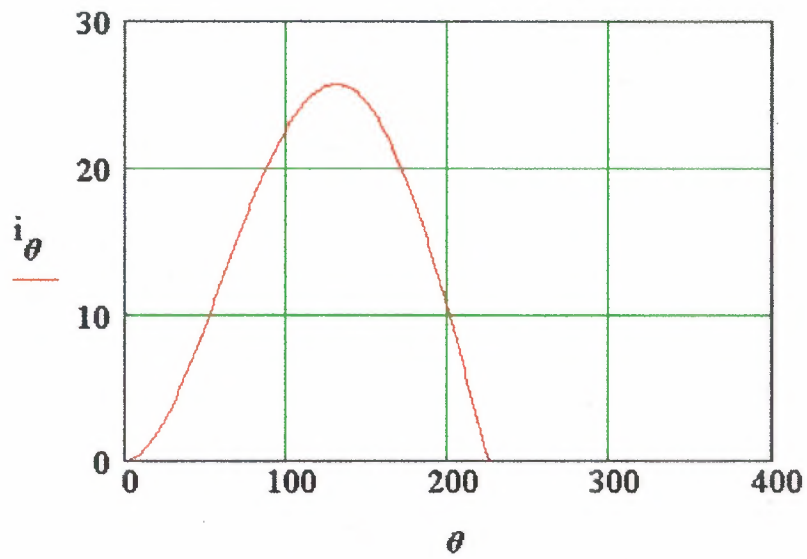


Figure 2.7.a Shows Current through the Diode.

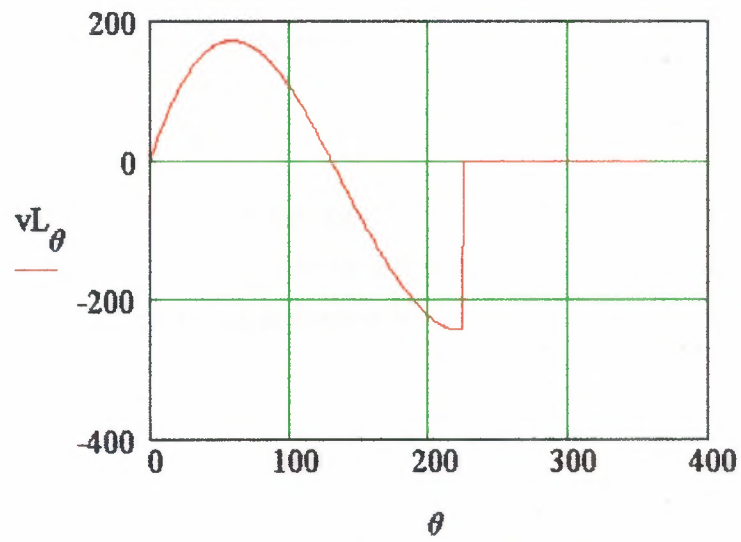


Figure 2.7.b Shows the Voltage Across the Inductor.

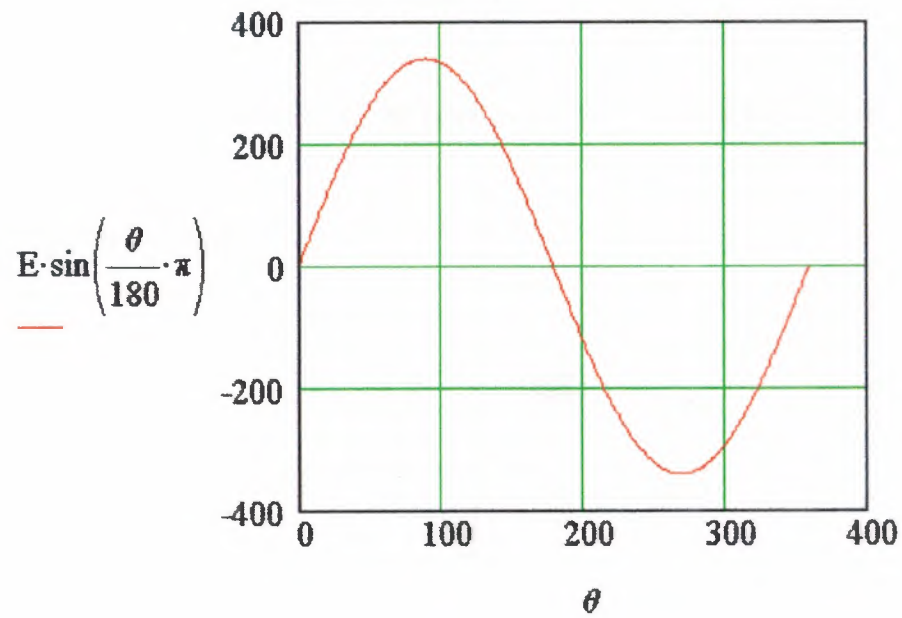


Figure 2.7.c shows the plot voltage source.

2.8 Summary

This chapter has described the circuit of a half-wave rectifier. It has been simulated using different programs. All the explanation and analysis which has been done in this chapter based on the ideal diode model.

CHAPTER 3

A DIODE CIRCUIT WITH A FREE-WHEELING DIODE

3.1 Circuit Diagram

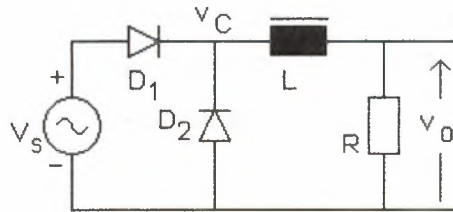


Figure 3.1 Shows a Diode Circuit with Free-Wheeling Diode.

The circuit shown in figure 3.1 differs from the circuit described in the previous chapter, which had only diode D_1 . This circuit has another diode, marked D_2 in the circuit shown above. This diode is called the free-wheeling diode. The circuit operation is described next. The explanation is based on the assumption that the reader knows how the circuit without a free-wheeling diode operates.

3.2 Circuit Operation

Let the source voltage v_s be defined to be $E \sin(\omega t)$. The source voltage is positive when $0 < \omega t < \pi$ radians and it is negative when $\pi < \omega t < 2\pi$ radians. When v_s is positive, diode D_1 conducts and the voltage v_c is positive. This in turn leads to diode D_2 being reverse-biased during this period. During $\pi < \omega t < 2\pi$, the voltage v_c would be negative if diode D_1 tends to conduct. This means that D_2 would be forward-biased and would conduct. When diode D_2 conducts, the voltage v_c would be zero volts, assuming that the diode drop is negligible. Additionally when diode D_2 conducts, diode D_1 remains reverse-biased, because the voltage v_s is negative.

When the current through the inductor tends to fall, it starts acting as a source. When the inductor acts as a source, its voltage tends to forward bias diode D_2 if the source voltage v_s is negative and forward bias diode D_1 if the source voltage v_s is positive. Even when the source voltage v_s is positive, the inductor current would tend to fall if the source voltage is less than the voltage drop across the load resistor.

During the negative half-cycle of source voltage, diode D_1 blocks conduction and diode D_2 is forced to conduct. Since diode D_2 allows the inductor current circulate through L, R and D_2 , diode D_2 is called the free-wheeling diode. We can say that the current free-wheels through D_2 .

3.3 Mathematical Analysis

An expression for the current through the load can be obtained as shown below. It can be assumed that the load current flows all the time. In other words, the load current is continuous. When diode D_1 conducts, the driving function for the differential equation is the sinusoidal function defining the source voltage. During the period defined by $\pi < \omega t < 2\pi$, diode D_1 blocks current and acts as an open switch. On the other hand, diode D_2 conducts during this period, the driving function can be set to be zero volts. For $0 < \omega t < \pi$, the equation (1) shown below applies.

For the negative half-cycle of the source, equation (2) applies. As in the previous case, the solution is obtained in two parts. The expressions for the complementary integral and the particular integral are the same. The expression for the complementary integral is presented by equation (3). The particular solution to the equation (1) is the steady-state response and is presented as equation (4). The total solution is the sum of both the complimentary and the particular solution. For $0 < \theta < \pi$, where $\omega t = \theta$, the total solution is presented as equation (5).

$$L \frac{di}{dt} + R * i = E * \sin(\theta). \quad (1)$$

$$L \frac{di}{dt} + R * i = 0. \quad (2)$$

$$i(\theta) = A * e^{\left(\frac{R\theta}{\omega L}\right)}. \quad (3)$$

$$i(\theta) = \left(\frac{E}{Z}\right) * \sin(\omega t - \alpha), \text{ where } \alpha = \tan^{-1} \left(\frac{\omega L}{R}\right), \text{ and } Z = \sqrt{R^2 + (\omega L)^2}. \quad (4)$$

$$i(\theta) = A * e^{\left(\frac{-R\theta}{\omega L}\right)} + \frac{E}{Z} * \sin(\theta - \alpha). \quad (5)$$

The difference in solution is in how the constant A in complementary integral is evaluated. In the case of the circuit without free-wheeling diode, $i(0) = 0$, since the

current starts building up from zero at the start of every positive half-cycle. On the other hand, the current-flow is continuous when the circuit contains a free-wheeling diode also. Since the input to the RL circuit is a periodic half-sinusoid function, we expect that the response of the circuit should also be periodic. That means, the current through the load is periodic. It means that $i(0) = i(2\pi)$.

Since the current through the load free-wheels during $\pi < \theta < 2\pi$, we get equation (6). We use $(\theta - \pi)$ for the elapsed period in radians instead of θ itself, since the free-wheeling action starts at $\theta = \pi$. From the total solution, we can get $i(\pi)$ from equation (7) by substituting $\theta = \pi$. To obtain A, the following steps are necessary. From the total solution, obtain an expression for $i(0)$ by substituting 0 for θ . Also obtain an expression for $i(\pi)$ by substituting π for θ in equation (7). Using this expression for $i(\pi)$ in equation (6), obtain $i(2\pi)$ by letting $\theta = 2\pi$. Since $i(0) = i(2\pi)$, we can obtain A from equation (8). In equation (8), the terms containing constant A are grouped on the left-hand side of equation and the other terms on the right-hand side.

$$i(\theta) = i(\pi) * e^{\left[-\frac{(\theta-\pi)}{\tau}\right]}, \text{ where } \tau = \frac{wL}{R}. \quad (6)$$

$$i(\theta) = A * e^{-\frac{\theta}{\tau}} + \left(\frac{E}{Z}\right) * \sin(\theta - \alpha), \quad (7)$$

$$\left[1 - e^{\left(-\frac{2\pi}{\tau}\right)}\right] A = \left(\frac{E}{Z}\right) * \left[\sin(\alpha) + \sin(\pi - \alpha) * e^{-\frac{\pi}{\tau}}\right]. \quad (8)$$

3.4 Simulation

The operation of the circuit can be simulated as shown below. During $0 < \theta < \pi$, the expression for current is presented as equation (9). During $\pi < \theta < 2\pi$, the expression for current is shown as equation (10).

$$i(\theta) = A * e^{\left(\frac{-R\theta}{\omega L}\right)} + \frac{E}{Z} * \sin(\theta - \alpha). \quad (9)$$

$$\text{where } \tau = \frac{\omega L}{R}, \alpha = \tan^{-1}(\tau), \text{ and } Z = \sqrt{R^2 + (\omega L)^2}.$$

$$i(\theta) = A * e^{-\frac{\theta}{\tau}} + \frac{E}{Z} * \sin(\theta - \pi) * e^{-\frac{\theta - \pi}{\tau}} \quad (10)$$

The voltage across the inductor is obtained to be

$$v_L(\theta) = v_s(\theta) - R * i(\theta), \text{ for } 0 < \theta < \pi \text{ and}$$

$$= -R * i(\theta), \text{ for } \pi < \theta < 2\pi.$$

$$v_s(\theta) = E * \sin(\theta).$$

It is preferable to normalize v_s with respect to E and the current with respect to E/R and then the only value required to be known for solving for the current is τ . The applet shown below simulates this circuit. You have to write the ratio τ then click on the Button.

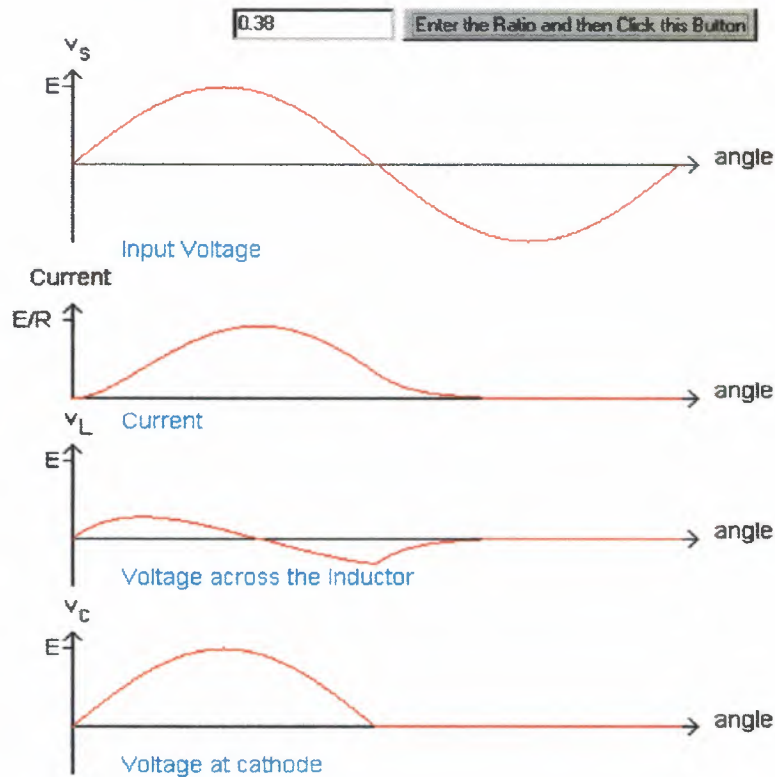
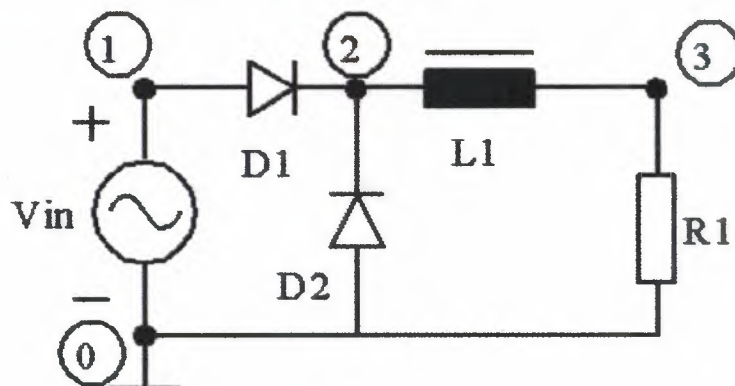


Figure 3.2 The Applet. Shows the Source Voltage, Current, Voltage Across the Inductor and Voltage at Cathode.

3.5 Pspice Simulation

The circuit that is used for Pspice simulation is shown below. The nodes are numbered and the components have been labeled.



For Pspice simulation

Figure 3.3 Shows A Circuit Used In Pspice Simulation

A Pspice program to simulate the circuit shown above is presented now.

* Half-wave Rectifier with free-wheeling diode and with RL Load

* A problem to find the diode current

```
VIN 1 0 SIN(0 340V 50Hz)
```

```
D1 1 2 DNAME
```

```
L1 2 3 31.8MH
```

```
R1 3 0 10
```

```
D2 0 2 DNAME
```

```
.MODEL DNAME D(IS=10N N=1 BV=1200 IBV=10E-3 VJ=0.6)
```

```
.TRAN 10US 60.0MS 20.0MS 10US
```

```
.PROBE
```

```
.OPTIONS (ABSTOL=1N RELTOL=.01 VNTOL=1MV)
```

```
.END
```

The waveforms obtained are presented now. Since the program specifies that the waveforms be displayed from the second cycle, there is no output for the first 20 ms.

The waveform of voltage at the cathode of both diodes is shown below.

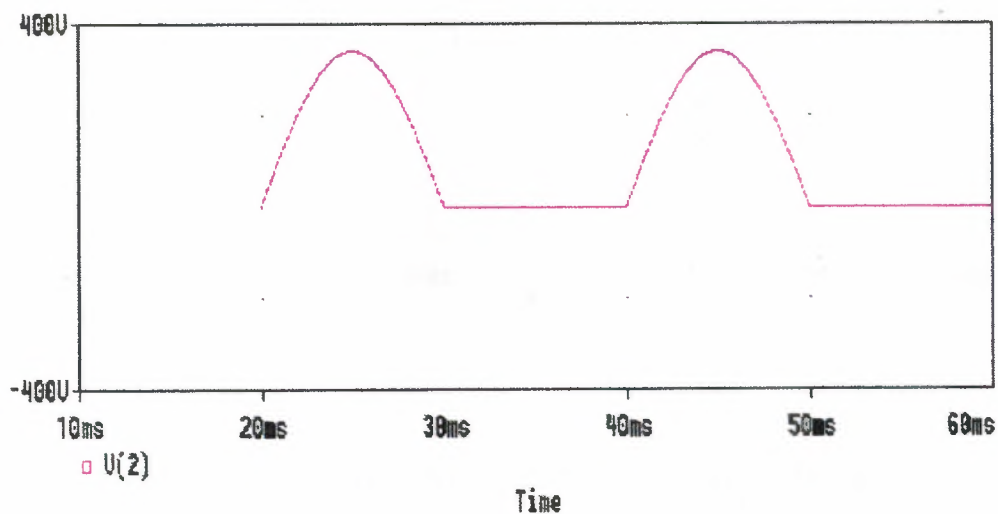


Figure 3.4.a Shows The Waveform Of Voltage At The Cathode Of Both Diodes

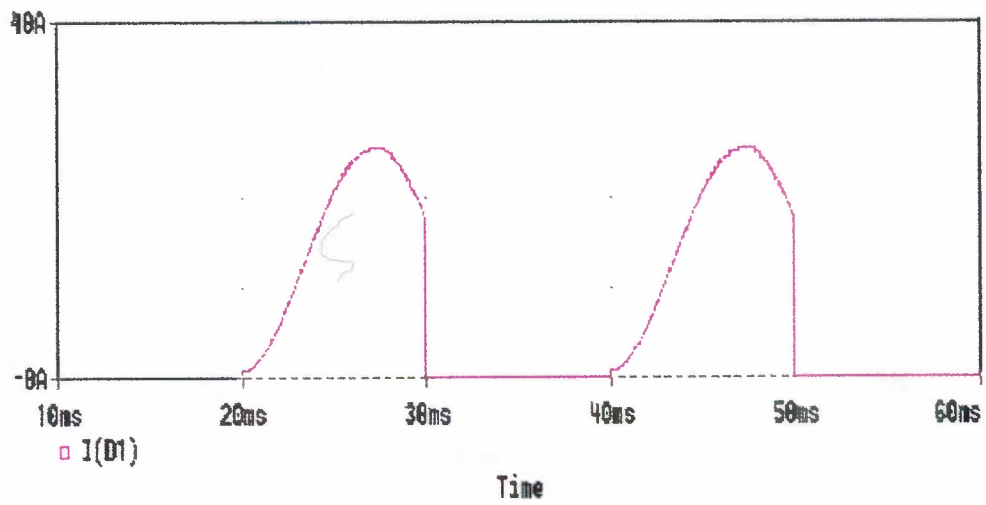


Figure 3.4.b The Waveform Of Current Through Diode D_1

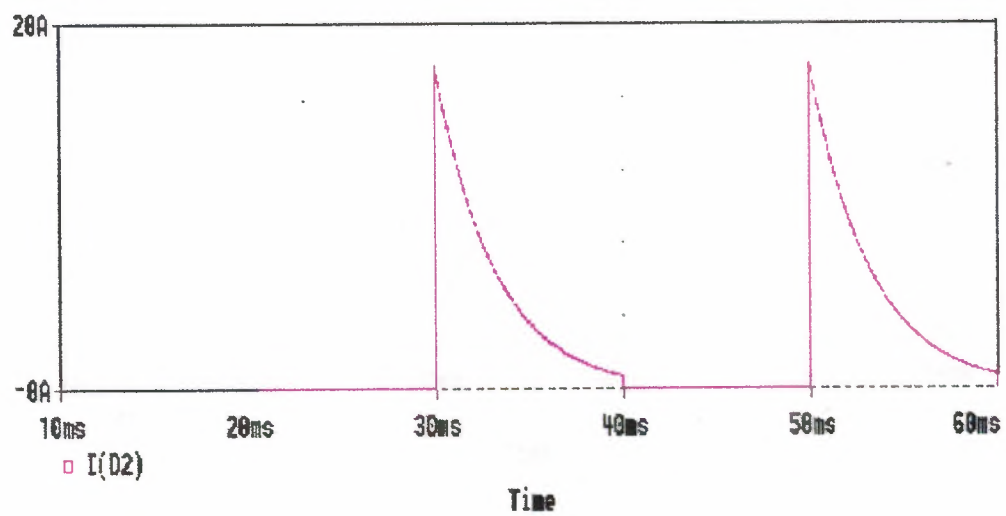


Figure 3.4.c Shows The Waveform Of Current Through Diode D_2

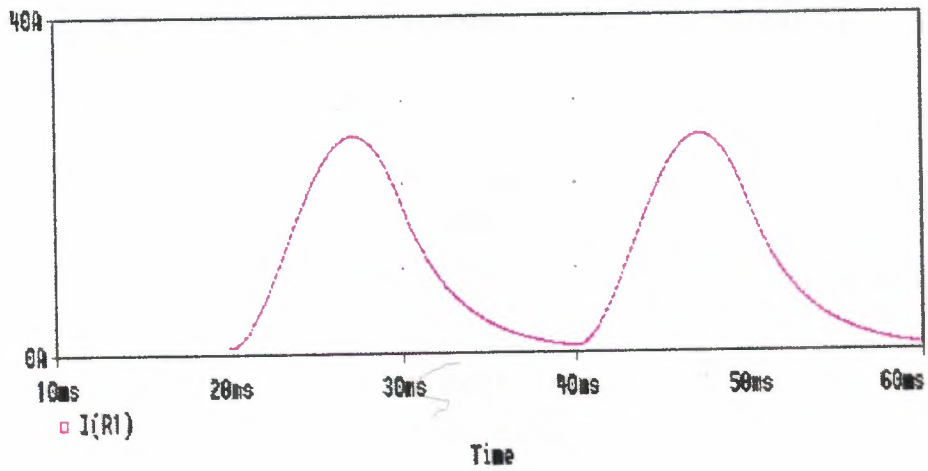


Figure 3.4.d Shows The Waveform Of Current Through Load Resistor, It Is The Sum Of Both Diode Currents

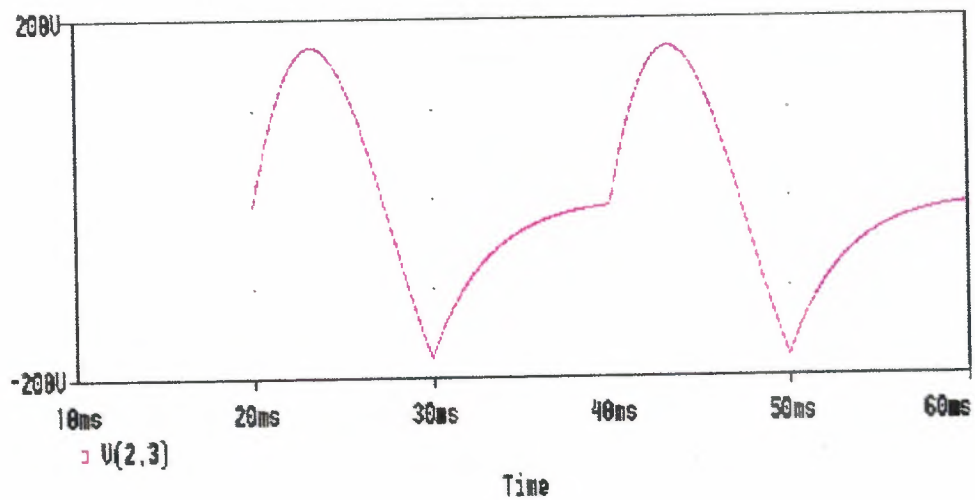


Figure 3.4.e Shows The Voltage Across The Inductor

The advantage with Pspice is the simplicity of the program. In addition, the devices used are also simulated using the spice models.

3.6 Matlab Simulation

A matlab program for simulating the half-wave rectifier with a free-wheeling diode is presented below.

```
% Program to simulate the half-wave rectifier circuit
% The circuit has a free-wheeling diode
% Enter the peak voltage, frequency, inductance L in mH and
resistor R
disp('Typical value for peak voltage is 340 V')
peakV=input('Enter Peak voltage in Volts>');
disp('Typical value for line frequency is 50 Hz')
freq=input('Enter line frequency in Hz>');
disp('Typical value for Load inductance is 31.8 mH')
L=input('Enter Load inductance in mH>');
disp('Typical value for Load Resistance is 10.0 Ohms')
R=input('Enter Load Resistance in Ohms>');
w=2.0*pi*freq;
X=w*L/1000.0;
if (X<0.001) X=0.001; end;
Z=sqrt(R*R+X*X);
tauInv=R/X;
loadAng=atan(X/R);
A1=peakV/Z*sin(loadAng);
A2=peakV/Z*sin(pi-loadAng)*exp(-pi*tauInv);
A3=(A1+A2)/(1-exp(-2.0*pi*tauInv));
Ampavg=0;
AmpRMS=0
for n=1:360;
    theta=n/180.0*pi;
    X(n)=n;
    if (n<180)
        cur=peakV/Z*sin(theta-loadAng)+A3*exp(-tauInv*theta);
        Ampavg=Ampavg+cur*1/360;
        AmpRMS=AmpRMS+cur*cur*1/360;
```

```

else
    A4=peakV/Z*sin(pi-loadAng)*exp(-(theta-pi)*tauInv);
    cur=A4+A3*exp(-tauInv*theta);
    Ampavg=Ampavg+cur*1/360;
    AmpRMS=AmpRMS+cur*cur*1/360;
end;
if (n<180)
    Vind(n)=peakV*sin(theta)-R*cur;
    Vout(n)=peakV*sin(theta);
    diode2cur(n)=0;
    diode1cur(n)=cur;
else
    Vind(n)=-R*cur;
    Vout(n)=0;
    diode2cur(n)=cur;
    diode1cur(n)=0;
end
iLoad(n)=cur;
end;
plot(X,iLoad)
title('The Load current')
xlabel('degrees')
ylabel('Amps')
grid
pause
plot(X,Vout)
title('Voltage at cathode')
xlabel('degrees')
ylabel('Volts')
grid
pause
plot(X,Vind)
title('Inductor Voltage')
xlabel('degrees')

```

```

ylabel('Volts')
grid
pause
plot(X,diode1cur)
title('Diode 1 current')
xlabel('degrees')
ylabel('Amps')
grid
pause
plot(X,diode2cur)
title('Diode 2 current')
xlabel('degrees')
ylabel('Amps')
grid
AmpRMS=sqrt(AmpRMS);
[A,message]=fopen('outhfr2.dat','w');
fprintf(A,'Avg Load Cur=\t%d\tRMS Load
Cur=\t%f\n',Ampavg,AmpRMS);
fclose(A)

```

The responses obtained for the typical specified values are shown in the next page.

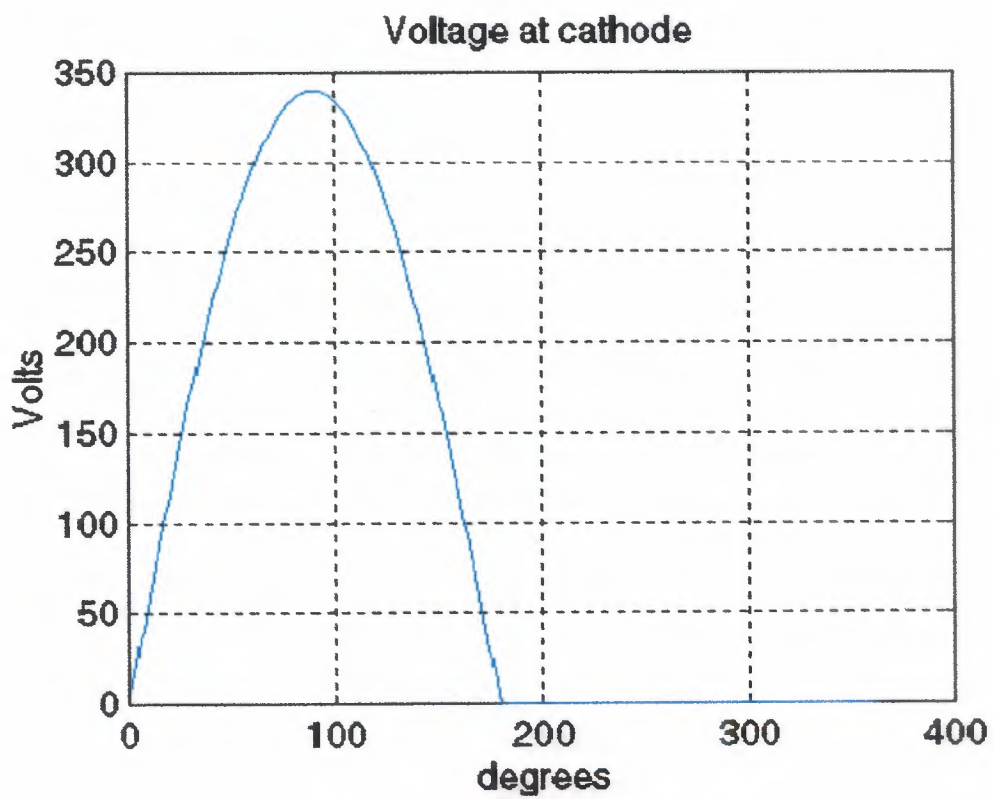


Figure 3.5.a Shows The Voltage At Cathode

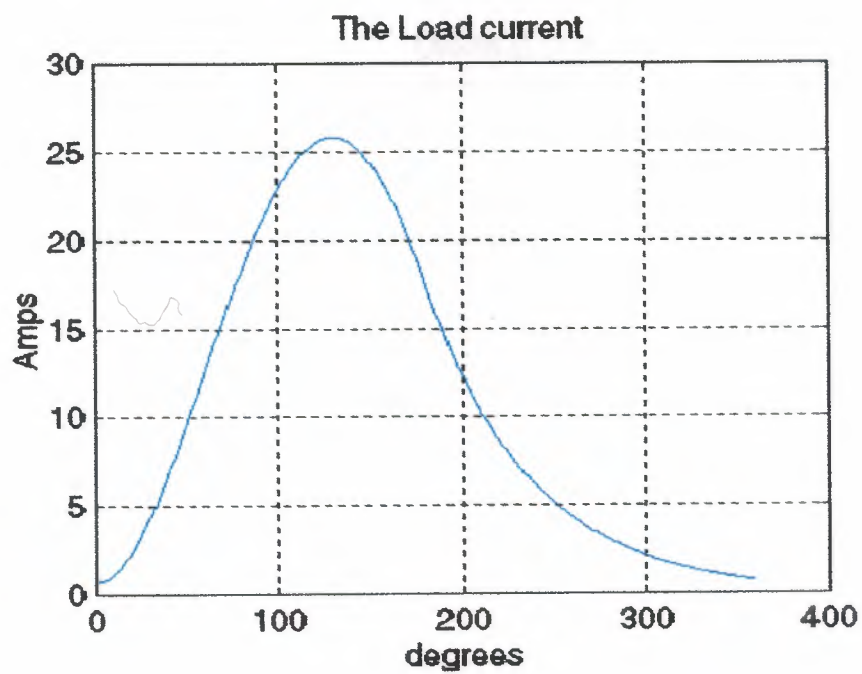


Figure 3.5.b Shows The Load Current

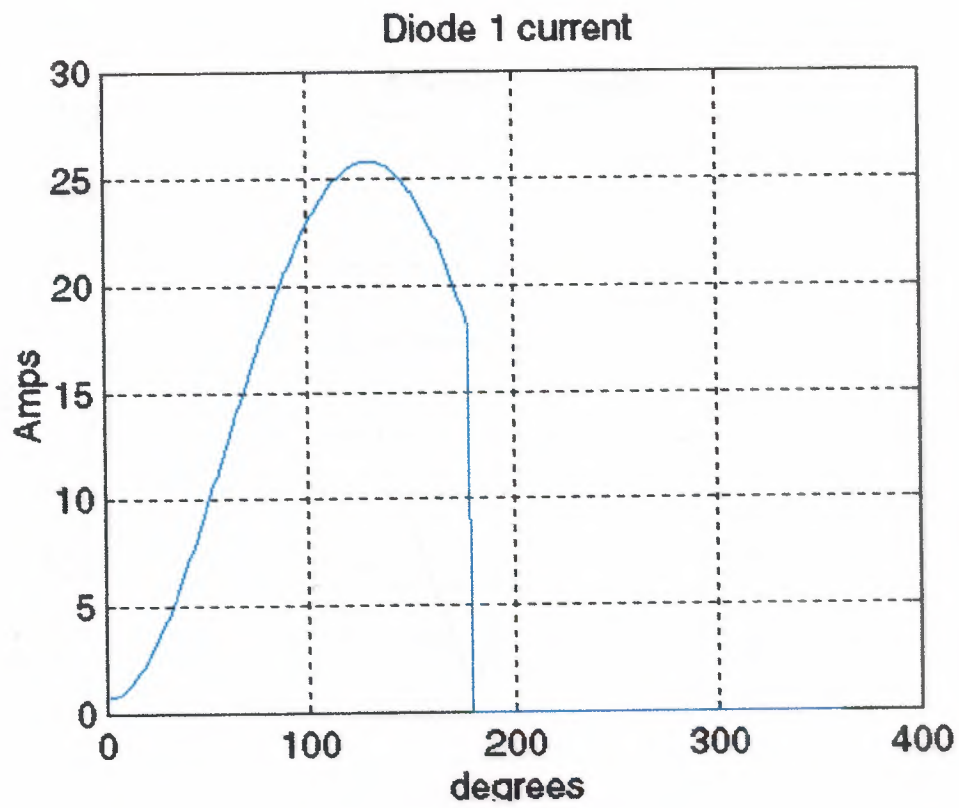


Figure 3.5.c Shows The Current Of D1

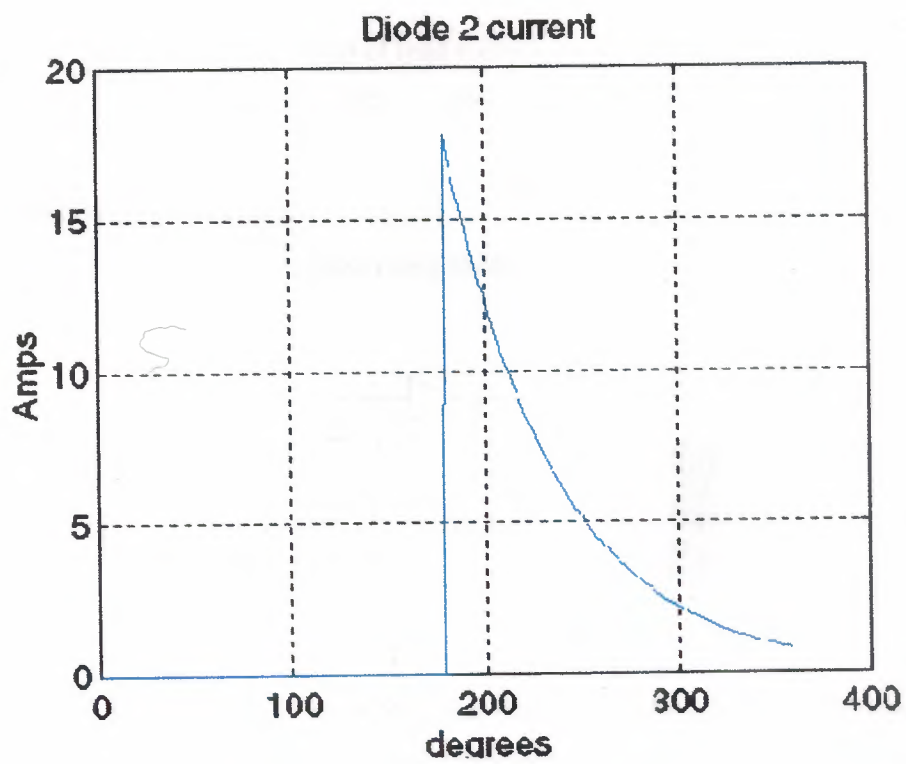


Figure 3.5.d Shows The Current Of D2

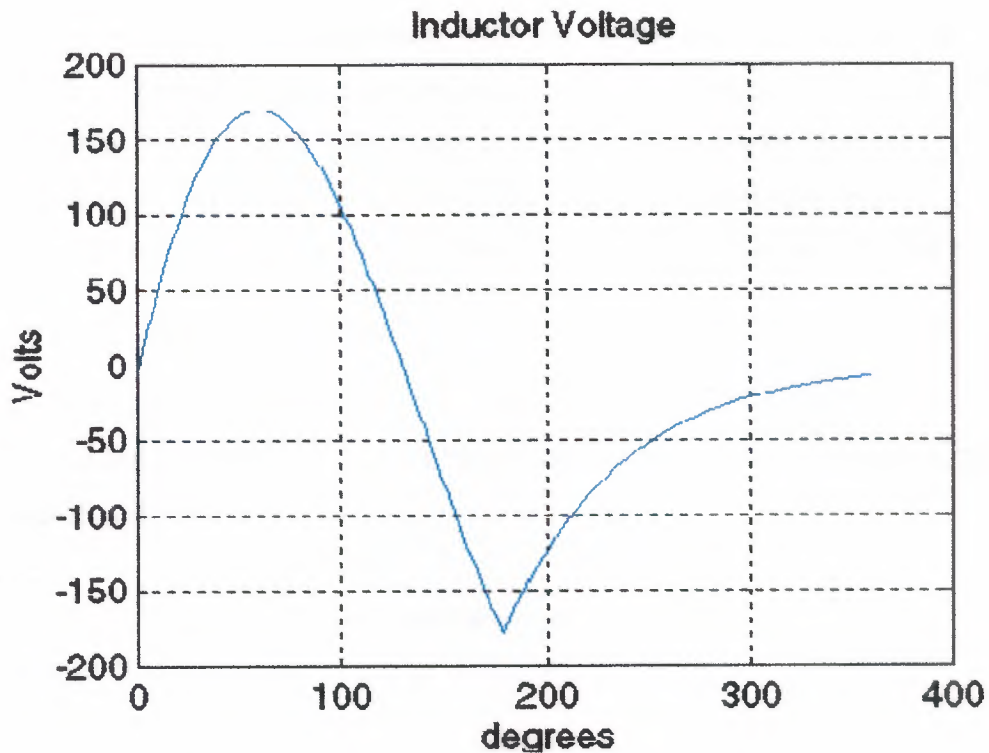


Figure 3.5.e Shows The Inductor Voltage

The average and rms values of load current are presented below.

Avg Load Cur=1.082254e+001 RMS Load Cur=13.954542

3.7 Mathcad Simulation

This circuit can be simulated using MathCad as shown below

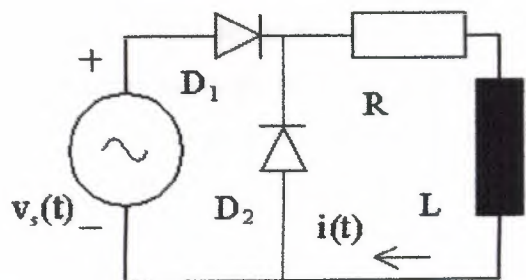


Figure 3.6 Shows Half-Wave Rectifier Circuit With Free-Wheeling Diode

This circuit differs from the half-wave rectifier circuit without a free-wheeling diode. Without a free-wheeling diode, the current through the RL load is discontinuous,

but it is continuous when there is a free-wheeling diode. Let $v_s(\omega t) = E \sin(\omega t)$. When $0 < \omega t < \pi$, diode D_1 conducts. When ωt crosses π , v_s becomes negative for $\pi < \omega t < 2\pi$. During this period, the inductor does not discharge its energy back to the source, for there is a path with a lower potential drop through D_2 . When $\pi < \omega t < 2\pi$, the current through the load decays exponentially. When the current response becomes periodic, the current at $\omega t = 0$ has the same value. Let the current at $\omega t = 0$ be A . Then

$$A = i(\pi) \exp[-R\pi / (\omega L)].$$

Also, $i(\omega t) = [E/Z] \sin(\omega t - \alpha) + A \exp[-(R\omega t)/(\omega L)]$, where $\alpha = \tan^{-1}(\omega L/R)$

$$\text{And } Z^2 = R^2 + (\omega L)^2.$$

The value of A can be obtained from the above expressions.

$$E := 340 \text{ V}$$

$$R := 10 \text{ } \Omega$$

$$\omega L := 10 \text{ } \Omega$$

$$Z := \sqrt{R^2 + (\omega L)^2}$$

$$Z = 14.142 \text{ } \Omega$$

$$\alpha := \tan^{-1}(\omega L/R)$$

$$\alpha = 0.785 \text{ rad}$$

Next the response over a cycle is computed. An array is created. The array index corresponding to degrees is converted to radians first. Next the value of load current at $\omega t = \pi$ is defined. Next an array called I_n is created. I_n is calculated differently, depending on whether the angle is less than or more than 180° . The voltage across the inductor is also stored as an array. Again, it is calculated differently for angle less than 180° or more. It is also shown how the current through each of the diodes can be computed.

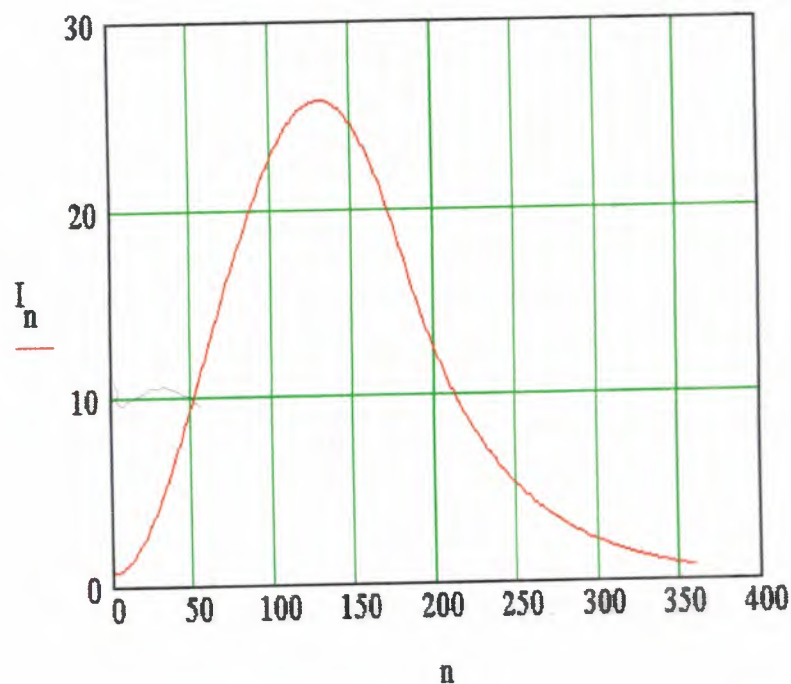
$$A = \left(\frac{E}{Z} \right) \cdot \frac{\sin(\alpha) \cdot e^{\frac{R \cdot \pi}{wL}} + \sin(\pi - \alpha)}{e^{\frac{R \cdot \pi}{wL}} - e^{-\frac{R \cdot \pi}{wL}}} \quad n = 0 \dots 360 \quad \theta_n = \frac{n}{180} \cdot \pi$$

$$\text{Cur}\pi = \frac{E}{Z} \cdot \sin(\pi - \alpha) + A \cdot e^{-\frac{R \cdot \pi}{wL}}$$

$$I_n = \text{if} \left(n < 180, \frac{E}{Z} \sin(\theta_n - \alpha) + A \cdot e^{-\frac{R \cdot \theta_n}{wL}}, \text{Cur}\pi \cdot e^{-\left[\frac{R \cdot (\theta_n - \pi)}{wL} \right]} \right)$$

$$VL_n = \text{if}(n < 180, E \cdot \sin(\theta_n) - R \cdot I_n, -R \cdot I_n) \quad d2\text{cur}_n = \text{if}(n < 180, 0, I_n)$$

$$d1\text{cur}_n = \text{if} \left(n < 180, \frac{E}{Z} \sin(\theta_n - \alpha) + A \cdot e^{-\frac{R \cdot \theta_n}{wL}}, 0 \right)$$



Figure

3.7.a Shows The Plot Of Load Current

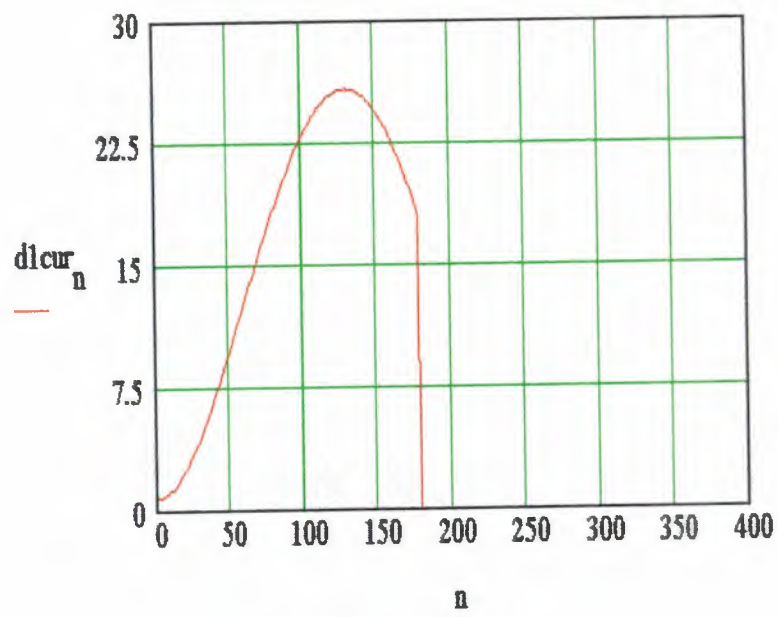


Figure 3.7.b Shows The Plot Of Current Through D1

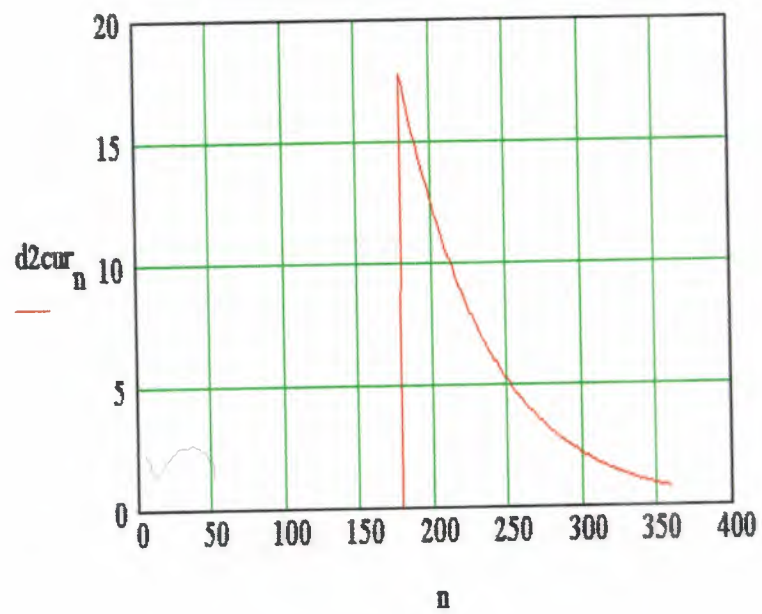


Figure 3.7.c Shows The Plot Of Current Through D2

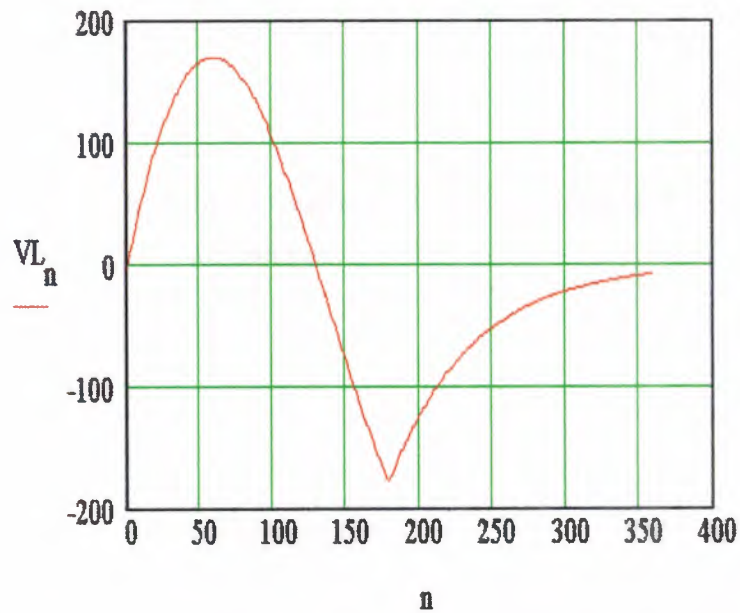


Figure 3.7.d Shows The Plot of Voltage Across the Inductor

Then the average and the RMS values of load current are computed. Two functions are created, one corresponding to angle less than 180° and the other corresponding to angle greater than 360° .

$$i1(y) = \frac{E}{Z} \sin(y - \alpha) + A \cdot e^{-\frac{R \cdot y}{wL}} \quad i2(y) = \text{Cur}\pi \cdot e^{-\frac{R \cdot (y - \pi)}{wL}}$$

$$\text{CurAvg} = \frac{1}{2 \cdot \pi} \left(\int_0^{\pi} i1(y) dy + \int_{\pi}^{2 \cdot \pi} i2(y) dy \right)$$

$$\text{CurRMS} = \sqrt{\frac{1}{2 \cdot \pi} \left(\int_0^{\pi} i1(y)^2 dy + \int_{\pi}^{2 \cdot \pi} i2(y)^2 dy \right)}$$

$\text{CurAvg} = 10.823 \text{ Amp}$

$\text{CurRMS} = 13.952 \text{ Amp}$

3.8 Summary

It has been shown how the half-wave rectifier with a free-wheeling diode can be simulated using different software packages.

CHAPTER 4

A SINGLE SCR CIRCUIT

4.1 Overview

This chapter describes a circuit with a single SCR. It is similar to the single diode circuit, the difference being that an SCR is used in place of the diode. Most of the power electronic applications operate at a relative high voltage and in such cases, the voltage drop across the SCR tends to be small. It is quite often justifiable to assume that the conduction drop across the SCR is zero when the circuit is analyzed. It is also justifiable to assume that the current through the SCR is zero when it is not conducting. It is known that the SCR can block conduction in either direction. The explanation and the analysis presented below is based on the ideal SCR model. It is also assumed that the reader knows how an SCR operates.

4.2 Circuit Operation

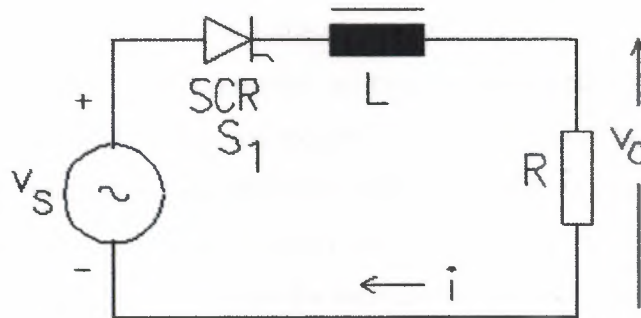


Figure 4.1 Shows A Single SCR Circuit

A circuit with a single SCR and an RL load is shown in figure 4.1. The source v_s is an alternating sinusoidal source. If $v_s = E \cdot \sin(\omega t)$, v_s is positive when $0 < \omega t < \pi$, and v_s is negative when $\pi < \omega t < 2\pi$. When v_s starts becoming positive, the SCR is forward-biased but remains in the blocking state till it is triggered. If the SCR is triggered at when $\omega t = \alpha$, then α is called the firing angle. When the SCR is triggered in the forward-bias state, it starts conducting and the positive source keeps the SCR in conduction till ωt reaches π radians. At that instant, the current through the circuit is

not zero and there is some energy stored in the inductor at $\omega t = \pi$ radians. The voltage across an inductor is positive when the current through it is increasing and it becomes negative when the current through the inductor tends to fall. When the voltage across the inductor is negative, it is in such a direction as to forward-bias the SCR.

There is current through the load at the instant $\omega t = \pi$ radians and the SCR continues to conduct till the energy stored in the inductor becomes zero. After that the current tends to flow in the reverse direction and the SCR blocks conduction. The entire applied voltage now appears across the diode.

4.3 Mathematical Analysis

An expression for the current through the SCR can be obtained as shown below. It is assumed that the current flows for $\alpha < \omega t < \delta$, where $\delta > \pi$. When the SCR conducts, the driving function for the differential equation is the sinusoidal function defining the source voltage. Outside this period, the SCR blocks current and acts as an open switch. For this period, there is no equation defining the behavior of the circuit. For $\alpha < \omega t < \delta$, equation (1) applies. Given a linear differential equation, the solution is found out in two parts. The homogeneous equation is given by equation (2), where α is the firing angle. The value of constant A in the complimentary solution is to be evaluated later. The particular solution is the steady-state response and is displayed as equation (3). The total solution is the sum of both the complimentary and the particular solution and is presented as equation (4). The value of A is obtained using the initial condition. Since the SCR starts conducting at $\omega t = \alpha$ and the current starts building up from zero, $i(\alpha) = 0$. In the expression above $\tau = \omega L/R$. Then A can be expressed as in equation (5).

Once the value of A is known, the expression for current is known. When the firing angle α and the extinction angle δ are known, the average output voltage at the cathode of the SCR can be evaluated as shown in equation (6).

$$L \frac{di}{dt} + R \times i = E \times \sin(\theta), \text{ where } \theta = \omega t \quad (1)$$

$$i(\omega t) = A \times e^{\left(-\frac{\omega t - \alpha}{\tau}\right)} \quad (2)$$

$$i(\theta) = \frac{E}{Z} \times \sin(\omega t - \beta), \quad (3)$$

$$\text{where } \beta = \alpha \tan\left(\frac{\omega L}{R}\right) \text{ and } Z = \sqrt{R^2 + (\omega L)^2}$$

$$i(\theta) = \frac{E}{Z} \times \sin(\theta - \beta) + A \times e^{\left(\frac{\theta - \alpha}{\tau}\right)} \quad (4)$$

$$A = \frac{E}{Z} \times \sin(\beta - \alpha) \quad (5)$$

$$V_{OAVG}(\alpha) = \frac{E}{2\pi} \int_{\alpha}^{\delta} \sin \theta \cdot d\theta = \frac{E}{2\pi} \times [\cos \alpha - \cos \delta] \quad (6)$$

The average load current can be obtained by dividing the average load voltage by the load resistance, since the average voltage across the inductor is zero.

4.4 Simulation

The operation of the circuit can be simulated as shown below. In order to simulate, the solution for current is presented in the following form, where $\tau = (\omega L)/R$. Then

Again it is preferable to normalize. Here E is set to unity and E/R is also set to unity. Then

$$v_s = \sin(\omega t).$$

$$v_o = v_s - i \text{ for } \alpha < \omega t < \delta, \text{ and}$$

$$v_L = v_s - i \text{ for } \alpha < \omega t < \delta.$$

To solve the expression, all we need to know is then the ratio τ . The applet shown in figure 4.2 simulates this circuit, You have to key-in the ratio τ and then click

on the button next to it. Enter the ratio τ in the left text-field of the click button and the firing angle in degrees in the text field to its right.

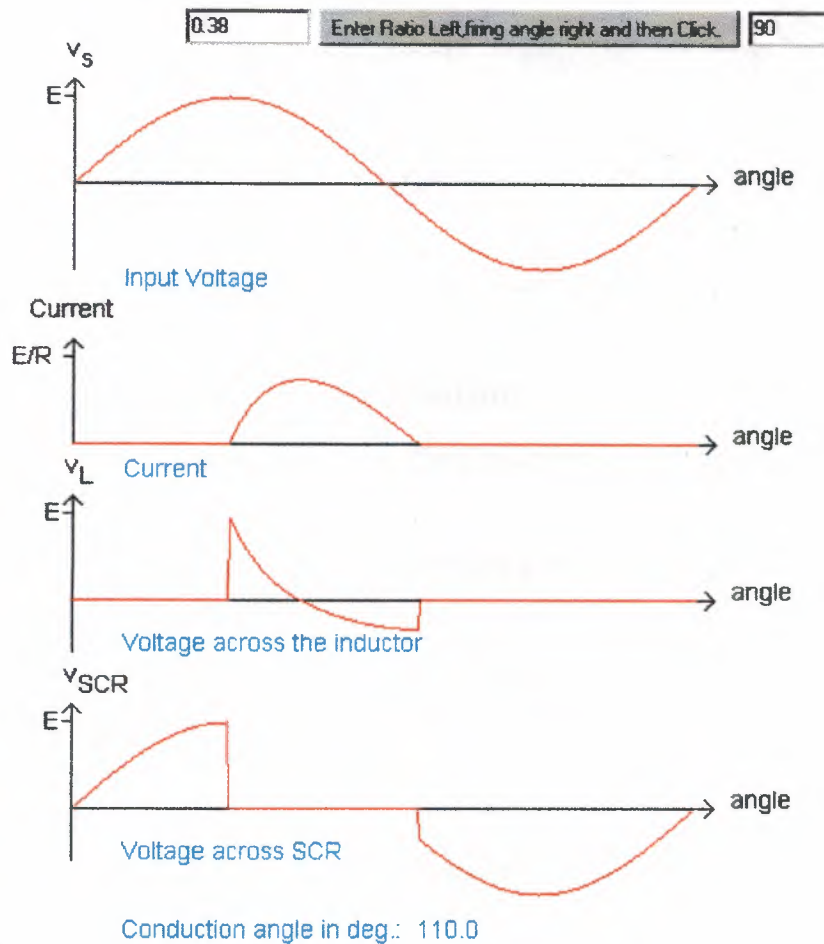
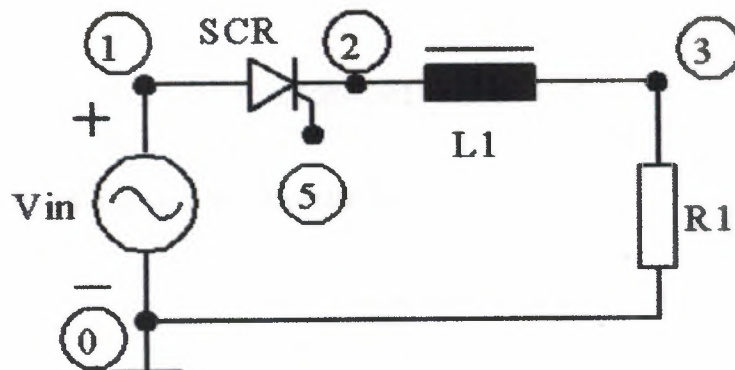


Figure 4.2 Shows The Source Voltage, Current, Voltage Across Inductor And Voltage Across SCR

4.5 Pspice Simulation

The program below presents a PSPICE program. The circuit used is shown in figure 4.3.



For Pspice simulation

Figure 4.3 Shows The Circuit Used In Pspice Simulation

The PSPICE program shown below presents the SCR as a sub circuit.

```
* Half-wave Rectifier with RL Load
* A problem to find the SCR current
VIN 1 0 SIN(0 340V 50Hz)
XT1 1 2 5 2 SCR
VP 5 2 PULSE(0 10 1667U 1N 1N 100U 20M)
L1 2 3 31.8MH
R1 3 0 10
* Subcircuit for SCR
.SUBCKT SCR 101 102 103 102
S1 101 105 106 102 SMOD
RG 103 104 50
VX 104 102 DC 0
VY 105 107 DC 0
DT 107 102 DMOD
RT 106 102 1
CT 106 102 10U
F1 102 106 POLY(2) VX VY 0 50 11
```

```

.MODEL SMOD VSWITCH(ROFF=10E+5 VON=0.5 VOFF=0)
.MODEL DMOD D((IS=2.2E-15 BV=1200 TT=0 CJO=0)
.ENDS SCR
.TRAN 10US 60.0MS 20.0MS 10US
.PROBE
.OPTIONS (ABSTOL=1N RELTOL=.01 VNTOL=1MV)
.END

```

The waveforms obtained are presented below.

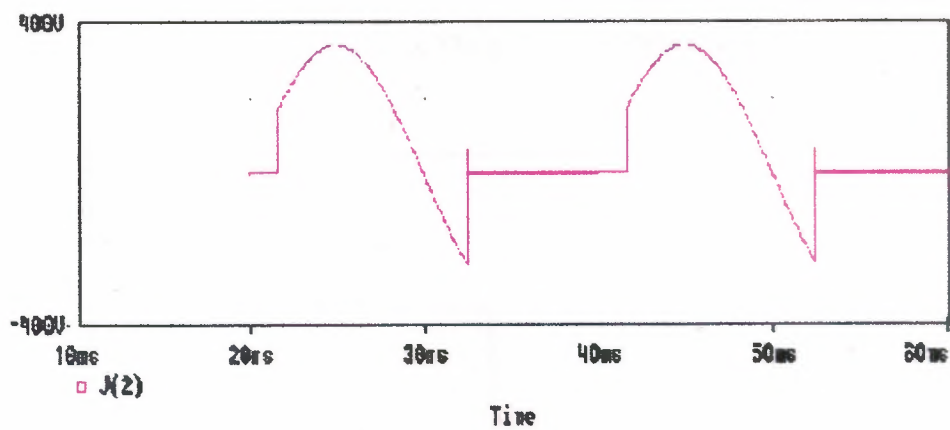


Figure 4.4.a Shows the Voltage Waveform At The Cathode Of The SCR

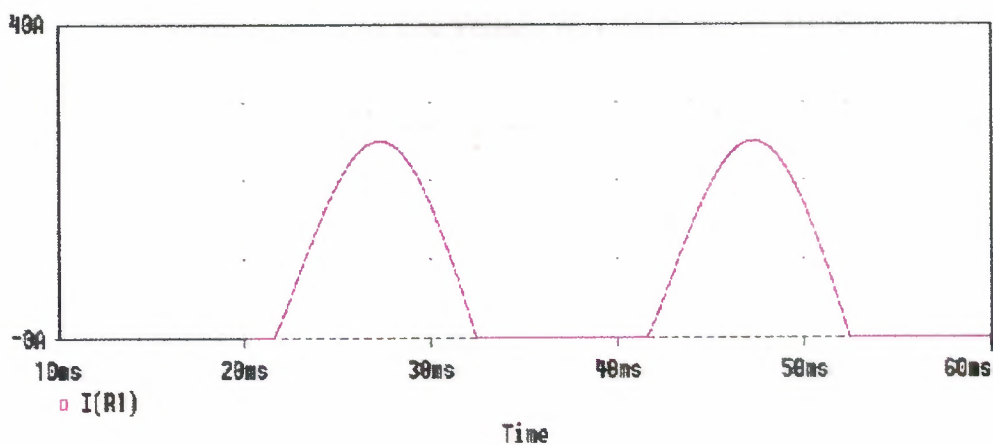


Figure 4.4.b Shows The Load Current Waveform

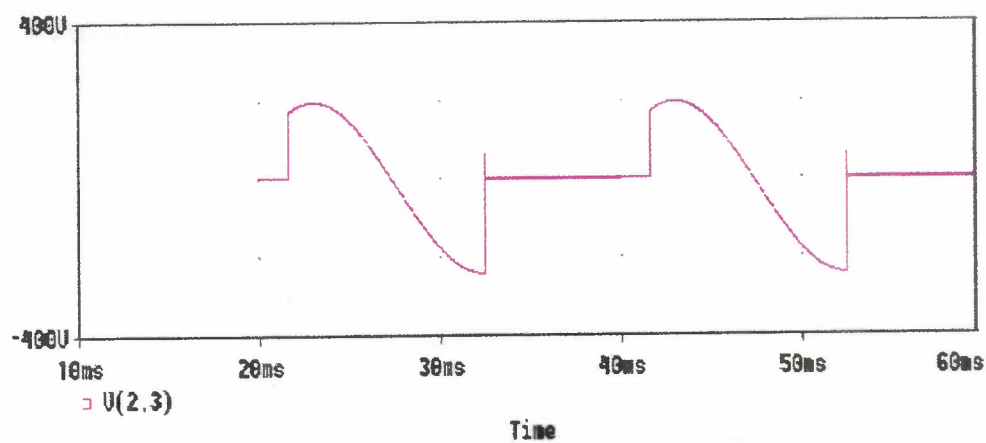


Figure 4.4.c Shows The Inductor Voltage Waveform

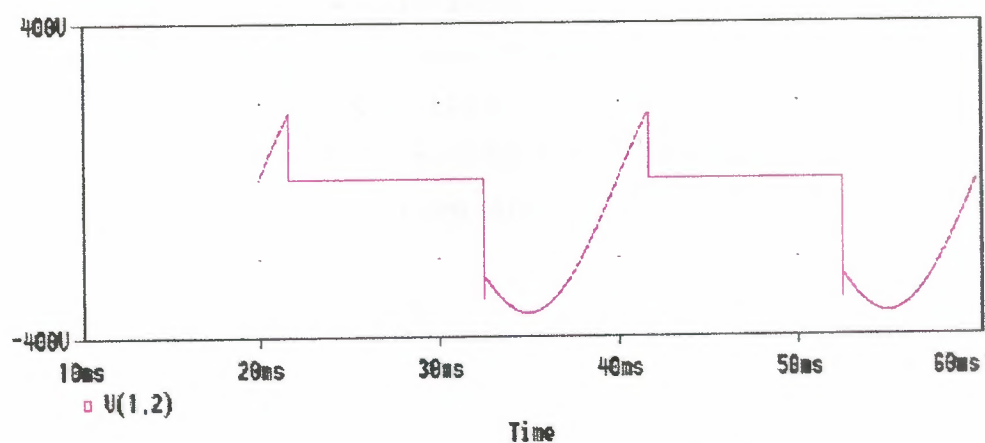


Figure 4.4.d Shows The Voltage Waveform Across The SCR

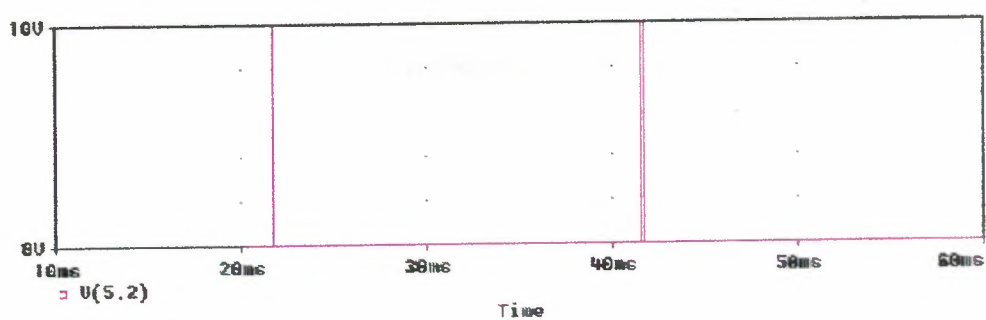


Figure 4.4.e Shows The Voltage Waveform Of The Pulse Source Used For Triggering The SCR

4.6 Matlab Simulation

The Matlab program used for simulation is presented below.

```
% Program to simulate the half-wave controlled rectifier
circuit
% Enter the peak voltage, frequency, inductance L in mH and
resistor R
disp('Typical value for peak voltage is 340 V')
peakV=input('Enter Peak voltage in Volts>');
disp('Typical value for line frequency is 50 Hz')
freq=input('Enter line frequency in Hz>');
disp('Typical value for Load inductance is 31.8 mH')
L=input('Enter Load inductance in mH>');
disp('Typical value for Load Resistance is 10.0 Ohms')
R=input('Enter Load Resistance in Ohms>');
disp('Typical value for Firing angle is 30.0 degree')
fangDeg=input('Enter Firing angle within range 0 to 180 in
deg>');
fangRad=fangDeg/180.0*pi;
w=2.0*pi*freq;
X=w*L/1000.0;
if (X<0.001) X=0.001; end;
Z=sqrt(R*R+X*X);
tauInv=R/X;
loadAng=atan(X/R);
A=peakV/Z*sin(loadAng-fangRad);
Ampavg=0;
AmpRMS=0;
for n=1:360;
    theta=n/180.0*pi;
    X(n)=n;
    if (n<fangDeg)
        cur=0.0;
        Vind(n)=0;
        iLoad(n)=0;
```

```

    Vout(n)=0;
else
    cur=peakV/Z*sin(theta-loadAng)+A*exp(-tauInv*(theta-
fangRad));
    if (cur>0)
        Ampavg=Ampavg+cur*1/360;
        AmpRMS=AmpRMS+cur*cur*1/360;
        Vind(n)=peakV*sin(theta)-R*cur;
        iLoad(n)=cur;
        Vout(n)=peakV*sin(theta);
    else
        Vind(n)=0;
        iLoad(n)=0;
        Vout(n)=0;
    end;
end;
end;
plot(X,iLoad)
title('The Load current')
xlabel('degrees')
ylabel('Amps')
grid
pause
plot(X,Vout)
title('Voltage at cathode')
xlabel('degrees')
ylabel('Volts')
grid
pause
plot(X,Vind)
title('Inductor Voltage')
xlabel('degrees')
ylabel('Volts')
grid

```

```

AmpRMS=sqrt(AmpRMS);
[A,message]=fopen('hwavecl.dat','w');
fprintf(A,'Avg      Load      Cur=\t%d\tRMS      Load
Cur=\t%f\n',Ampavg,AmpRMS);
fclose(A)

```

The waveforms obtained for the typical specified values are displayed below.

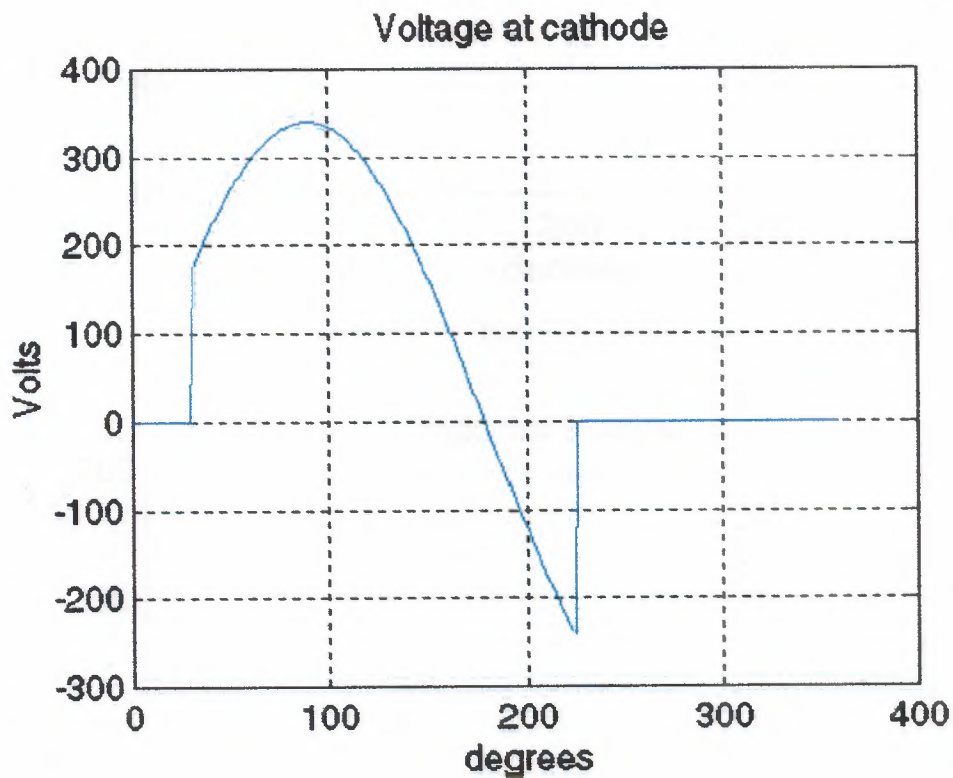


Figure 4.5.a Shows The Voltage At Cathode

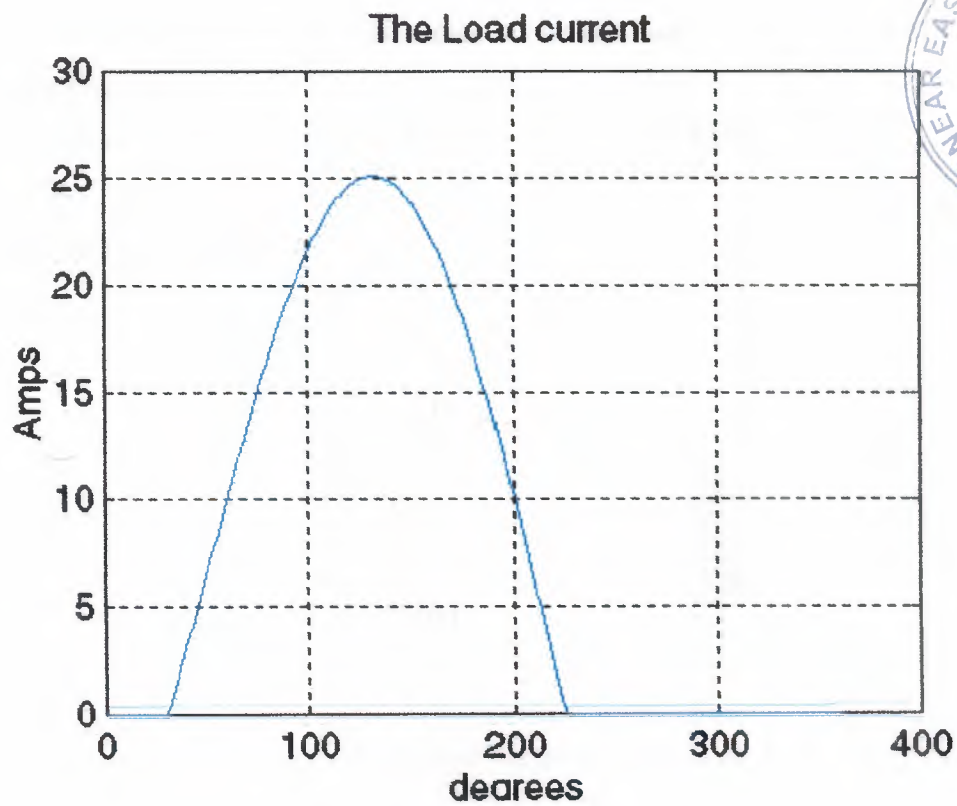


Figure 4.5.b Shows The Load Current

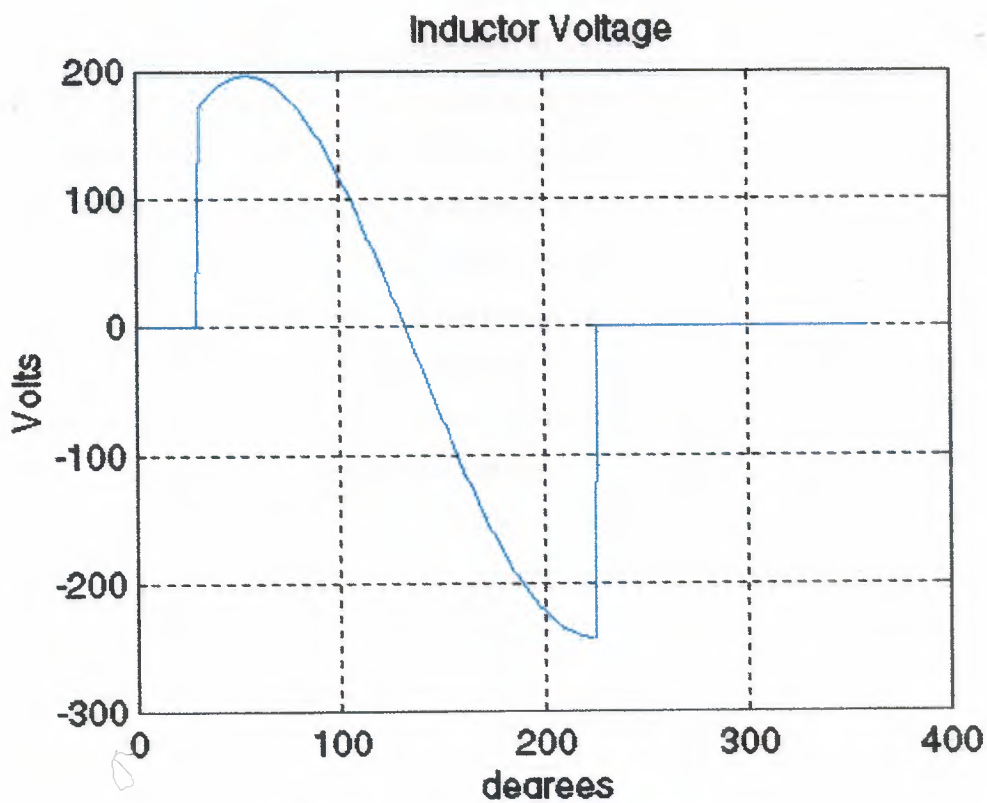


Figure 4.5.c Shows The Inductor Voltage

The output file containing the values of average load current and the RMS load current is presented below.

Avg Load Cur= 8.481852e+000 RMS Load Cur= 12.878237

4.7 Mathcad Simulation

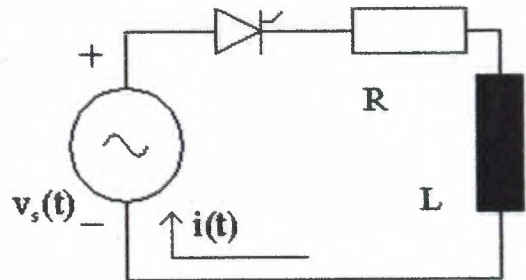


Figure 4.6 Half-Wave Controlled Rectifier Circuit With An RL Load

The operation of the RL circuit supplied by a half-wave controlled rectifier is illustrated in this program. Let $v_s(t)$ be defined to $E \cdot \sin(\omega t)$. At $\omega t = 0$, the current through the circuit is zero. As ωt becomes >0 , v_s becomes positive. If a diode instead of an SCR has been used, the diode would start conduction at $\omega t = 0$. With an SCR, the conduction does not start till the SCR is triggered. Let the SCR be triggered when $\omega t = \alpha$. Then α is called the firing angle and the SCR continues to conduct.

When $\omega t = \pi$, the source becomes zero, but at this instant, the current through the circuit is not zero and there is some energy stored in the inductor. When v_s becomes negative, the current through the circuit would not become zero suddenly because of the inductor. The inductor acts as a source and keeps the SCR forward-biased till the energy stored in the inductor becomes zero. Let the current through the circuit become zero at $\omega t = \beta$ and the value of $\beta > \pi$. For $\beta < \omega t < 2\pi$, the current through the circuit is zero. Then

$$L \left(\frac{di}{dt} \right) + Ri = E \cdot \sin(\omega t) \text{ for } \alpha < \omega t < \beta,$$

$$i(\alpha) = i(\beta) = 0, \quad i(\omega t) = 0 \text{ for } 0 < \omega t < \alpha \text{ and}$$

$$i(\omega t) = 0 \text{ for } \beta < \omega t < 2\pi$$

The complementary solution is;

$i(\omega t) = A \cdot \exp [-(R(\omega t - \alpha) / \omega L)]$, where A is a constant to be evaluated.

The particular solution is:

$$i(\omega t) = [E/Z] \sin (\omega t - \phi), \text{ where } \phi = \tan^{-1} (\omega L/R), Z^2 = R^2 + (\omega L)^2.$$

The total solution is then:

$$i(\omega t) = [E/Z] \sin (\omega t - \phi) + A \cdot \exp [-(R/\omega L) * (\omega t - \alpha)].$$

Since $i(\alpha) = 0$, $A = [E/Z * \sin (\phi - \alpha)]$. The solution is illustrated below.

First specify the values of parameters as shown below.

$$E := 340 \text{ V} \quad R := 10 \, \Omega \quad \omega L := 10 \, \Omega \quad \phi := \text{atan}(\omega L/R) \quad \phi = 0.785 \text{ rad}$$

$$Z := \text{sqrt} [(R^2 + (\omega L)^2)] \quad Z = 141.42 \, \Omega$$

Let firing angle α be: $\alpha := \pi/6 \text{ rad}$

Next compute the coefficient A as shown below. Then define a range variable n to find solution at each degree within a cycle and express the angle within a cycle in radians. Find the load current. If the angle is less than the firing angle, assign it zero value. The expression for load current calculated thus would be negative if ωt exceeds the extinction angle, β . The extinction angle is that angle at which load current becomes zero. Create an array for current, called I_n . This array has the same value as Cur_n if $\text{Cur}_n > 0.0$. Otherwise the other elements of array I_n are set to zero.

The voltage across the SCR is zero when $I_n > 0$. Otherwise it is equal to the applied voltage. Note that when $\omega t < \alpha$, the voltage across the SCR is positive. Then the SCR blocks forward conduction. Next find the extinction angle. Assign a guess value first.

Next the average value of load current is found out. The RMS load current is evaluated after that.

$$A = \frac{E}{Z} \cdot \sin(\phi - \alpha) \quad n = 0..360 \quad \theta_n = \frac{n}{180} \cdot \pi$$

$$Cur_n = \text{if} \left[\theta_n < \alpha, 0, \frac{E}{Z} \cdot \sin(\theta_n - \phi) + A \cdot e^{-\left[\frac{R \cdot (\theta_n - \alpha)}{wL} \right]} \right]$$

$$I_n = \text{if}(Cur_n > 0.0, Cur_n, 0.0) \quad VSCR_n = \text{if}(I_n > 0.0001, 0.0, E \cdot \sin(\theta_n))$$

$$\beta = \frac{7 \cdot \pi}{6}$$

Given

$$\frac{E}{Z} \cdot \sin(\beta - \phi) + A \cdot e^{-\left[\frac{R \cdot (\beta - \alpha)}{wL} \right]} = 0 \quad \delta = \text{Find}(\beta)$$

$$\text{extinction_angle} = \frac{\delta \cdot 180}{\pi}$$

$$CurAvg = \frac{1}{2 \cdot \pi} \cdot \left[\int_{\alpha}^{\beta} \frac{E}{Z} \cdot \sin(y - \phi) + A \cdot e^{-\left[\frac{R \cdot (y - \alpha)}{wL} \right]} dy \right]$$

$$CurRMS = \sqrt{\frac{1}{2 \cdot \pi} \cdot \left[\int_{\alpha}^{\beta} \left[\frac{E}{Z} \cdot \sin(y - \phi) + A \cdot e^{-\left[\frac{R \cdot (y - \alpha)}{wL} \right]} \right]^2 dy \right]}$$

$A = 6.222 \text{ Amp}$ $\delta = 3.936 \text{ rad}$

$\text{extinction_angle} = 225.489 \text{ deg}$

The extinction angle is computed to be 225.49° .

$\text{Curavg} = 8.339 \text{ Amp}$

$\text{CurRMS} = 12.851 \text{ Amp}$

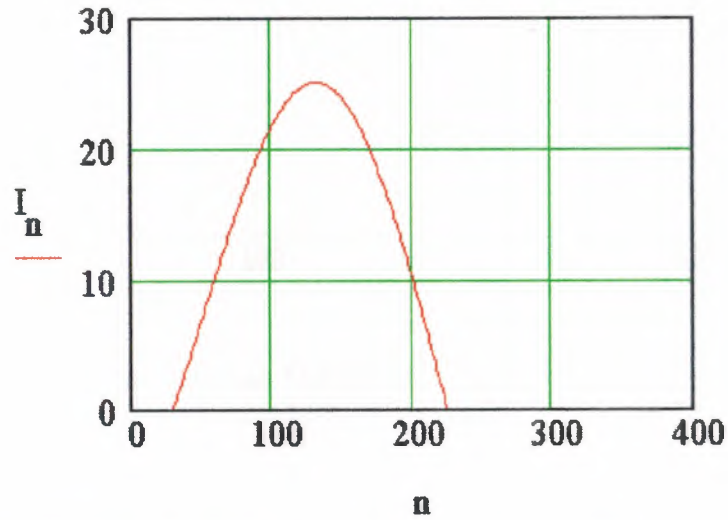


Figure 4.7.a Shows The Load Current Waveform

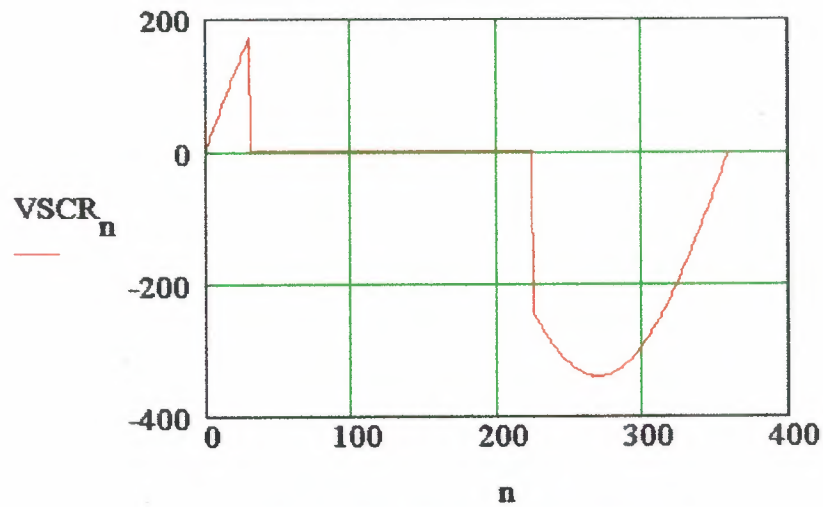


Figure 4.7.b Shows The Voltage Across SCR

$V_{out_n} := \text{if } (n > 0.001, E.\text{Sin}(\theta_n), 0.0)$

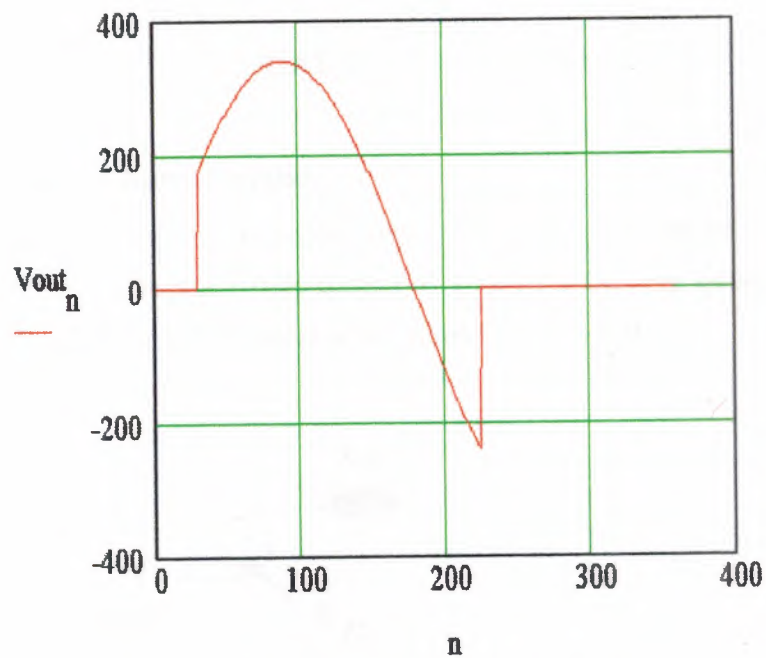


Figure 4.7.c Shows The Plot Of Output Voltage

4.8 Summary

This chapter has described how the half-wave controlled rectifier circuit operates by using pspice simulation, matlab simulation and mathcad simulation.

CHAPTER 5

A TWO-QUADRANT DC DRIVE

5.1 Performance Characteristics

This chapter describes how a separately-excited DC motor can be controlled in closed-loop with a single-phase fully-controlled rectifier supplying dc source to its armature. The operation of a DC motor is described briefly at first.

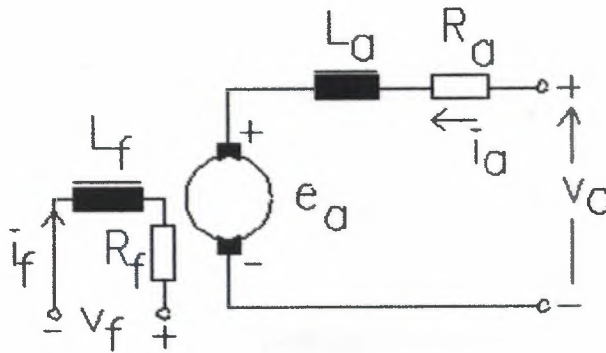


Figure 5.1 shows the DC Motor Representation

A symbolic representation of a separately-excited DC motor is shown in figure 5.1. The resistance of the field winding is R_f and its inductance is L_f , where the resistance of the armature is R_a and its inductance is L_a . In the description of the motor, the armature reaction effects are ignored. It is justifiable since the motor used has either inter poles or compensating winding to minimize the effects of armature reaction. The field current is described by equation (1). If a steady voltage V_f is applied to the field, the field current settles down to a constant value, as shown in equation (2). When the field current is constant, the flux induced by the field winding remains constant, and usually it is held at its rated value ϕ . If the voltage applied to the armature is v_a , then the differential equation that is to be applied to the armature circuit is shown in equation (3). In steady-state, equation (4) applies. The voltage, e_a , is the back e.m.f. in volts. In a separately-excited DC motor, the back e.m.f. is proportional to the product of speed of motor w rad/s and the field ϕ Webers, as shown by Equation (5).

$$L_f \frac{di_f}{dt} + R_f * i_f = v_f \quad (1)$$

$$I_f = \frac{V_f}{R_f} \quad (2)$$

$$L_a \frac{di_a}{dt} + R_a * i_a + e_a = v_a . \quad (3)$$

$$R_a * I_a + E_a = V_a . \quad (4)$$

$$E_a = K_m \phi \omega , \quad (5)$$

In equation (5), K_m is a coefficient and its value depends on the armature winding. If the armature current in steady-state be I_a , then the power P that is supplied to the armature is $E_a I_a$. This electric power is converted to mechanical power by the armature of the DC motor. Let the torque developed by the armature be T_e , the unit for torque being Nm (Newton-meter). Then power and torque can be related as shown in equation (6). On canceling the common term on both sides, the torque T_e developed by the armature is obtained as presented in equation (7).

If the instantaneous armature current is i_a , then equation (8) applies. Torque has been denoted by T_e in both equations.

$$P_a = E_a * I_a = K_m \phi \omega I_a = T_e * \omega . \quad (6)$$

$$T_e = K_m \phi I_a N - m . \quad (7)$$

$$T_e = K_m \phi i_a N - m . \quad (8)$$

The speed of the motor can be controlled by varying V_a and holding V_f constant at its rated value. Then as the voltage applied to the armature is raised, the armature current increases first. As the armature current increases, the torque developed by motor increases and hence the speed of motor increases. The drop across the armature resistance tends to be small and hence the motor speed rises almost proportionately with the voltage applied to the armature. But there is a limit to the voltage that can be applied to the armature and that limit is the rated voltage of the armature voltage. The speed of the motor corresponding to the rated armature voltage and the rated field voltage is its rated speed. Thus the speed of a motor can be varied below its rated speed by controlling the armature voltage. It would be desirable that the motor should be able to develop as high as a torque as possible and hence the voltage rated applied to the field is held at its rated value. Applying higher than the rated voltage to either the field or the armature is not recommended. When the rated voltage is applied to the field, the flux would be near the saturation level in the poles. If a voltage higher than its rated voltage is applied to the field, the flux would saturate and there would not be any significant increase in the torque that the motor can deliver. On the other hand, this would only result in increased losses in the winding. Since the total heat which the DC motor can dissipate is fixed due to its surface area and cooling system, increased losses from the excitation system would mean that the other losses would have to reduce, implying that the armature current cannot be at its rated level and the maximum torque that the motor can deliver may reduce. Increasing the armature voltage above its rated value is not recommended because the insulation of the armature is designed for operation of the motor with the rated voltage applied to its armature. Moreover, the torque that the motor can deliver depends on the armature current and the field current. If the motor is operated continuously, the maximum armature current should not be higher than its rated value. When the armature current and the field voltage are at their rated level, the motor generates the rated torque. Hence the maximum torque the motor can deliver continuously over a long period of time is its rated torque when its speed is varied from a low value to its rated speed. Over this period, $0 < \omega < \omega_r$, where ω_r is its rated speed, the power output is given by:

$$P_{a,max} = T_{e,max cont} \omega .$$

The maximum torque which the motor can deliver continuously is called $T_{e,max cont}$. What is being referred to here is the maximum torque the motor can deliver, and

not the actual torque the motor delivers. The actual torque the motor delivers depends on the mechanical load connected to its shaft. If the speed of the motor is to be increased beyond its rated value, the voltage applied to the armature can be held at its rated value and the field can be weakened by reducing the voltage applied to it. When the speed of the motor is in this manner, the maximum power that can be supplied to the armature is fixed, since both the voltage applied to the armature and the armature current cannot exceed the rated level over a long period. That means the maximum torque the motor can develop above the rated speed is:

$$T_{a,\max \text{ cont}} = \frac{E_{a,\text{rated}} * I_{a,\text{rated}}}{w}, \text{ where } w > w_{\text{rated}}.$$

The plots of $T_{e,\max \text{ cont}}$ and the maximum power $P_{a,\max}$ can be plotted as a function of rotor speed as shown below in figure 5.2. The rated values of speed, torque and power to the armature have been set equal to unity.

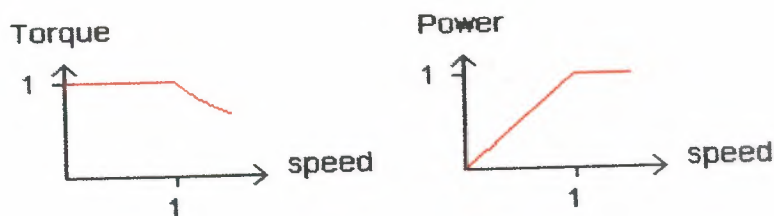


Figure 5.2 Shows The Maximum Torque and Maximum Power

A separately-excited dc motor can be controlled, either by varying the voltage applied to the field winding or by varying the voltage applied to the armature. This section describes how the motor can be controlled by varying the armature voltage and it is assumed that the field is excited by a constant voltage, equaling the rated voltage of the field winding. It means that the discussion to follow assumes that the field current remains steady at its rated value.

5.2 Block Diagram

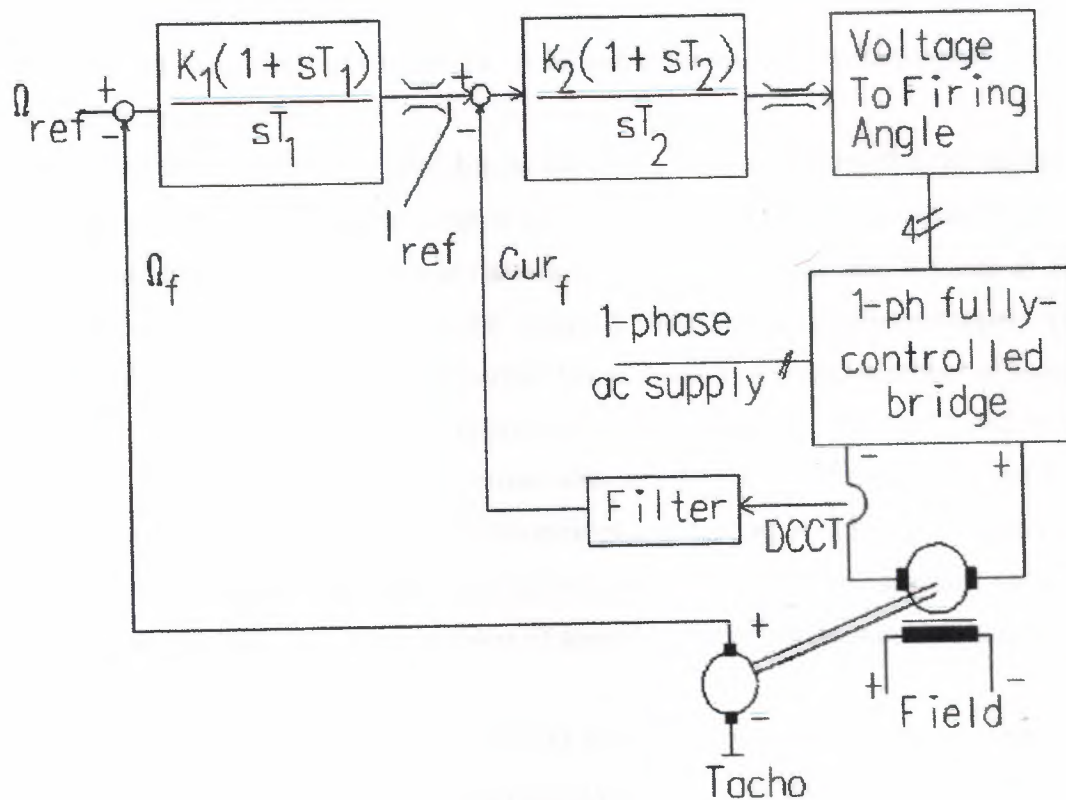


Figure 5.3 Shows The Block Diagram Of A Dc Drive

The block diagram of a dc drive is shown in figure 5.3 does not show all details. The DC motor has not been represented in the form of a block diagram and the details of the load the motor drives have also not been shown. The block diagram functions as follows.

For the system described here, the output of the system is the speed of the motor. Hence when this system is to be controlled in closed-loop, the parameter that is to be set is what that speed should be. It is denoted to be Ω_{ref} . In order to control the speed in closed-loop, we need a feedback signal too. It can be obtained in several ways. A digital tachometer or an analogue tachogenerator can be used. It is assumed that an analogue tachogenerator is used here. It is coupled to the motor shaft and its output

voltage varies linearly with its speed. Let the speed feedback signal be Ω_f . This signal can be compared with the speed reference signal and the error can be processed by a controller. The controller can be of one of several types. It can be an integral controller, or a PI controller and PDF (pseudo-derivative feedback) controller or a PID controller or a rule-based fuzzy logic controller. Here both the controllers used are PI (proportional plus integral) controllers. A PI controller can lead to fast response and zero-error for a step input.

The PI controller for speed has as its input the error between the two signals, Ω_{ref} and Ω_f . If the speed feedback signal Ω_f is lower than the reference signal Ω_{ref} , it means that the DC motor speed is running below the set speed and it needs to be accelerated. In order to accelerate the motor, it should develop greater torque. To develop greater torque, its armature current has to increase. Hence the output of speed controller is set to function as the reference signal for armature current. It will be a voltage corresponding to armature current with an appropriate coefficient linking the two quantities. When $\Omega_f < \Omega_{ref}$, the difference causes the output of speed controller to increase. Since the output of speed-controller is set to function as the armature current reference signal, an increase in the value of speed-controller output would in turn lead to an increase in the armature current.

The rectifier circuit is made up of SCRs and the SCRs have a current rating. Hence it is necessary to ensure that the current through the SCRs remains within a safe level. Hence the output of speed controller is limited at both ends. Its maximum value corresponds to the safe level for SCRs. It is not normally the rated current of the motor and it is usually set at a value ranging from 1.5 times to 2 times the rated armature current. The reason is that the motor may have to develop more than the rated torque under transient conditions to achieve fast response. In order to ensure that the motor armature current remains within its rated value, another supervisory loop may be used. Another option is to use a circuit-breaker. The instantaneous trip action in the circuit breaker can be due to magnetic effect and the overload trip can be due to thermal action. A bi-metallic strip within the circuit-breaker expands due to temperature and would trip circuit-breaker. The lower limit on the output of speed-controller would correspond to zero current in the armature, since the motor current in this scheme cannot be in the reverse direction.

The current controller has two inputs, the reference current signal which is the output of the speed controller and a feedback signal proportional to the armature current. The feedback signal can be obtained in several ways. A current transformer can be introduced in the path of ac current from the ac supply. Another option would be to use a DC current transducer that makes use of a Hall-effect sensor or isolated opamp.

The transducer used produces a voltage proportional to the current in the armature. The difference between these two signals is processed by another PI controller and its output is also limited to correspond to 0° and 180° firing angle. The output of current controller may vary between 0 V and 10 V, with 0 V corresponding to 180° firing angle and 10 V corresponding 0° firing angle. If the firing angle be α and the output of current controller V_C , then

$$\alpha = 18 * (10 - V_C) \text{ degrees.}$$

As the output voltage of current controller increases due to the difference between the reference signal and the feedback signal corresponding to armature current, the firing angle is advanced towards 0° and the average output voltage of the bridge rectifier increases. This in turn leads to increased torque generation and the motor accelerates.

If the speed reference is brought down suddenly, the current in the motor cannot be reversed and hence the motor slows down due to friction and the load. This process can be slow.

The question that can be raised is whether we need the current loop. The answer is that it improves the performance. If there is a change in the supply voltage even by a small amount, the output of the bridge circuit tends to fall a bit for the same firing angle. The reduction in output voltage causes a large change in the armature current, with the speed remaining more or less constant. The current loop comes into action, correcting the firing angle to the required value. The time constant of the armature, due to its inductance and resistance, tends to be of the order of a few tens of ms and the mechanical time constant, due to the moment of inertia of motor and load and the friction, is of the order of a few tenths of a second. If a current controller is not used, the speed would have to change before the speed controller can come into action. Since the mechanical time constant is about at least 10 times greater, there would be a significant change in speed if there be no current controller.

Normally a filter may be necessary in the feedback circuit for speed. The tachometer signal usually contains a small ripple superimposed on its dc content. The frequency of the ripple is usually dependent on the speed and the lower the speed is the lower is the frequency of this ripple. Hence the time constant of the filter may have to be set to correspond to the lowest speed at which the motor would be required to run. Usually the motor speed does not have to vary over a range larger than 0.1 p.u to 1 p.u. Since the power output varies proportionately with the speed, there is usually no justification to run the motor at an extremely low speed. The next section describes how the simulation is carried out. The routines are explained with the help of pseudo-code that can be understood by a reader with some knowledge of one of the programming languages such as C, PASCAL, BASIC, Fortran or Matlab.

5.3 Closed-Loop Control

This section explains how the simulation can be carried out.

Initialize_Routine:

```
Set and get Parameters
Initialize controller Outputs
Go to Calculation_Routine
Calculation_Routine
Execute One_Cycle_Routine
Plot the results
One_Cycle_Routine
Set angle to zero.
For (angle= 0; angle <360°; angle +stepsize)
    {Set the SCR pair based on firing angle and angle.
        Go to Next_Values}
Next_Values
Calculate the increments in
armature current
motor speed
tachometer filter output
speed controller output
current controller output
Add the increments
```


Compute the firing angle

The pseudo-routine presents only the main steps.

5.4 Simulation

Before selecting the type of response, set the value of the selected parameter. When you select a parameter, the text field shows the default value set inside the program. Change the parameter value if you want to and then you must click on the *SET VALUE* button for the change to take effect. You can go from one type of response to another after the present calculations are carried out.

When you have selected a new type of response, you must click on *Click to Start*. If you click on *Reset* button, initializing routine is carried out and the motor speed is set to zero, and the other values are also reset. The program has been written assuming that the frequency of operation is 50 Hz. If the frequency is different, the parameter values should be scaled suitably as follow in the next page.

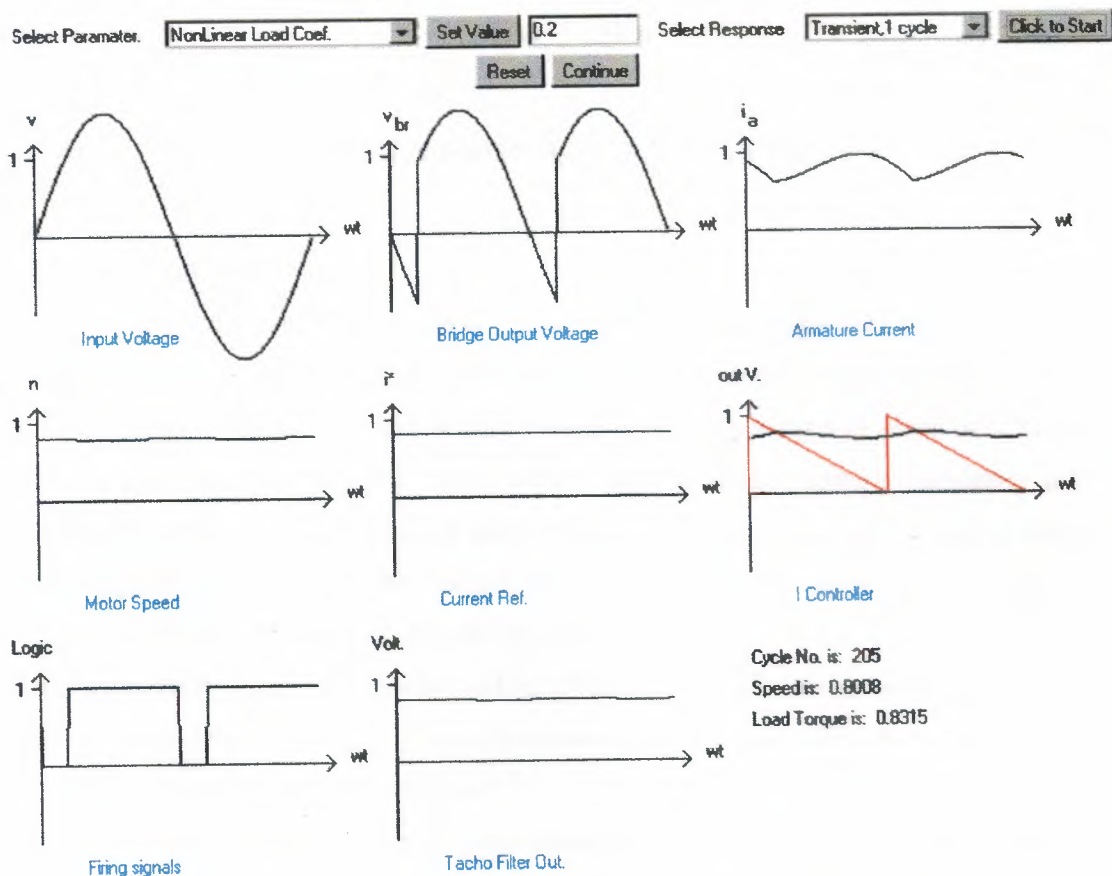


Figure 5.4 Shows The Input Voltage, Bridge Output Voltage, Armature Current, Speed Controlled Output Signal, Current Reference Signal, Current Controlled Output, Firing Signal And Tacho Filter Output

5.5 Summary

This chapter described how the separately-excited dc motor can be controlled by varying the armature voltage and the rated voltage of the field winding by assuming that the field current remains steady at its rated value. Also explained how the simulation can be carried out.

CHAPTER 6

STEP-DOWN SMPS/BUCK CONVERTER

6.1 Introduction

A buck converter or step-down switch mode power supply can also be called a switch mode regulator. Popularity of a switch mode regulator is due to its fairly high efficiency and compact size and a switch mode regulator is used in place of a linear voltage regulator at relatively high output, because linear voltage regulators are inefficient. Since the power devices used in linear regulators have to dissipate a fairly large amount of power, they have to be adequately cooled, by mounting them on heat sinks and the heat is transferred from the heat sinks to the surrounding air either by natural convection or by forced-air cooling. Heat sinks and provision for cooling makes the regulator bulky and large. In applications where size and efficiency are critical, linear voltage regulators cannot be used.

A switch mode regulator overcomes the drawbacks of linear regulators. Switched power supplies are more efficient and they tend to have an efficiency of 80% or more. They can be packaged in a fraction of the size of linear regulators. Unlike linear regulators, switched power supplies can step up or step down the input voltage. The buck converter is introduced in this page using the evolutionary approach. Let us consider the circuit in Figure 6.1, containing a single pole double-throw switch.

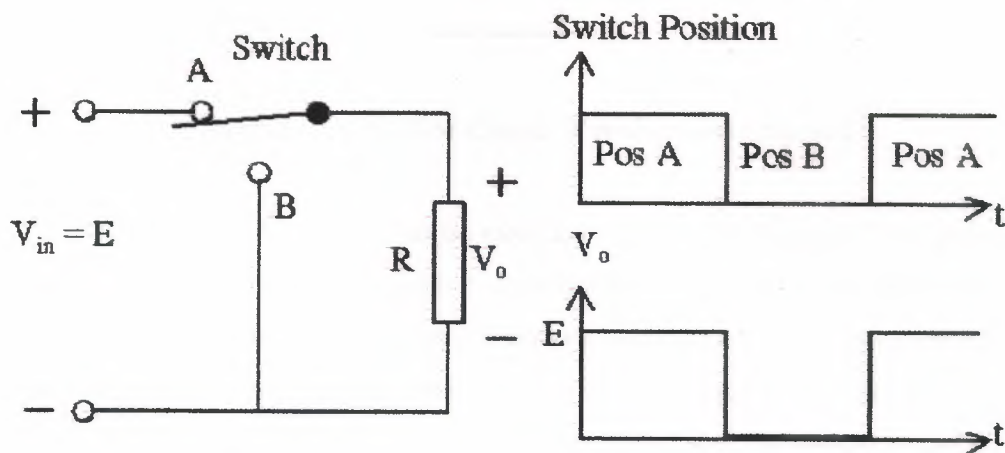


Figure 6.1 Shows A Resistor With A Single-Pole Double-Throw Switch

For the circuit in Figure 6.1, the output voltage equals the input voltage when the switch is in position A and it is zero when the switch is in position B. By varying the duration for which the switch is in position A and B, it can be seen that the average output voltage can be varied, but the output voltage is not pure dc. The output voltage contains an average voltage with a square-voltage superimposed on it, as shown in Figure 6.2. Usually the desired outcome is a dc voltage without any noticeable ripple content and the circuit in Figure 6.1 is to be modified.

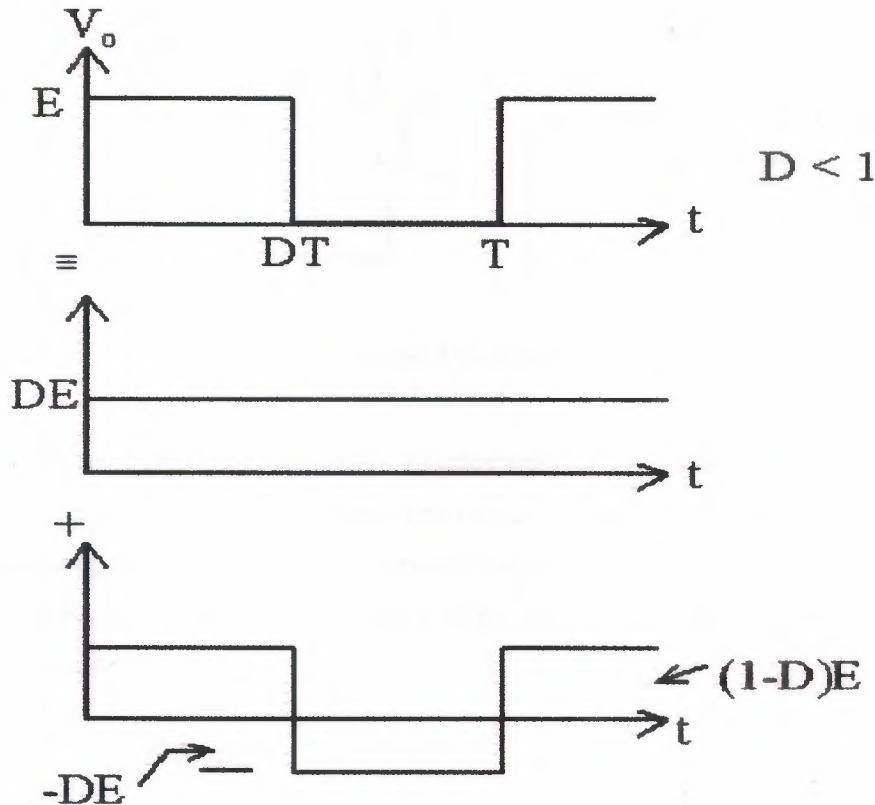


Figure 6.2 Shows The Output Waveform Decomposed

The circuit in Figure 6.1 can be modified as shown in Figure 6.3 by adding an inductor in series with the load resistor. An inductor reduces ripple in current passing through it and the output voltage would contain less ripple content since the current through the load resistor is the same as that of the inductor. When the switch is in position A, the current through the inductor increases and the energy stored in the inductor increases. When the switch is in position B, the inductor acts as a source and maintains the current through the load resistor. During this period, the energy stored in the inductor decreases and its current falls. It is important to note that there is

continuous conduction through the load for this circuit. If the time constant due to the inductor and load resistor is relatively large compared with the period for which the switch is in position A or B, then the rise and fall of current through inductor is more or less linear, as shown in Figure 6.3.

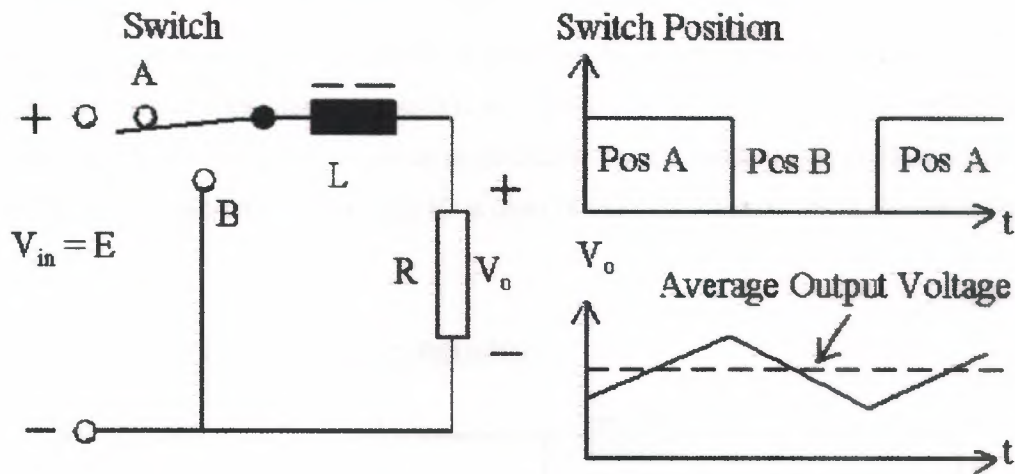


Figure 6.3 Shows The Effect Of Inductor

The next step in evolutionary development of the buck converter is to add a capacitor across the load resistor and this circuit is shown in Figure 6.4. A capacitor reduces the ripple content in voltage across it, whereas an inductor smoothes the current passing through it. The combined action of LC filter reduces the ripple in output to a very low level.

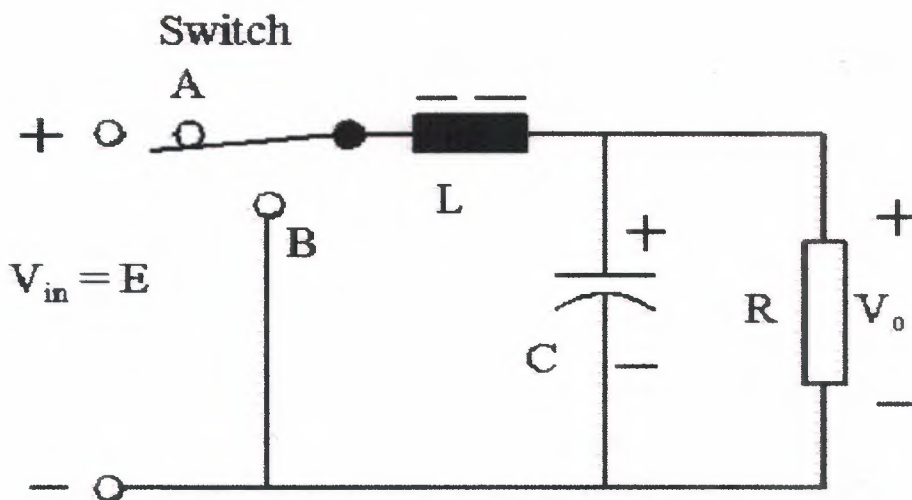


Figure 6.4 Shows The Circuit With An Lc Filter

The circuit in Figure 6.4 contains a single-pole double-throw switch. It is a difficult configuration to realize using power semiconductor devices. On the other hand, an understanding of the circuit in Figure 6.4 leads to a realizable and simple configuration. When the switch is in position A, the current through the inductor and it decreases when the switch is in position B. It is possible to have a power semiconductor switch to correspond to the switch in position A. When switch is in position B, the inductor current free-wheels through it and hence a diode can be used for free-wheeling operation. Then only the power semiconductor switch needs to be controlled, and in practice, a pulse-width modulating IC is used. The circuit that results is shown in Figure 6.5.

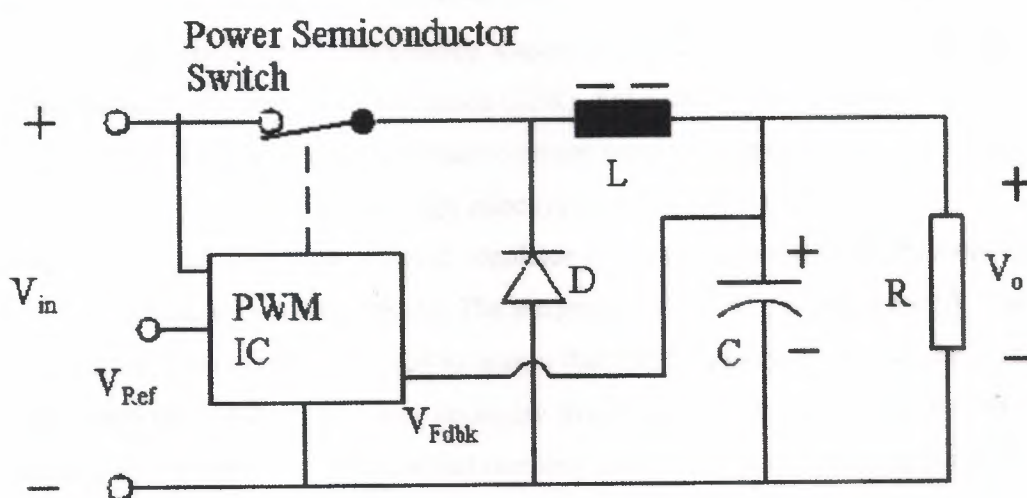


Figure 6.5 Shows The Step Down Switch Mode Power Supply

Generally any basic switched power supply consists of five standard components:

- A pulse-width modulating controller,
- A transistor switch,
- An inductor ,
- A capacitor and
- A diode.

Control by pulse-width modulation, usually effected by an IC, is necessary for regulating the output. The transistor switch is the heart of the switched supply and it controls the power supplied to the load. Power MOSFETs are more suited than BJTs at power outputs of the order of 50 W. Transistors chosen for use in switching power

supplies must have fast switching times and should be able to withstand the voltage spikes produced by the inductor.

An inductor is used in a filter to reduce the ripple in current. This reduction occurs because current through the inductor cannot change suddenly. When the current through an inductor tends to fall, the inductor tends to maintain the current by acting as a source. Inductors used in switched supplies are usually wound on toroidal cores, often made of ferrite or powdered iron core with distributed air-gap to minimize core losses at high frequencies.

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. Loss in a capacitor occurs because of its internal series resistance and inductance. Capacitors for switched regulators are chosen on the basis of effective series resistance (ESR). Solid tantalum capacitors are the best in this respect. For very high performance power supplies, sometimes it is necessary to parallel capacitors to get a low enough effective series resistance.

The diode used in a switched regulator is usually referred to as free-wheeling diode or sometimes as a catch diode. The purpose of this diode is not to rectify, but to direct current flow in the circuit and to ensure that there is always a path for the current to flow into the inductor. It is also necessary that this diode should be able to turn off relatively fast. Diodes known as the fast recovery diodes are used in these applications.

Most of the switched supplies needs a minimum load, in order to ensure that the inductor carries current always. If the current flow through the inductor is not continuous, regulation may become poorer.

The buck converter or SMPS can be controlled in two ways, known as :

1. Constant-frequency operation or pulse-width modulation control
2. Variable-frequency operation or control by frequency modulation

With pulse-width modulation control, the regulation of output voltage is achieved by varying the duty cycle of the switch, keeping the frequency of operation constant. Duty cycle refers to the ratio of the period for which the power semiconductor is kept ON to the cycle period. Usually control by pulse width modulation is the preferred method since constant frequency operation leads to optimization of LC filter and the ripple content in output voltage can be controlled within the set limits. On the other hand, if the load on the converter is below a certain level, voltage regulation of

output becomes a problem and in such a case, control by frequency modulation is to be preferred.

When control by frequency modulation is to be achieved, the ON period of the power semiconductor switch is kept constant and the frequency of operation is varied to effect voltage regulation. Design of LC filter is not easy in such a case.

If a micro-controller is used instead of a specific PWM IC, it is possible to switch from one mode of control to the other depending on the load conditions.

6.2 Basic Circuit Operation

The operation of the buck converter is explained first. This circuit can operate in any of the three states as explained below. The first state corresponds to the case when the switch is ON. In this state, the current through the inductor rises, as the source voltage would be greater than the output voltage, whereas the capacitor current may be in either direction, depending on the inductor current and the load current. When the inductor current rises, the energy stored in it increases. During this state, the inductor acquires energy.

When the switch is closed, the elements carrying current are shown in red color in Figure 6.6, whereas the diode is in gray, indicating that it is in the off state. In Figure 6.6.a the capacitor is getting charged, whereas it is discharging in Figure 6.6.b.

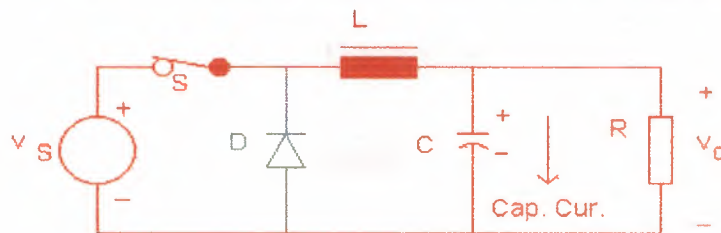


Figure 6.6.a

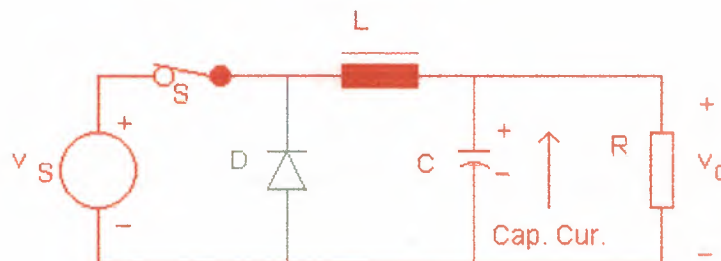


Figure 6.6.b

Figure 6.6 shows the Buck Converter of First State

The equations that govern the operation of the circuit in the first state are shown below.

$$\frac{di_L}{dt} = \frac{v_s - v_o}{L} \quad (1)$$

$$\frac{dv_o}{dt} = \frac{i_L - v_o/R}{C} \quad (2)$$

The second state relates to the condition when the switch is off and the diode is ON. In this state, the inductor current free-wheels through the diode and the inductor supplies energy to the RC network at the output. The energy stored in the inductor falls in this state. In this state, the inductor discharges its energy and the capacitor current may be in either direction, depending on the inductor current and the load current Figure 6.7 illustrates the second state.

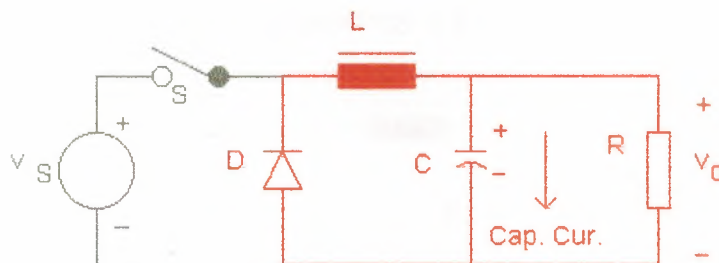


Figure 6.7.a

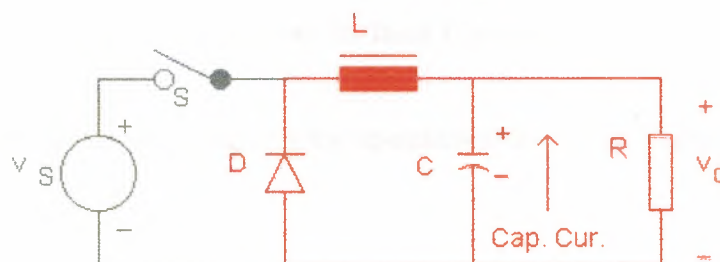


Figure 6.7.b

Figure 6.7 shows the Buck Converter of Second State

The equations that govern the operation of the circuit in the second state are shown below.

$$\frac{di_L}{dt} = -\frac{v_O}{L} \quad (3)$$

$$\frac{dv_O}{dt} = \frac{i_L - v_O/R}{C} \quad (4)$$

When the switch is open, the inductor discharges its energy. When it has discharged all its energy, its current falls to zero and tends to reverse, but the diode blocks conduction in the reverse direction. In the third state, both the diode and the switch are OFF and Figure 6.8 illustrates the third state. During this state, the capacitor discharges its energy and the inductor is at rest, with no energy stored in it. The inductor does not acquire energy or discharge energy in this state.

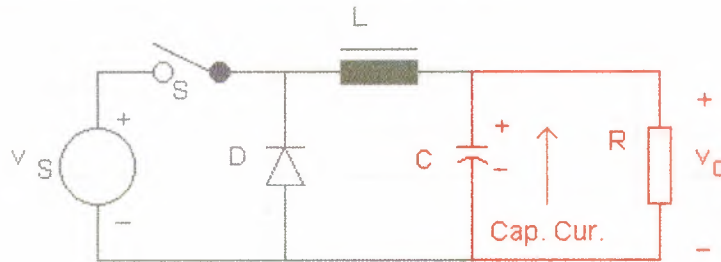


Figure 6.8 shows the Buck Converter of Third State

The equation that governs the operation of the circuit in the third state is shown below.

$$\frac{dv_O}{dt} = -\frac{v_O/R}{C} \quad (5)$$

When the circuit receives a periodic signal, the response of the circuit also becomes periodic. Here it is assumed that the source voltage remains constant with no ripple, and the frequency of operation is kept fixed with a fixed duty cycle. If the RC time constant due to the load resistor and the filter capacitor is very large compared to the cycle period of the switching frequency, the output voltage is more or less constant, with no noticeable ripple. When both the input voltage and the output voltage are

constant, the current through the inductor rises linearly when the switch is ON and it falls linearly when the switch is OFF. Under this condition, the current through the capacitor also varies linearly when it is getting charged or discharged.

The responses obtained for a particular set of parameters are displayed in Figure 6.9, The values of parameters used are:

Source voltage = 100 V dc,

Switching frequency = 20 kHz,

$L = 500 \mu\text{H}$,

$C = 500 \mu\text{F}$,

$R = 10 \Omega$, and

duty cycle = 0.5.

The value of 1 in a voltage plot in Figure 6.9 corresponds to 100 V and the value of 1 in a current plot corresponds to 10 A. Figure 6.9 displays the responses over one cycle.

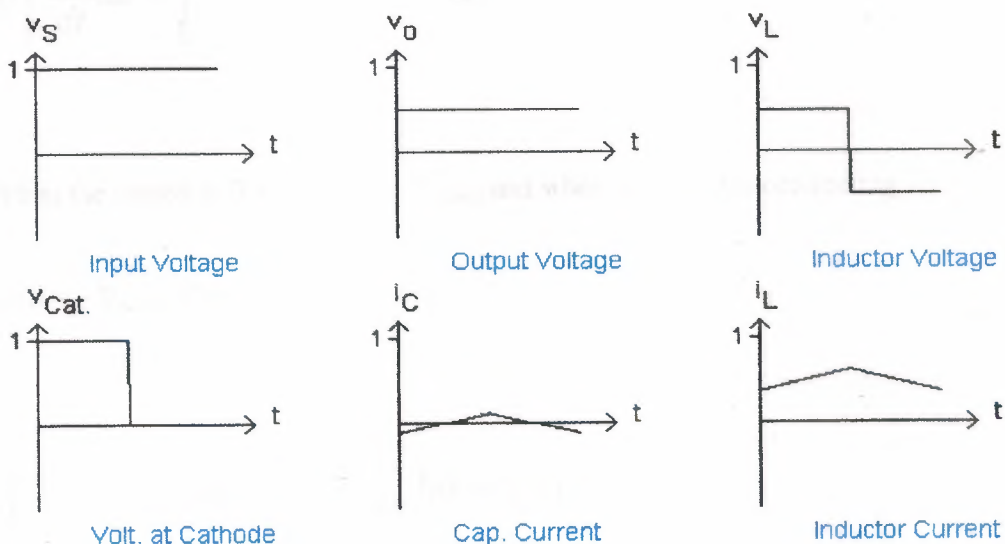


Figure 6.9 shows the Periodic Response with a dc voltage Input

An expression for the average output voltage can be obtained as follows. It is assumed that there is continuous conduction in the inductor. Given that the cycle period is T , the ON-period is DT , and the source voltage is E ,

$$V_{o,avg} = \frac{1}{T} \left(\int_0^{DT} E \cdot dt \right) = D \cdot E \quad (6)$$

In equation (6), D stands for the duty cycle. The same expression for output voltage can be obtained in another way. When the responses in the circuit are periodic, the inductor current is the same at the beginning and end of a cycle. That is,

$$i_L(0) = i_L(T) \quad (7)$$

Equation (7) can be expressed as follows:

$$L \cdot \int_0^T \frac{di_L}{dt} \cdot dt = \int_0^T v_L(t) \cdot dt = 0 \quad (8)$$

When the switch is ON, $v_L(t) = E - V_{o,avg}$ and when the diode is conducting,

$v_L(t) = -V_{o,avg}$. Therefore

$$\int_0^{DT} (E - V_{o,avg}) \cdot dt + \int_{DT}^T (-V_{o,avg}) \cdot dt = 0 \quad (9)$$

2

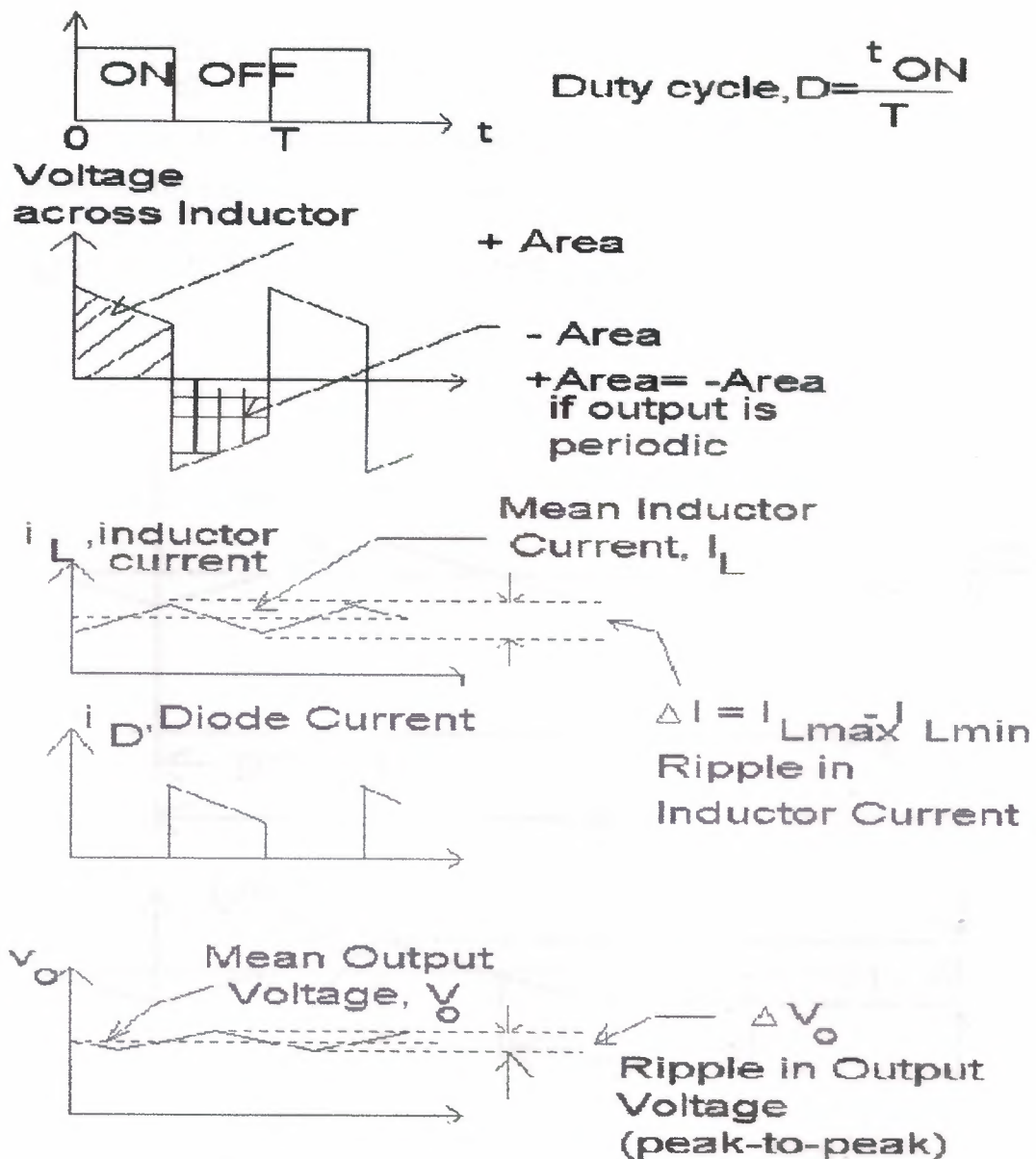


Figure 6.10 Shows The Waveforms For Step-Down Switch- Mode Regulator

On evaluation,

$$(E - V_{o,avg})DT - V_{o,avg}(1-D).T = 0$$

$$\text{That is, } V_{o,avg} = D.E \quad (10)$$

The change in inductor current when the switch is On can be determined as follows. Let the change in inductor current be ΔI , as shown in Figure 6.10. In this figure, the change in output voltage has been exaggerated for sake of clarity. When the switch is ON, the voltage across the inductor can be expressed as:

$$v_L(t) = L \frac{di_L}{dt} = E - v_0 \quad (11)$$

When the output voltage remains steady at $V_{o,avg}$, the inductor current linearly during the ON period of the switch. Then

$$\Delta I = \frac{E - V_{o,avg}}{L} \times DT = \frac{D(E - V_{o,avg})}{fL}, \because f \times T = 1 \quad (12)$$

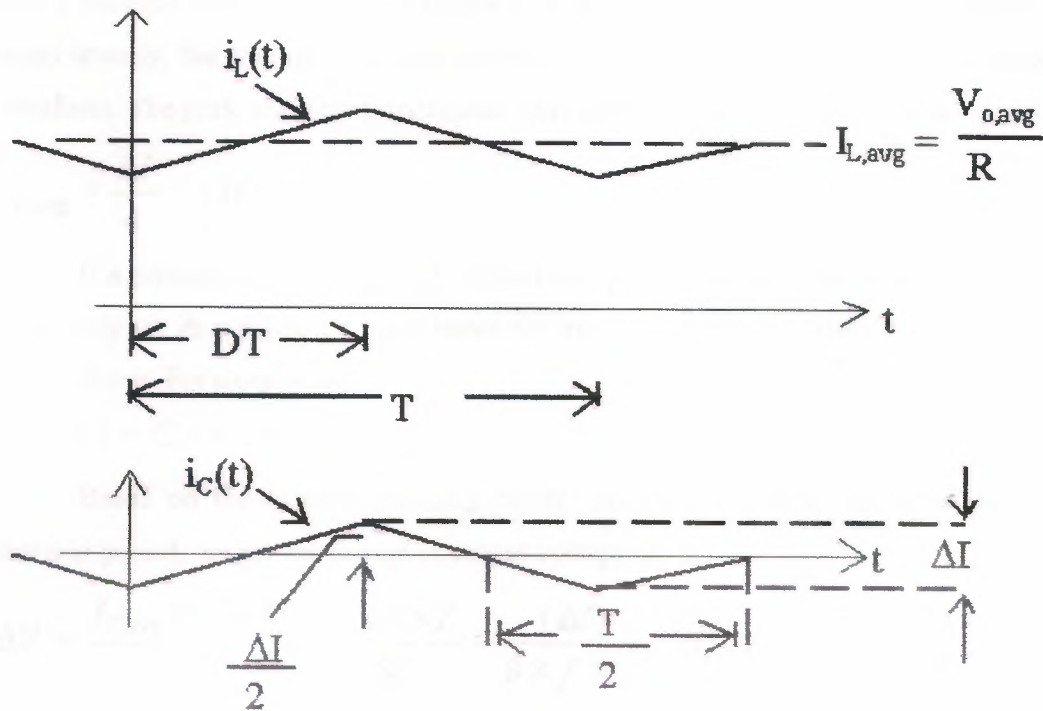


Figure 6.11 Shows The Capacitor Current

During the ON-period, the inductor current rises from $(V_{o,avg}/R - \Delta I/2)$ to $(V_{o,avg}/R + \Delta I/2)$. That is,

$$i_L(0) = i_L(T) = \frac{V_{o,avg}}{R} - \frac{\Delta I}{2}, \quad i_L(DT) = \frac{V_{o,avg}}{R} + \frac{\Delta I}{2} \quad (13)$$

The capacitor current i_C is expressed as follows:

$$i_C(t) = i_L(t) - i_R(t) = i_L(t) - \frac{V_{o,avg}}{R} \quad (14)$$

$$i_C(0) = i_C(T) = -\frac{\Delta I}{2}, i_C(DT) = \frac{\Delta I}{2} \quad (15)$$

Now an assumption is made to find out the change in output voltage. It is assumed that the capacitor gets charged for half of the cycle period and gets discharged during the other half, as shown in Figure 6.11. Since the current through the capacitor varies linearly, the average charging current is half of its peak value of the triangular waveform. The peak value of its triangular waveform is shown to be $\Delta I/2$. Hence

$$I_{C,avg} = \frac{\Delta I}{4} \quad (16)$$

If a periodic signal has zero dc value over its cycle period, its average is defined based only on its positive part and hence the average capacitor current is obtained as shown above. For a capacitor

$$q = i \times t = C \times v \quad (17)$$

Based on the average charging current and half of the cycle period as the charging period, we get the change in output voltage ΔV as:

$$\Delta V = \frac{I_{C,avg} \times (T/2)}{C} = \frac{(\Delta I) \times T}{8C} = \frac{(\Delta I)}{8 \times f \times C} \quad (18)$$

Using equation (12), the above equation can be expressed as:

$$\Delta V = \frac{D \times (E - V_{o,avg})}{8f^2 LC} \quad (19)$$

Assuming that the ripple in output voltage is sinusoidal, the rms value of ripple content in output voltage is:

$$V_{rms,ripple} = \frac{\Delta V}{2\sqrt{2}} = \frac{D \times (E - V_{o,avg})}{(16 \times \sqrt{2})f^2 LC} \quad (20)$$

Note that the variation in output voltage is not shown to be sinusoidal in Fig. 10.. Even though the variation appears to be triangular, equation (20) gives a better approximation of the rms value of ripple content in output voltage.

Given that source voltage = 100 V dc, switching frequency = 20 kHz, $L = 500 \mu\text{H}$, $C = 500 \mu\text{F}$, $R = 10 \Omega$, and duty cycle = 0.5, the results obtained are:

$$V_{o,avg} = 50 \text{ V},$$

$$\Delta I = 2.5 \text{ A},$$

$$\Delta V = 31.25 \text{ mV}, \text{ and}$$

$$V_{rms,ripple} = 11.05 \text{ mV}.$$

In order that the capacitor current and the inductor current vary linearly, it is necessary that the RC time constant should be relatively large, equal to about four or five times the cycle period. When the RC time constant is much smaller than the cycle period, the responses obtained are not linear. To illustrate, Figure 6.12 displays another set of responses. The only change is that a $1 \mu\text{F}$ capacitor is used in place of the $500 \mu\text{F}$ capacitor.

When the RC time constant is small, the output voltage contains noticeable ripple. In addition, the ripple in output voltage appears to be sinusoidal, justifying the equation used for finding out the rms value of the ripple content in output voltage. Another aspect can be noticed in Figure 6.12. It is that the ripple in output voltage goes through its negative half-cycle when the switch is ON. When this circuit is to be controlled by negative feedback, the feedback at the ripple frequency would become positive and closed-loop control effected without taking this aspect into account would produce a larger ripple in the output.

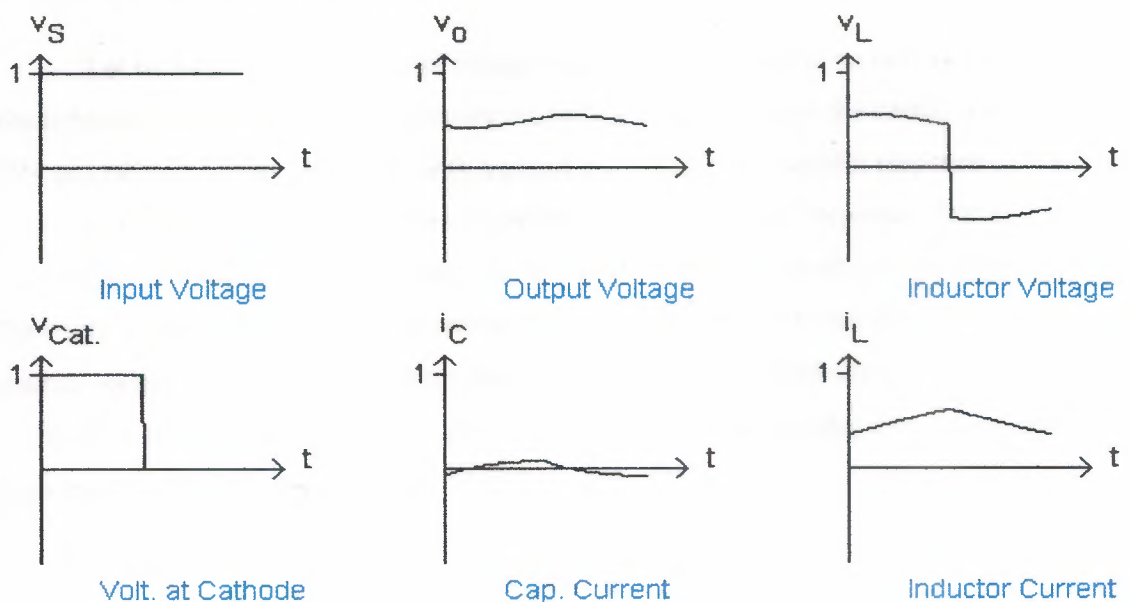


Figure 6.12 Shows The Periodic Response With a DC Voltage Input

Transient Response

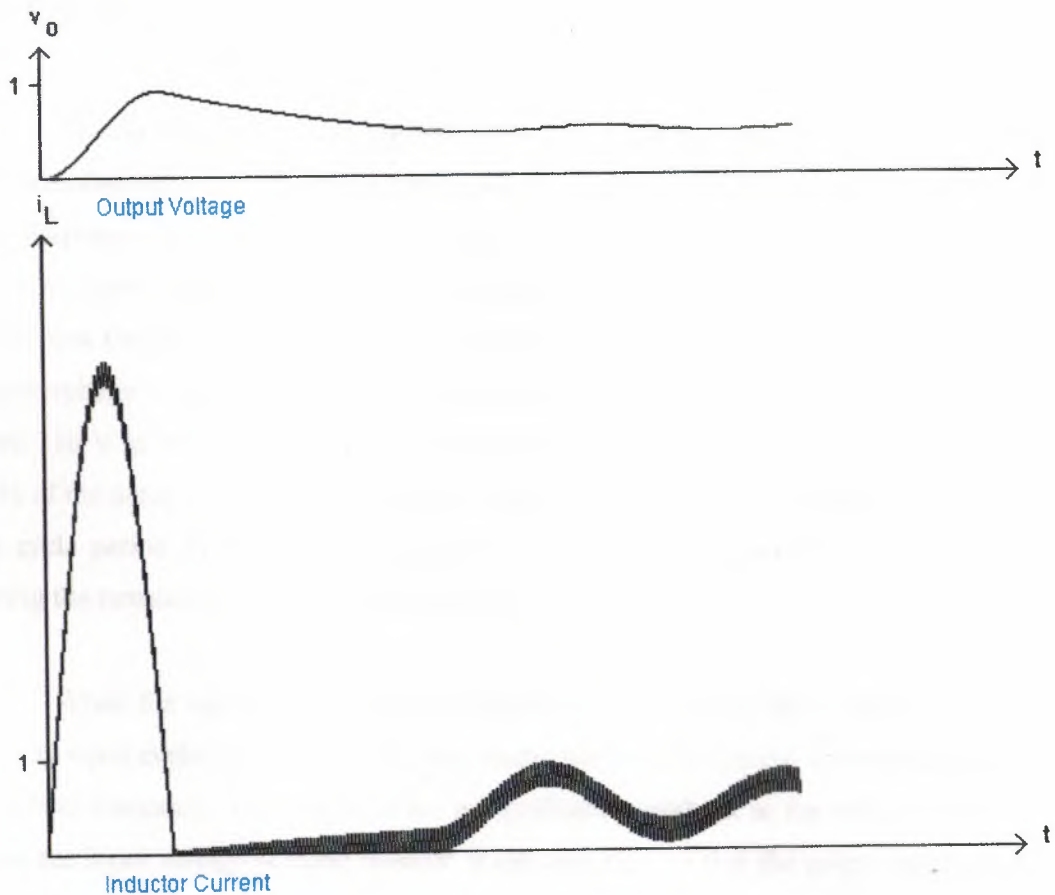


Figure 6.13 shows the Transient Response

Let us assume that the output voltage is zero and that there is no current through the inductor at start. If the source voltage is connected suddenly and the switch is turned ON and OFF at a fixed frequency with a preset duty cycle, the transient response of the circuit lasts for several cycles before it settles down to periodic response. The inrush current through the inductor is quite high, several times the maximum current that can flow under settled conditions. The transient response obtained over the first 10 ms with source voltage = 100 V dc, switching frequency = 20 kHz, $L = 500 \mu\text{H}$, $C = 500 \mu\text{F}$, $R = 10 \Omega$, and duty cycle = 0.5, is shown in Figure 6.13. Even after 200 cycles, the response is still in the transient state.

6.3 Effect Of Ripple In Input Voltage

Usually the input to an SMPS happens to be an unregulated dc voltage provided by a rectifier-filter circuit. Such a filter contains significant ripple content at double the line frequency. The first applet in this page illustrates the response obtained when the input voltage contains ripple. In this program, the ripple frequency, the peak-to-peak ripple and the source voltage can be set. If the source voltage = 100 V, peak-to-peak ripple voltage = 20 V, and the ripple frequency = 100 Hz, then the input voltage falls from 110 V to 90 V in the first 7.5 ms and rises from 90 V to 110 V in the remaining 25% of the input cycle period. The input voltage falls linearly in the initially for 75% of the cycle period from $(E + V_{\text{rip,pk-to-pk}}/2)$ to $(E - V_{\text{rip,pk-to-pk}}/2)$ and then rises linearly during the remainder of the input cycle period.

When the input voltage varies cyclically, the response of the circuit is periodic over its input cycle period and it is not periodic not over the period corresponding the switching frequency. In addition, there is significant overshoot in the inductor current when the input voltage is rising linearly. It can also be seen that the output voltage has nearly the same waveform as the input voltage, which is only to be expected. Since the duty cycle is kept fixed, the output voltage would tend to rise as the input voltage rises.

The response obtained with a peak-to-peak ripple voltage of 20 V at 100 Hz is shown in Figure 6.14. It becomes clear from the response that closed-loop control is necessary to maintain the output voltage when the input voltage has some ripple content. The closed-loop control circuit has to be designed with care, since the duty cycle has to be continually varied to maintain the output voltage at its set value.

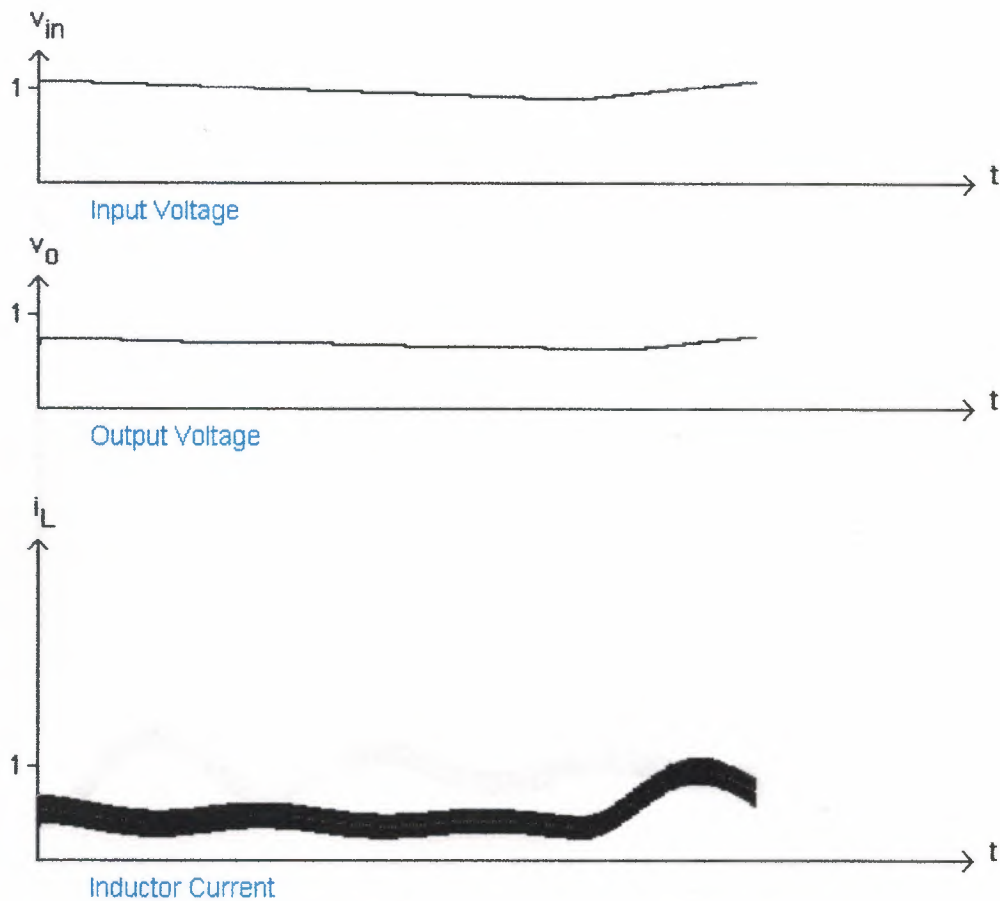


Figure 6.14 Shows The Periodic Response Over One Input Cycle Period

6.4 Effect of Step Change in Load

When there is a step change in load, the circuit goes through transient response before it settles back to periodic response. Here the circuit is allowed to be a settled state with a load resistance of $10\ \Omega$. Then the load resistance is changed to $5\ \Omega$ and the transient response that is obtained is presented in Figure 6.15. for this figure, '1' on the axis for corresponds to 10 A.

When the load resistor was $10\ \Omega$, the load current would have been 5 A given that the duty cycle is 0.5 and the input voltage is 100 V. It can be seen that after the step change in load resistor, the output voltage dips first and then recovers. If the change is in the other direction from $5\ \Omega$ to $10\ \Omega$, the output voltage rises first before falling back. Effective closed-loop control would reduce the transients. The under-damped nature of inductor current response can be improved.

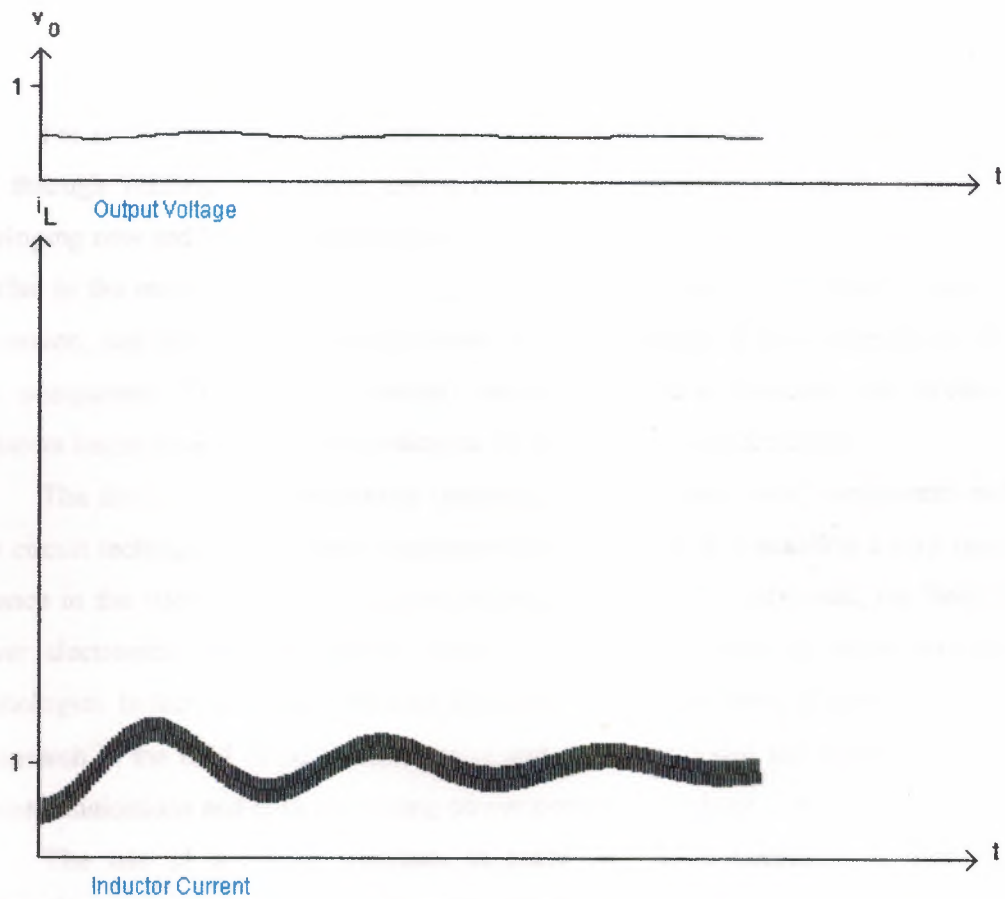


Figure 6.15 shows the Effect of Step Load Change for Increase in Load

6.5 Summary

This chapter has described some of the operation of a switch mode step-down power supply circuit. For description in this chapter, it has been assumed that the components used in the power circuit are ideal, whereas they are not ideal in reality.

CONCLUSION

For many years, the only means of accomplishing a power conversion function was through rotating machinery, and a tremendous amount of research went into developing new and better "commutation" techniques. The invention of the mercury arc rectifier in the early part of this century suddenly brought new possibilities for power conversion, and new circuits were invented to take advantage of the properties of this new component. Thus, "static" power conversion became possible, and creative engineers began developing the foundations for modern power electronics.

The field of power electronics reached its full potential, new components and new circuit techniques have been complementing each other and enabling a very rapid advance in the state of the art of power electronics. With these advances, the field of power electronics has been able to keep pace with the needs of other evolving technologies. In fact, as is often the case, the space program provided a significant boost to research in the field of power electronics and clearly provided the roots of modern telecommunications and data processing power system technology.

The use of a circuit simulator is more and more necessary in electrical engineering or power electronics, this technique makes it possible to obtain results when the hardware is missing and simulation being widely used in the industry it is thus necessary to initiate us to this technique, and power electronics simulation is very important because you can draw the model of the power circuit and the control in one schematic. The simulation is very fast because a special switch models are used, you do not have any convergence problems, by using simulation a special blocks for power electronics are controlled and you can model any type of power electronics circuit. You can model switched mode power supplies, inverters and rectifiers.

It is satisfying to look back at the early beginnings of power electronics and see how the engineers who have worked in this field have responded to needs and have been so creative in developing new components, theories, and well engineered applications.

Today's power electronics engineers are continuing the tradition by contributing to so many areas of modern electro technology.

REFERENCE

- [1] Muhammad H. Rashid., Power Electronics, Circuits, Devices, and Applications, 2nd ed, McGraw-Hill, New Jersey, 1988.
- [2] Joseph Vithayathil, Ph.D., Power Electronics, Principles and Applications, California Polytechnic State University, USA, 1995.
- [3] Cyril W. Lander, Power Electronics, School of Electronic and Electrical Engineering, Leicester Polytechnic, England, 1987.
- [4] P C SEN, Professor of Electronic and Telecommunication Engineering, Power Electronics, 2nd ed, Jadavpur University, New Delhi, 1990.
- [4] www.orcad.com/product/simulation/Pspice/eval.asp
- [5] www.edf.fr/der/html/oroduits/...
- [6] <http://simulate.engineering-e.com>