Design and Analysis of a Resonant Inverter fed from a Ćuk Converter for use in a Remote Area Telecom System.

By

M Mahbubur Rahman

A thesis submitted to the Department of Electrical and Electronic Engineering
Of
Bangladesh University of Engineering and Technology
In fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN ELECTRICAL AND ELECTRONIC ENGINEERING

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY

JANUARY 2008

DECLARATION

I hereby declare that this thesis work has been done by me and it has not been submitted elsewhere for the award of any degree or diploma.

Countersigned

23/01/2008

(Dr. Aminul Hoque)
Professor
Department of Electrical and Electronics Engineering,
BUET, Dhaka- 1000, Bangladesh.

23.01.08

(M Mahbubur Rahman)

The thesis entitled **"Design and Analysis of a Resonant Inverter from a Cûk Converter fed for use in an Remote Area Telecom System"** Submitted M Mahbubur Rahman, Roll No100006101P, Session October 2000 has been accepted as satisfactory in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE IN ELECTRICAL AND ELECTRONICS ENGINEERING.

BOARD OF EXAMINERS

1.---------------------------------- 23/01/2008

(Dr. Aminul Hoque) Professor Department of Electrical and Electronics Engineering, BUET Dhaka- 1000, Bangladesh.	(Supervisor)	Chairman

2.---------------- 23/1/08 ---- (Ex- Officio)

(Dr. S.P. Majumder) Professor Department of Electrical and Electronics Engineering, BUET Dhaka- 1000, Bangladesh.	Member

3.----------------------------------

(Dr. Mohammad Ali Choudhury) Professor Department of Electrical and Electronics Engineering, BUET Dhaka- 1000, Bangladesh.	Member

4.--------------- 23.1.08 ---------------

(Dr. Md. Ashraful Hoque) Professor Department of Electrical and Electronics Engineering, IUT Gazipur	Member (External)

Acknowledgements

I am very much grateful to the Almighty Allah for the successful completion of the work. I am greatly indebted and respectful to my supervisor, Dr. Aminul Hoque, for his great support, guidance, and encouragement, not only to my research work, and for his diligence and generosity.

I would like to specially thank to Dr. Mohammad Ali Choudhury, Professor, Department of Electrical and Electronic Engineering, BUET, a brilliant teacher and excellent human being, who lighted my way through the course of my graduate work and life for the past two years. His enthusiasm, broad knowledge and sharp thinking gained my most sincere admiration. His caring and understanding touched me deeply. Through his teaching, discussions and contributions, I gained significant insight into the field of design optimization.

I am also grateful to Professor Dr. Satya Prasad Majumder, Head of the Department, Department of Electrical and Electronic Engineering, BUET, for his guidance, and hole hearted support for the Thesis work.

My sincere thanks to Kazi Muzibur Rahman, Professor, Dept. of EEE, BUET, whose expertise in design optimization and guidance also enhanced the work to reach the goal.

I also extend my thank and gratitude to the staffs of EEE department who helped me time to time in the Laboratory and also in the department to carryout my research work smoothly.

ABSTRACT

In remote areas various security forces and law enforcing agencies need to use modern tools and communication equipments for national interest and security. Also, in hilly areas and tactical points of the country, the military forces need to use modern communication equipments and electronics. All these need to investigate alternative supply sources and delivery mechanisms for those systems. Community participation in off-grid electrification projects, using renewable energy sources, is a fast-growing method of increasing access to electricity. Storage power supplies, such as, batteries and fuel cells have been used in situations where electric power from the grid is unavailable; in remote area power systems, earth orbiting satellites or space probes, consumer systems, e.g. handheld calculators or wrist watches, remote radiotelephones and water pumping applications. Presently, solar arrays are used to supply communication equipments in remote areas.

Users in remote areas use DC equipment and systems suitable for storage power or alternative power sources. Historically, solar cells have been used in situations where electric power from the grid is unavailable. Recently solar cells are particularly used in assemblies of solar modules (photovoltaic arrays) connected to the electricity grid through an inverter, often in combination with a net metering arrangement. In this research work proposed equipments that are built to accept DC power supplies of solar system at 12V or 24V DC. In such applications common communication or telecom apparatus of 120V AC 60/50 Hz or 230V AC 60/50 Hz cannot be used. If a power supply unit using such a system may be designed and fabricated to provide conventional AC voltage at 50/60 Hz, then commercially available communication equipments may be used in remote installations without customised modules. This paper describes a new strategy for converting the solar power for use in a commercial telecom/communication set using a Resonant Inverter and a Ćuk Converter. The main objective is to investigate the solar electric system. The comprehensive system consists of PV array, Ćuk converter, resonant inverter, battery and battery charger. The Solar array, Ćuk converter and resonant inverter have been widely studied. A useful discussion has also been included.

CONTENTS

DECLARATION.. i

BOARD OF EXAMINERS.. ii

ACKNOWLEDGEMENT.. .iii

ABSTRACT.. iv

TABLE OF CONTENTS.. v

LIST OF FIGURES.. ix

LIST OF ABBREVIATIONS.. xiii

Chapter 1

Introduction

1.1 Introduction to Power for Remote Area Communication Equipment 1

1.1.1 Remote area alternative power 2

1.1.2 Considerations for alternative power 2

1.1.3 Power Supplies for Remote Area Telecommunication Equipment 4

1.1.4 Battery Powered Equipments 6

1.1.5 Solar Powered Equipment 7

1.2 Power Electronics and Power Supplies for Remote Area Telecom Equipments 8

1.2.1 DC-DC Power Converters 8

1.2.2 Basic Switching of DC-DC Converters 9

1.2.3 Converter Circuit topologies 10

1.2.4 DC-AC Power Converters 12

1.2.5 Inverters 12

1.2.6 Sine Wave Inverters 13

1.2.7 Modified Sine Wave Inverters 13

1.2.8 Basic Inverter Operation 13

1.2.9 Inverter output waveforms 14

1.2.10 H-Bridge Inverter 15

1.2.11 Literature Review of Ćuk Converter and Resonant Inverter 16

1.3 Objective of the Thesis 21

1.4 Outline of the Thesis 23

Chapter 2

Ćuk Converter Fed Resonant Inverter

2.1. Introduction 24

2.2 Ćuk Regulator 24

2.2.1 Analysis of Ćuk Converter 25

2.3.1 Series Resonant Inverter 30

2.3.2 Series Resonant Inverter with Bidirectional Switches 38

2.3.3 Frequency Response of Series Resonant Inverters 42

2.3.4 Battery and Subsystem 44

2.4 Design of Ćuk Regulator Fed Resonant Inverter 44

2.4.1 Ćuk Converter... 45

2.4.2 Resonant Inverter 47

2.5 Conventional Ćuk Regulator Fed Resonant Inverter 52

2.5.1 Efficiency Variation with Duty Cycle 53

2.5.2 Efficiency for Single Stage Ćuk Converter 55

2.5.3 Efficiency for Double Stage Ćuk Converter 57

2.6 Comparison between Ideal and Practical Circuit 60

2.6.1 Single Stage Converter 60

2.6.2 Double Stage Converter 66

2.6.3 Resonant Inverter 69

2.7 Ćuk Converter Fed Resonant Inverter 71

2.7.1 Modified Ćuk Converter Fed Resonant Inverter (Using ideal switch) ... 72

2.7.2 Modified Ćuk Converter Fed Resonant Inverter (Using IGBTs) 74

2.7.3 Modified Ćuk Converter Fed Resonant Inverter (Using switch and IGBTs)...76

2.8 Discussion on Result 78

Chapter 3

Conclusion and Recommendations

3.1 Conclusions 81

3.2 Limitations 82

3.3 Recommendations 83

References 83

LIST OF FIGURES

Fig 1.1: Several basic DC-DC converters and their dc conversion ratios $M(D) = V/V_g$ ...11

Fig 2.1: Boost - Buck (Ćuk) Converters wired in series 25

Fig 2.2: Analysis of Ćuk Converter operation; (a) Circuit diagram and waveform, (b) Mode-1 of operation, (c) & (d) Mode-2 of operation ...27

Fig 2.3(a): Resonant Inverter 29

Fig 2.3(b): Current wave shape of Resonant Inverter 30

Fig 2.4: Series resonant inverters with unidirectional switching and Modes of operation of series resonant inverter 31

Fig 2.5: Gating signals for thyristors and the waveforms of Resonant Inverters with Unidirectional Switches 32

Fig 2.6: Mode 1 of operation of Ćuk Converter 33

Fig 2.7: Mode 2 of operation of Ćuk Converter 34

Fig 2.8: Mode 3 of operation of Ćuk Converter 35

Fig 2.9: Full bridge series resonant inverter 37

Fig 2.10: Series Resonant Inverters with bidirectional switch 38

Fig 2.11: Waveforms of Series Resonant Inverter... 39

Fig 2.12(a): Circuit of Half-bridge series inverters with bidirectional switches 40

Fig 2.12(b): Waveform of Half-bridge series inverters with bidirectional switches 41

Fig 2.13: Full-bridge series inverter with bidirectional switches 41
(a) Circuit (b) Waveform
Fig 2.14: Series loaded circuit and input voltage 42
Fig 2.15: Frequency response of series loaded circuit 43
Fig 2.16: Ćuk (Boost and Buck) Converter using conventional switch 45
Fig 2.17: Ćuk (Boost and Buck) Converter using IGBT 45
Fig 2.18: Practical 2-stage Ćuk converter circuit using IGBTs 47
Fig 2.19: Output of Ćuk converter using IGBTs 47
Fig 2.20(a): GTO bridge Resonant Inverter 48
Fig 2.20(b): Inverter current and voltage waves for GTO bridge Resonant Inverter ...48
Fig 2.21: Equivalent circuit of resonant inverter 49
Fig 2.22: Resonant Inverter circuit using IGBTs 50
Fig 2.23: Wave shape of Resonant Inverter circuit using IGBTs 50
Fig 2.24: Resonant Inverter circuit using IGBTs (Inductor at the output 51
is replaced by a transformer)

Fig 2.25: Conventional Ćuk Regulator Fed Resonant Inverter 52
Fig 2.26: Single stage Ćuk converter operation 54
Fig 2.27: Efficiency, η Vs. Duty Cycle, D for single stage Ćuk converter 56
Fig 2.28: Voltage transfer function Vs. duty cycle V_0/Vin Vs. Duty Cycle, D 57
for single stage Ćuk

Fig 2.29: Efficiency, η Vs. Duty Cycle, D for double stages Ćuk converter 58

Fig 2.30: Voltage transfer function, V_0/Vin Vs. Duty Cycle, D for double stage Ćuk ...61

Fig 2.31: Operation of single stage Ćuk converter (Ideal case) 62

Fig 2.32: (a) Voltage transfer function Vs duty cycle (b) Efficiency Vs duty cycle of a single stage Ćuk converter 63

Fig 2.33: Single stage Ćuk converter using compensator circuit... 64

Fig 2.34(a): Voltage transfer function Vs duty cycle of a single stage Ćuk converter using compensator circuit ...64

Fig 2.34(b): Efficiency Vs duty cycle of a single stage Ćuk converter using compensator circuit 65

Fig 2.35: Practical single stage Ćuk converter using compensator circuit 65

Fig 2.36: Double stage Ćuk converter circuit 66

Fig 2.37: (a) Voltage transfer function Vs duty cycle (b) Efficiency Vs duty cycle of a double stage Ćuk converter 67

Fig 2.38: Double stage Ćuk converter using compensator circuit to get positive output...68

Fig 2.39(a): Voltage transfer function Vo/Vin Vs duty cycle of a double stage Ćuk converter using compensator circuit 68

Fig 2.39(b): Efficiency Vs. duty cycle of a double stage Ćuk converter using compensator circuit 69

Fig 2.40: Modified double stage Ćuk converter 69

Fig 2.41: Resonant Inverter circuit 70

Fig 2.42: Wave shape of ideal Resonant Inverter circuit... 70

Fig 2.43: Ćuk Regulator fed Resonant Inverter 71

Fig 2.44: Wave shape of Ćuk Regulator fed Resonant Inverter 72

Fig 2.45: Modified Ćuk Regulator fed Resonant Inverter 73

Fig 2.46: Output of modified Ćuk Regulator fed Resonant Inverter 73
(Ideal switch implementation)

Fig 2.47: Modified Ćuk Regulator fed Resonant Inverter 75

Fig 2.48: Output of modified Ćuk Regulator fed Resonant Inverter 75
(Practical BJT switch implementation)

Fig 2.49: Modified Ćuk Regulator fed Resonant Inverter using Switches and IGBTs ...76

Fig 2.50: Wave shape of modified Ćuk Regulator fed Resonant Inverter 77
(practical IGBT switch implementation)

Fig 2.51: Block diagram of the proposed power supply 78

LIST OF ABBREVIATION

PWM	Pulse Width Modulation
SEPIC	Single Ended Primary Inductor Converter
THD	Total Harmonic Distortion
PSU	Power Supply Unit
SMPS	Switched Mode Power Supply
ZVS	Zero Voltage Switching
ZCS	Zero Current Switching
EMI	Electro-Magnetic Interference
IGBT	Insulated Gate Bipolar Transistor
MOSFET	Metal Oxide Semiconductor Field Effect Transistor

Chapter 1

Introduction

1.1 Introduction to Power for Remote Area Communication Equipments

'Remote Area' in terms of electrical power availability is concerned, is defined as the area in the country where the grid power is unavailable due to its geographical location and terrain. The remote areas have a variety of terrain like riverines, hilly areas and coastal islands. There is hardly any item commercially available like remote area telecommunication equipments, except few commercial DC items which, not specially designed for the requirements of remote areas [1].

In this research an alternative power source (Solar system, fuel cell, wind power etc.) at 12V or 24V DC is assumed to be available in remote area. A power supply unit is to be designed and fabricated to provide conventional AC voltage at 50/60 Hz, so that the commercially available communication equipments may be used in remote installations without specially made customised modules.

With the spread of wireless voice and data into increasingly remote areas, the network operators face a number of challenges. Such challenges include expensive and complex civil works, long distance equipment transportation, high installation and commissioning costs. In addition, these sites will require electrical power for the base stations (telephone exchanges) and other associated equipment. Power supply to these sites is often the key issue for service providers building in remote or rural locations. Many ongoing researches are being continued to facilitate or provide alternative power solutions for communication operators in all technologies.

1.1.1 Remote Area Alternative power

Recent developments in fuel cells, microturbines and flywheels cause telecom engineers to think differently about how to power the telecommunication network in a remote area. Power engineers have long considered alternate energy sources as exotic, quirky, specialized or expensive for general purpose telecom applications. But telecom power technology is on the threshold of significant breakthroughs. Industry professionals are now opening their minds to alternate energy sources that can deliver quality power at reduced life-cycle costs in a variety of applications. Alternate energy sources generate power independently of the electrical grid. These sources can operate in stand-alone mode or they can be interconnected directly to the grid. Telecom power engineers are expressing renewed interest in alternate energy sources for use in primarily low-power installations, such as, remote terminals and wireless radio telephones.

The power equipments for remote area telephone system should have the following desirable qualities:

a. Low power requirement
b. Comparable low costs
c. Less maintenance
d. Longer life

1.1. 2 Considerations for Alternative Power

Alternate energy sources are designed for unattended operation over long periods. Less maintenance means fewer site visits and lower maintenance costs. Batteries used in telecom are designed for long life 5 to 10 years, but they rarely reach such long life. Frequent discharging/recharging, wide variations in ambient temperature and inadequate maintenance contribute to early battery demise, often in three to five years or less. Replacing batteries before their time is expensive and labor-intensive.

Alternate energy generation systems include fuel cells and microturbines, along with solar and wind generators. They can serve as a primary energy source or as a backup to utility power. Fuel cells and microturbines, more than solar or wind sources, appear to hold promise for telecom applications in terms of output power, efficiency, long-term operation and cost-effectiveness. Flywheels are the main energy storage alternative to batteries. Compared with standard lead-acid batteries, flywheels operate for a longer time, require little maintenance and, consequently, have lower life-cycle costs. In a telecom application, fuel cells could be installed at a site as a direct replacement of generators and batteries. The fuel cell is capable to deliver DC power to the load. Originally developed for the space program more than 30 years ago, fuel cells have come down to earth.

The appeal of fuel cells for telecom applications is simple. They use a highly efficient electrochemical process to convert hydrogen or hydrocarbon fuels into high-quality, highly reliable DC power with no emissions. Fuel cell technologies use solid electrolytes sandwiched between a cathode and an anode. Pre-commercial solid electrolyte fuel cell technologies include proton exchange membrane and solid oxide fuel cells [2].

Fuel cells, microturbines provide a source of clean, reliable AC power right at the site. Microturbines can be installed at locations with critical loads, such as, in telecom co-location buildings or Web hosting sites.

Microturbines can operate in a stand-alone mode as a primary power source or in a grid-connect mode with the grid as backup. Depending on the configuration, a small battery reserve (minutes, not hours) may be needed until the system gets started. Microturbines are versatile and can use a variety of fuels, including natural gas, propane, diesel, kerosene or even methane.

Realistically, it is still in the early stage of evaluation and deployment of alternate energy technologies in a remote area where the power is unavailable. Moreover, one technology does not fit all the requirements; each deployment must be considered on its own merit. In the end, carriers can realize improved network power performance at lower operating costs with prudent alternate energy choices.

A variety of alternate energy sources are on the market today. However, it is important to distinguish between energy generation systems and energy storage systems.

1.1.2 Power Supplies of Remote Area Telecommunication Equipment

When planning remote telecom, it has a number of possible power solution options. Selection of the optimum solution will depend on the local circumstances and would include:

Generators: These use internal combustion engines to drive generators, usually with an AC output. Generator sets are often used as a backup source of electricity for when the renewable sources are insufficient. The process is expensive and requires more maintenance. These will need to be refueled, and due to portability and value of both the generators and associated fuel, they may not be affordable always. Bio fuel generators are more environment friendly, though may not overcome issues of cost effectiveness.

Wind power technologies: Wind power has progressed in recent years and the cost of these has been steadily falling as volumes have increased. The point is being reached now where they can be considered as supplementary and the primary power source for cell sites in difficult locations/remote areas. As costs for these continue to fall, and the cost and scarcity of fossil fuels increase, wind, solar and other renewable energies will become increasingly cost effective compared with more conventional power sources.

Like solar power, the availability and maturity of grid, industrial, and domestic wind power generators has accelerated. The available products show a high degree of development, and are reliable, durable and affordable. A number of trade-offs need to be considered in selecting a wind power turbine for a cell site. The peak wind speeds determines the size of structure required to mount the turbine, as there is a relationship between the height above ground and wind speed. Options for mounting the turbine include a smaller turbine on a high tower or other structure, while in other cases a lower tower with a larger (and more costly) turbine will be more cost effective. Clearly the choice of turbine and structure needs to be considered within the context of the complete site as the selection of a tower height is driven by many factors. Strong cylindrical towers are available for mounting turbines and these could also be used for mounting the antennas or even mini or micro Base Stations or Remote Heads.

Solar Power: The development of high efficiency and affordable solar power has progressed to the point that domestic solutions are feasible in areas of high sunlight [3]. New solar cell technologies are moving the price point steadily down at a time when fossil fuels are increasing in cost. In addition many countries have incentives, such as, grants to encourage people to buy and use these systems, and when there is excess power this can be sold back to the local power company. Once installed solar arrays require minimal maintenance, though occasional cleaning will prevent a gradual loss of panel efficiency. Cloud and rainfall may reduce power of the solar panel. There is a range of manufacturers of solar power systems, at a number of price points depending upon the environmental conditions within which the array will operate. There is significant scope for the involvement of local contractors to provide supporting frames and tracking equipment.

Bio Fuels: The use of bio fuels such as bio diesel is increasing as both the technology to manufacture and use them matures and the cost of fossil fuels continues to rise. Bio diesel is comparatively simple to manufacture and is a very suitable alternative in emerging markets. By growing and using a suitable crop in country the import of fuel is avoided, and employment provided for local manpower.

Fuel Cells: Fuel cells are being developed as a potential power source. They are clean and efficient alternative to generators for prime power or as an alternative to batteries for backup power. The technology has matured in recent years and has many benefits compared to generators in terms of fuel efficiency, climate resistance, reliable start-up and are very compact. A valuable aspect of fuel cells is the silent operation. As they reach volume manufacture in the next few years the prices will fall, they will challenge conventional engine driven generators in applications where other technologies are not cost effective.

Microhydro Generator: When a steady and reliably source of flowing water is available, microhydro generators can be used to produce electricity. As with a wind turbine, the device is used to drive a generator.

Pico Hydro: There are regions in the world with high seasonal rainfalls but with low solar radiation and low average wind speeds. A steep flowing stream or a river is a source of energy and experimental small hydro power solutions have been tested in some locations with promising results. One significant benefit of such systems is that much of the civil work can be done by local residents, and the turbine and generating systems are not of high technology and are easily maintained. In common with other alternative power sources the systems can be sized to provide power to small local communities in addition to the cell site. Other small hydro systems such as submersible propeller turbines can be used in fast flowing rivers.

Power Storage: The nature of power systems which utilize solar, wind or hydro power is that there will be frequent periods where excess power will have to be dumped. In its research on optimizing cell site power solutions investigation is in process to find out the more efficient methods of managing this process, minimizing the amount of generated power that has to be wasted.

1.1.4 Battery Powered Equipments

To store excess energy generated during periods of low demand and supply electricity during periods of high demand, an energy storage mechanism is required. The most common form of energy storage in remote areas is a bank of electrochemical batteries. Rechargeable batteries are the most common type of battery used.

By using battery power tools following advantages are achieved:

a. Less electricity consumption, i.e. it also takes less power to re-charge the batteries.

b. Can be used when there is no power, great for the handyman or when a job has to be done away from mains power.

c. An alternative to this if there a generator, still have to supply it fuel and all that costs money and time.

Battery power is equally important in mobile telecommunication applications as well. The installations include mountain-top repeater sites, microwave relays, and portable radio power systems. Industrial design technicians assess system demands based on location restrictions to create a complete and reliable solution.

With networks of mountain-top repeaters accessible only by helicopter, site reliability is of the utmost importance. Solar power systems require little to no ongoing maintenance, thus making them an attractive alternative to generator or potash battery systems. Environmental concerns are also addressed with pollution-free solar modules [4]. It is provided with the highest reliability factors, array and battery systems which can endure months of hostile weather and snow cover while still providing power to critical systems.

1.1.5 Solar Powered Equipments

Solar technology has devised a range of solar panels using the latest advances to capture the sun's energy and convert it into electrical current to power for a range of applications. Solar technologies have distinct advantages over conventional technologies for electricity generation, mainly for remote areas where grid power is unavailable for environmental disadvantages. However solar technologies have not been exploited fully. If it would be possible to exploit the solar energy effectively, worlds energy crisis could be minimized to a great extent [5].

With continued research in this field, solar cell technology is well on its way to replace conventional methods of electricity generation. In addition to its size, solar energy has two other factors in its favour. Firstly, unlike fossil fuels and nuclear power, it is an environmentally clean source of energy. Secondly, it is free and available in adequate quantities in almost all parts of the world. Mankind has always used the energy of the sun as far back as humans have existed on this planet. Solar equipments are widely used in the following applications [6]:

a. Power supply for remote areas
b. Earth orbiting satellites or space probes
c. Consumer systems, e.g. hand held calculators, wrist watches etc.
d. Remote radiotelephones, and
e. Water pumping applications.

1.2 Power Electronics and Power Supplies for Remote Area Telecom Equipments

For particular interest, only electronics for solar power will be discussed. The power electronics that are commonly used are as follows:

a. DC-DC power converter.
b. DC-AC power converter.
c. Battery Charger

1.2.1 DC-DC Power Converters

In many industrial applications, it is required to convert a fixed-voltage DC source into another level or a variable-voltage DC source. A DC converter can be considered as DC equivalent to an AC transformer with a continuously variable turn ratio. Like transformer, it can be used to step down or step up a DC voltage source.

DC converters are widely used for traction motor control in electric automobiles, trolley cars, marine hoists, forklift trucks, and mine haulers. DC converters are used in DC voltage regulators; and also are used in conjunction with an inductor, to generate a DC current source, especially for the current source inverter.

DC-DC power converters are employed in a variety of applications, including power supplies for personal computers, office equipment, spacecraft power systems, laptop computers, and telecommunication equipments, as well as, DC motor drives. The input to a DC-DC converter is an unregulated dc voltage V_g. The converter produces a regulated output voltage V, having a magnitude (and possibly polarity) that differs from V_g (input voltage). For example, in a computer off-line power supply, the 120 V or 240 V AC utility voltage is rectified, producing a dc voltage of approximately 170 V or 340 V, respectively. A DC-DC converter then reduces the voltage to the regulated 5 V or 3.3 V required by the processor ICs. High efficiency is invariably required, since cooling of inefficient power converters is difficult and expensive. The ideal DC-DC converter exhibits 100% efficiency; in practice, efficiencies of 70% to 95% are typically obtained. This is achieved using switched-mode, or chopper, circuits whose elements dissipate negligible power. Pulse-width modulation (PWM) allows control and regulation of the total output voltage. This approach is also employed in applications involving alternating current, including high-efficiency DC-AC power converters (inverters and power amplifiers), AC-AC power converters, and some AC-DC power converters (low-harmonic rectifiers) [7].

1.2.2 Basic switching of DC-DC converters

Basic converters are of four types:

- a. Buck
- b. Boost
- c. Buck-Boost
- d. Ćuk

1.2.3 Converter circuit topologies

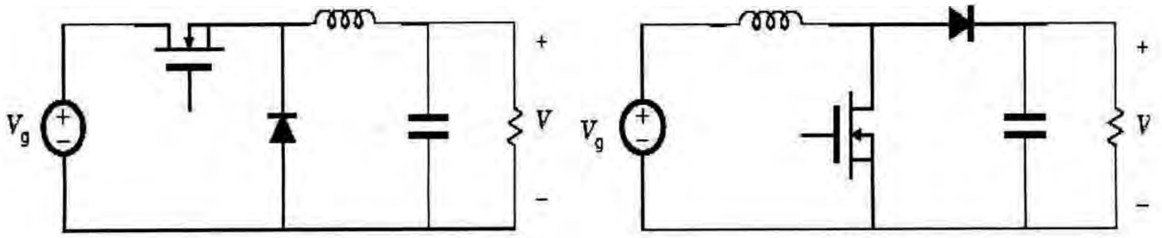
A large number of DC-DC converter circuits are known that can increase or decrease the magnitude of the DC voltage and/or invert its polarity. Fig 1.1 illustrates several commonly used DC-DC converter circuits, along with their respective conversion ratios. In each example, the switch is realized using a power MOSFET and diode; however, other semiconductor switches such as IGBTs, BJTs, or thyristors can be substituted if desired [8].

The first converter is the buck converter, which reduces the dc voltage and has conversion ratio M(D) = D, where D is the duty cycle. In a similar topology known as the boost converter, the positions of the switch and inductor are interchanged. This converter produces an output voltage V that is greater in magnitude than the input voltage Vg. Its conversion ratio is M(D) = 1/(1 – D).

In the buck-boost converter, the switch alternately connects the inductor across the power input and output voltages. This converter inverts the polarity of the voltage, and can either increase or decrease the voltage magnitude. The conversion ratio is M(D) = - D/(1 – D).

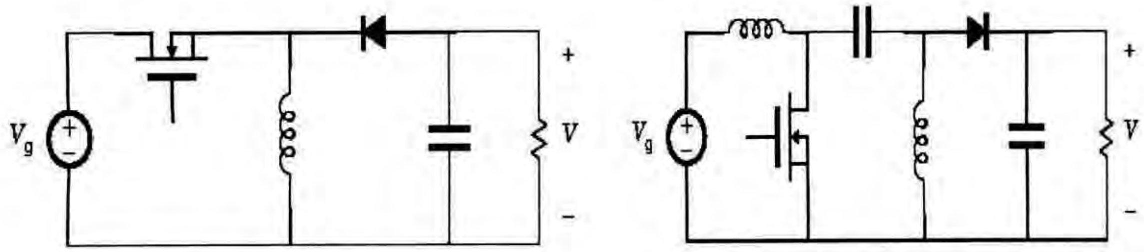
The Ćuk converter contains inductors in series with the converter input and output ports. The switch network alternately connects a capacitor to the input and output inductors.

The conversion ratio M(D) is identical to that of the buck-boost converter. Hence, this converter also inverts the voltage polarity, while either increasing or decreasing the voltage magnitude.



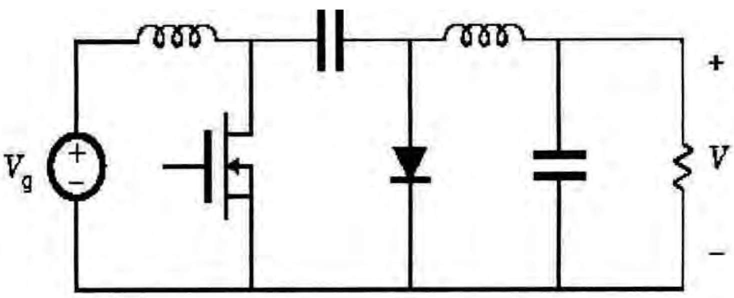
Buck converter

Boost converter



Buck-boost converter

Sepic converter



Ćuk converter

Fig 1.1: Several basic DC-DC converters and their dc conversion ratios $M(D) = V/V_g$.

The single-ended primary inductance converter (SEPIC) can also either increase or decrease the voltage magnitude. However, it does not invert the polarity. The conversion ratio is $M(D) = D/(1 - D)$.

1.2.4 DC-AC Power Converters

Most of the alternative source of energy topologies produces DC power, and hence power electronics and control equipment are required to convert the DC power into AC power. Inverters are used to convert DC to AC. There are two types of inverters:

a. Stand-alone inverter
b. Grid-connected inverter.

The two types have similarities, but are different in terms of control functions. A stand-alone inverter is used in off-grid applications with battery storage. With backup diesel generators (such as PV-diesel hybrid power systems), the inverters may have additional control function such as operating in parallel with diesel generators and bidirectional operation (Battery charging and inverting). Grid-interactive inverters must follow the voltage and frequency characteristics of the utility-generated power presented on the distribution line. For both types of inverters, the conversion efficiency is a very important consideration.

1.2.5 Inverter

The inverter is a basic component of any independent power system that requires AC power. Inverters convert DC power stored in batteries or DC power directly obtained from alternative sources into AC power to run conventional appliances.

Just over a decade ago inverters were inefficient and unreliable, so that many people restricted themselves to 12 volt lights and appliances. The efficient and reliable modern inverter and the availability of efficient, inexpensive 120 volt AC lighting has led many people to wire their dwellings for AC power only.

1.2.6 Sine Wave inverters

There are three waveforms produced by solid state inverters. The simplest, a square wave, used to be all that was available. But now a days, many appliances will not operate on a square wave. True sine wave inverters represent the latest inverter technology. The waveform produced by modern inverters is the same as or better than the power delivered by the utility. Harmonics are virtually eliminated and all appliances operate properly with this type of inverter. They are, however, significantly more expensive than their modified sine wave versions.

1.2.7 Modified Sine Wave inverters

Modified sine wave or quasi-sine wave inverters were the second generation of power inverter. They are a considerable improvement over square wave inverters. These popular inverters represent a compromise between the low harmonics (a measure of waveform quality) of a true sine wave inverter and the higher cost and lower efficiency of a true sine wave inverter.

Modified sine wave inverters approximate a sine wave and have low enough harmonics that they do not cause problems with household/commercial equipment. They run TVs, stereos, induction motors (including capacitor start), universal motors, computers, microwave/communication equipments, and more quite well. The main disadvantage of a modified sine wave inverter is that the peak voltage varies with the battery voltage. Inexpensive electronic devices with no regulation of their power supply may behave erratically when the battery voltage fluctuates.

1.2.8 Basic Inverter Operation

In one simple inverter circuit, DC power is connected to a transformer through the centre tap of the primary winding. A switch is rapidly switched back and forth to allow current to flow back to the DC source following two alternate paths through one end of the primary winding and then the other. The alternation of the direction of current in the primary winding of the transformer produces alternating current (AC) in the secondary circuit.

The electromechanical version of the switching device includes two stationary contacts and a spring supported moving contact. The spring holds the movable contact against one of the stationary contacts and an electromagnet pulls the movable contact to the opposite stationary contact. The current in the electromagnet is interrupted by the action of the switch so that the switch continually switches rapidly back and forth. This type of electromechanical inverter switch called a vibrator or buzzer, was once used in vacuum tube automobile radios. As they have become available, transistors and various other types of semiconductor switches have been incorporated into inverter circuit designs.

1.2.9 Inverter output waveforms

The switch in the simple inverter described above produces a square voltage waveform as opposed to the sinusoidal waveform that is the usual waveform of an AC power supply. Using Fourier analysis, periodic waveforms are represented as the sum of an infinite series of sine waves. The sine wave that has the same frequency as the original waveform is called the fundamental component. The other sine waves, called harmonics that are included in the series have frequencies that are integral multiples of the fundamental frequency.

The quality of the inverter output waveform can be expressed by using the Fourier analysis data to calculate the total harmonic distortion (THD). The total harmonic distortion is the square root of the sum of the squares of the harmonic voltages divided by the fundamental voltage.

The quality of output waveform that is needed from an inverter depends on the characteristics of the connected load. Some loads need a nearly perfect sine wave voltage supply in order to work properly. Other loads may work quite well with a square wave voltage.

1.2.10 H – Bridge Inverter

There are many different power circuit topologies and control strategies used in inverter designs. Different design approaches are used to address various issues that may be more or less important depending on the way that the inverter is intended to be used. A H-bridge Inverter (full-bridge) is used to obtain the full wave output.

The issue of waveform quality can be addressed in many ways. Capacitors and inductors can be used to filter the waveform. If the design includes a transformer, filtering can be applied to the primary or the secondary side of the transformer or to both sides. Low-pass filters are applied to allow the fundamental component of the waveform to pass to the output while limiting the passage of the harmonic components. If the inverter is designed to provide power at a fixed frequency, a resonant filter can be used. For an adjustable frequency inverter, the filter must be tuned to a frequency that is above the maximum fundamental frequency.

Since most loads contain inductance, freewheeling antiparallel diodes are often connected across each semiconductor switch to provide a path for the peak inductive load current when the semiconductor switch is turned off.

Fourier analysis reveals that a waveform, like a square wave, that is anti-symmetrical about the 180 degree point contains only odd harmonics, the 3rd, 5th, 7th etc. Waveforms that have steps of certain widths and heights eliminate or "cancel" additional harmonics. For example, by inserting a zero-voltage step between the positive and negative sections of the square-wave, all of the harmonics that are divisible by three can be eliminated. That leaves only the 5th, 7th, 11th, 13th etc. The required width of the steps is one third of the period for each of the positive and negative voltage steps and one sixth of the period for each of the zero-voltage steps.

Changing the square wave as described above is an example of pulse-width modulation (PWM). Modulating, or regulating the width of a square-wave pulse is often used as a method of regulating or adjusting an inverter's output voltage. When voltage control is not required, a fixed pulse width can be selected to reduce or eliminate selected harmonics. Harmonic elimination techniques are generally applied to the lowest harmonics because filtering is more effective at high frequencies than at low frequencies. Multiple pulse-width or carrier based PWM control schemes produce waveforms that are composed of many narrow pulses. The frequency represented by the number of narrow pulses per second is called the switching frequency or carrier frequency. These control schemes are often used in variable-frequency motor control inverters because they allow a wide range of output voltage and frequency adjustment while also improving the quality of the waveform [9].

Multilevel inverters provide another approach to harmonic cancellation. Multilevel inverters provide an output waveform that exhibits multiple steps at several voltage levels. For example, it is possible to produce a more sinusoidal wave by having split-rail direct current inputs at two voltages, or positive and negative inputs with a central ground. By connecting the inverter output terminals in sequence between the positive rail and ground, the positive rail and the negative rail, the ground rail and the negative rail, then both to the ground rail, a stepped waveform is generated at the inverter output. This is an example of a three level inverter: the two voltages and ground [10].

1.2.11 Literature Review of Ćuk Converter and Resonant Inverter

Ćuk Converter

Switch-mode power conversion emerged as an interdisciplinary field which requires a fundamental knowledge in three areas [11]:

a. Power circuit configurations

b. Control systems, and

c. Basic switched- mode conversion topologies, properties and simple analysis method.

Principles of magnetic circuit analysis provide better understanding of power inductor and power transformer design requirements. Closing the feedback loop in pulse width modulation (PWM) systems require basic understanding of DC-DC converter dynamics, and so that the accompanying transfer functions and frequency response methods are also reviewed. With the basic building blocks well understood, sophisticated and complex structures of modern electronic power processing systems may be more easily and reliably designed.

Since a switched-mode converter can operate at significantly high frequencies, then a smaller transformer using ferrite cores can be used. Also since the high rectified mains voltage is chopped, then energy storage for hold-up can be accomplished on the primary side of the step-down transformer and so much smaller capacitors than the linear counterpart can be used.

Switched-mode power supply or SMPS, is an electronic power supply unit (PSU) that incorporates a switching regulator. While a linear regulator uses a transistor biased in its active region to specify an output voltage, an SMPS actively switches a transistor between full saturation and full cutoff at a high rate. The resulting rectangular waveform is then passed through a low-pass filter (typically an inductor and capacitor) to achieve an approximated output voltage. Advantages of this method include smaller size, better power efficiency, and lower heat generation. Disadvantages include the fact that SMPSs are generally more complex than linear supplies, generate high-frequency electrical noise that may need to be carefully suppressed, and have a characteristic ripple voltage at the switching frequency [12].

A switch mode DC-to-DC converter is used to convert the unregulated DC input into controlled DC output at a desired voltage level. This converter is very often used in conjunction with a transformer for electrical isolation in DC power supplies and most often without isolation in DC motor drives. There are five major types of DC-DC switch mode converters. The two basic converter topologies are the step down (buck) converter and the step up (boost) converter. From the combination of these two basic topologies are the Buck-Boost converter and the Ćuk converter.

With a clearly defined goal of achieving non-pulsating currents, the desired converter configuration gradually emerges: an inductor is needed in series with both input source and output load for either switch position. Then, energy transfer and level conversion is achieved by use of a single capacitance and a single switch, or its bipolar transistor, diode implementation, known as Ćuk converter. The Ćuk converter is formed by combining the Buck and the Boost converter. The Ćuk converter is a type of DC-DC converter that has an output voltage magnitude that is either greater than or less than the input voltage magnitude, with an opposite polarity. It uses a capacitor as its main energy-storage component, unlike most other types of converter which use an inductor. It is named after Slobodan Ćuk of the California Institute of Technology, who first presented the design.

The main component that controls the flow of energy from input to output is the capacitor in between. Ćuk converter feature capacitive energy transfer to attain high efficiency. When the switch is open the current from the input and output flows through the diode. The first capacitor (C1) is charged by the combined energy from the input inductor and the source. While at the load side, inductor-2 (L_2) supplies the load. These causes the current at the input and output inductor to decrease. During the ON position the diode is reverse biased by the capacitor current causing the currents at the input and output to flow to the switch. The source current then charges the input inductor causing the inductor current to increase. At the output side the capacitor energizes the load and the inductor. This causes the current at the inductor to increase, ready for the next switching cycle. The output voltage could be determined by multiplying the ratio of the duty cycle over the difference of subtracting the duty cycle from one with the input voltage. This relationship is similar to the Buck-Boost converter. The advantage of this type of converter over the buck-boost converter is that both the input current and the current feeding the output are reasonably ripple free. It is possible to simultaneously eliminate the ripples at the two inductor currents completely leading to lower external filtering requirements. A significant disadvantage however is the requirement of a large capacitor that could contain a large ripple current.

An important generalization in modeling, which essentially solved the problem of modeling the transfer properties of switch mode modulators and converters, was made by Middlebrook and Ćuk in 1976. In 1976, a complete small signal modeling information on the three basic converters operating in the constant frequency continuous conduction mode came in operation. One of the most interesting results was the discovery of the existence of the right-half-plane zero in the control-to-output transfer functions of the boost and the buck-boost converters. This discovery has brought about significant understanding of the nature of the non-linearities of the two basic converters. However, the behavior of these two converters is rather different when operating in the constant frequency discontinuous conduction mode. While doing investigations in power converter modeling, Ćuk also discovered that, by applying the principles of duality, new converters are obtainable. Thus, the boost converter was found to be a dual of the buck converter. Delving into the dual of the flyback (buck-boost) converter, Ćuk invented the optimum topology (Ćuk) converter, a converter utilizing the principle of capacitive energy transfer [15].

Another by-product of Ćuk's investigation was that the windings of the input and output inductors of the new optimum topology converter could be wound on the same magnetic core, producing the coupled-inductor Ćuk converter. A natural evolution from the coupled-inductor converter was the integrated magnetic converter. After many years of design and experimentation, a workable approach to the design of coupled inductor power converters is now available, Ćuk and Zhang, who made a thorough investigation of the problems surrounding the coupled inductor and emerge with some elegant solutions. Zhang's findings also served to provide an interesting solution to the integrated magnetic converter problem. Since most of the popular power conversion topologies (the bridge converter, the half-bridge converter, the forward converter, and the push-pull converter) are buck-derived, they can be similarly analyzed with no difficulties.

Resonant Inverter

DC to AC converters are known as inverters. The function of an inverter is to change a dc input voltage to a symmetrical ac output voltage of desired magnitude and frequency. The output voltage waveform of an ideal inverter should sinusoidal. However, the waveforms of practical inverters are non-sinusoidal and contain certain harmonics. The harmonics can be minimized or reduced significantly by switching techniques [16].

Inverters are broadly classified into two types:

a. Single phase inverters
b. Three phase inverters.

Disadvantages of conventional inverters:

a. Output wave shape is not pure sine wave.
b. The switches are subjected to high-voltage stress.
c. Switching loss increases linearly with switching frequency.
d. The switches have turn-off and turn-on loss.
e. Electromagnetic interference is present due to high di/dt and dv/dt in the converter waveforms.

All these disadvantages can be eliminated or minimized using a resonant inverter. The switching devices are turned "ON" and turned "OFF" when the voltage across the device or its current becomes zero (ZVS or ZCS), so that the switching loss is zero and the switches are not subjected to high-voltage stress. The voltage and current are forced to pass through zero crossing by creating an LC resonant circuit.

In the 1980s, the concept of incorporating resonant tank in the converter to create oscillatory (usually sinusoidal) voltage and/or current waveform so that zero voltage switching (ZVS) or zero current switching (ZCS) was achieved.

In the late 1990s, new generation soft-switched converters that combine the advantages of conventional PWM converters and resonant converters were developed, which makes the wave shape 'smooth' and with no transient spikes.

The latest development on resonant inerter is the resonant dc link inverters and the resonant pole inverters. They offer reduction in switching loss and thermal requirement, possibility of high frequency operation, snubberless operation, better suppression of EMI, improved performance and efficiency through ZVS and ZCS [17].

1.3 Objective of the Thesis

Telecommunication technology for remote areas needs to explore alternative energy source for uninterrupted power supply round the clock. In remote areas, as the grid power is unavailable, the alternative power should be cost effective and environment friendly. Recent development of solar has devised a range of solar panels using the latest technology to capture the sun's energy and convert it into electrical current to power for a range of applications. Solar technologies have distinct advantages over other conventional alternative technologies for electricity generation, mainly for remote areas where grid power is unavailable for environmental disadvantages. However, solar technologies have yet to be exploited. The power output from the sun is 3.86 x 10^{20} MW [18], which is many thousand of times larger than the present consumption rate on the earth of all commercial energy sources. They are not yet a completely effective substitute for conventional technologies for electricity generation.

This thesis work is aimed on power electronics application and involves a large number of design variables and the application of knowledge from several different engineering fields (electrical, magnetic, thermal, solar and mechanical). In order to simplify the design problem, traditional design procedures fix a guideline of the design variables and introduce assumptions (simplifications) based on the experience and understanding of the problem. These simplifications allow an initial design to be obtained in a reasonable amount of time, but further iterations through hardware prototype testing are usually required. The ability and expertise of the designer usually leads to good, but not optimum.

The aim of this work is to design and propose a new and efficient photovoltaic/renewable power interface circuit incorporated with a converter (boost-buck) and a resonant inverter. The boost-buck converter (also known as 'Ćuk' converter) will raise the voltage level up, whereas the resonant inverter will operate at low switching frequency of 50 to 60Hz, converting the output of the Ćuk converter into AC power, of which the operating frequency will be 50-60Hz as required.

This thesis describes a strategy for converting the alternative source DC power for use in a commercial telecom/communication set using a resonant inverter and a Ćuk converter. The voltage of the storage cells (solar), typically 12V or 24V DC will be converted to 300V DC by a DC-DC Ćuk converter. The 300V DC will again be converted to 240V AC by a resonant inverter. The parameters of the inverter will be so chosen to obtain desired AC voltage to run conventional communication equipment or 230V AC 50Hz supply. Step up DC-DC conversion will be achieved by duty cycle control of Ćuk converter topology. Ćuk topology is the most efficient and light weight unit among all switch mode power supplies as they transfer energy capacitively [19]. In this work, the converter will be operated in step up mode of operation. The output of Ćuk converter will be fed to a resonant inverter circuit to obtain direct sinusoidal supply for communication equipment. Resonant inverters are soft switched inverters with very low switching loss and they are usually designed and operated at very high frequency. In this work, the design and operation of a resonant inverter is for 50Hz, which will be a challenging work in terms of component size. Also, the LC of the inverter has to match with the front end DC-DC converter.

1.4 Outline of the Thesis

In this thesis there are four chapters. Chapter -1 deals with the introduction to Remote Area Telecommunication Equipments, Power Supplies of Remote Area Telecommunication Equipment, Battery Powered Equipments, Solar Powered Equipments, Power Electronics and Power Supplies for Remote Area Telecommunication Equipments, DC-DC Power Converters, DC-AC Power Converters, and the Objective of the Thesis and Outline of Thesis.

Chapter -2 includes, the study of Ćuk Regulator Fed Resonant Inverter, introduction to Ćuk Regulator and Resonant Inverter, Design of Ćuk Regulator Fed Resonant Inverter; Ćuk Regulator Resonant Inverter their detail circuit diagram and operation.

Chapter - 3 Concludes the thesis with summary, achievements and recommendations on future developments.

Chapter 2

Ćuk Regulator Fed Resonant Inverter

2.1 Introduction

The voltage regulator is a device by which the voltage can be set to a desired value and can be maintained constant all the time. The field of application extends from very large power systems to small electronic apparatus. As a result, the types of regulators are also numerous. The design of the regulator system depends mainly on the power requirement and degree of stability. In this research work, a Ćuk regulator is used to step up the DC voltage level of the source power. A Ćuk converter featuring clamping action, pulsewidth modulation, and soft-switching commutation is used in this research to step up voltage and fed the step up voltage to a resonant inverter. The resonant circuits absorb almost all parasitic reactances of switches, including transistor output capacitances [20]. Although this converter is suitable for high-frequency operation, it is designed for 50Hz operation for providing 50Hz supply necessary in commercially available telecom equipments. A resonant inverter is a high frequency switching topology used in many applications. Resonant switching topologies are efficient power conversion circuits, when compared to traditional pulse width modulation (PWM) topologies. This is due to the zero current and/or zero voltage transistor switching that is inherent. This also provides an additional benefit of eliminating undesirable electromagnetic radiation normally associated with switching supplies [21].

2.2 Ćuk Regulator

A large number of DC-DC converter circuits are known that can increase or decrease the magnitude of the DC voltage and/or invert its polarity. Fig 2.1 illustrates a Ćuk converter along with it's conversion ratios. In this example, the switch can be realized using a power MOSFET or IGBT and a diode; however, other semiconductor switches such as BJTs, or MCT can be substituted if desired.

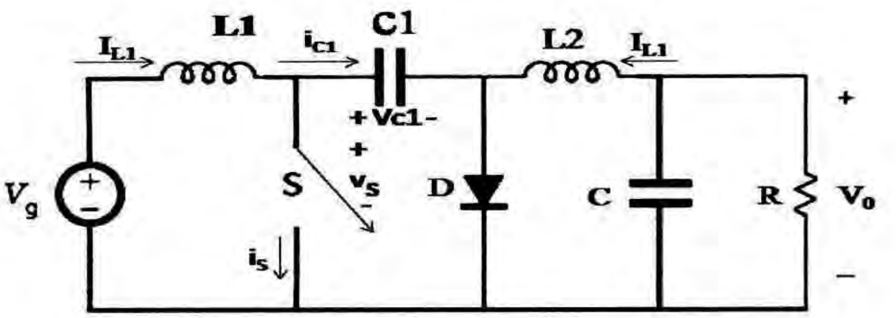


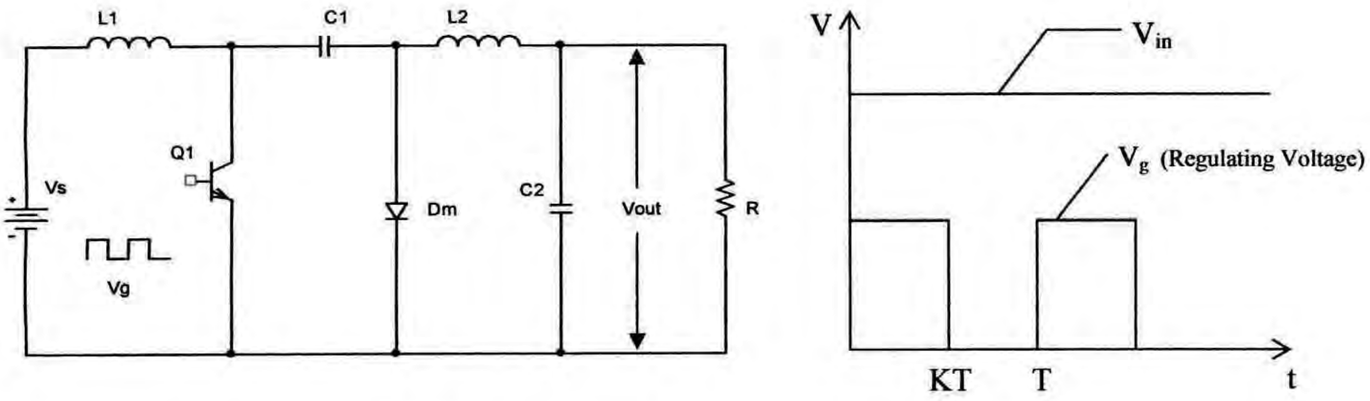
Fig 2.1: Boost - Buck (Ćuk) Converters wired in series

The Cûk converter shown in Fig 2.1, consists of a dc input voltage source Vg, an input inductance L1, controllable switch S, energy transfer capacitance C1, diode D, filter inductance L2, filter capacitance C and load resistance R. An important advantage of Ćuk topology is a continuous current at both the input and the output of the converter. Disadvantages of the Ćuk converter are a high number of reactive components and high current stresses on the switch, the diode and the capacitor.

2.2.1 Analysis of Cũk Converter

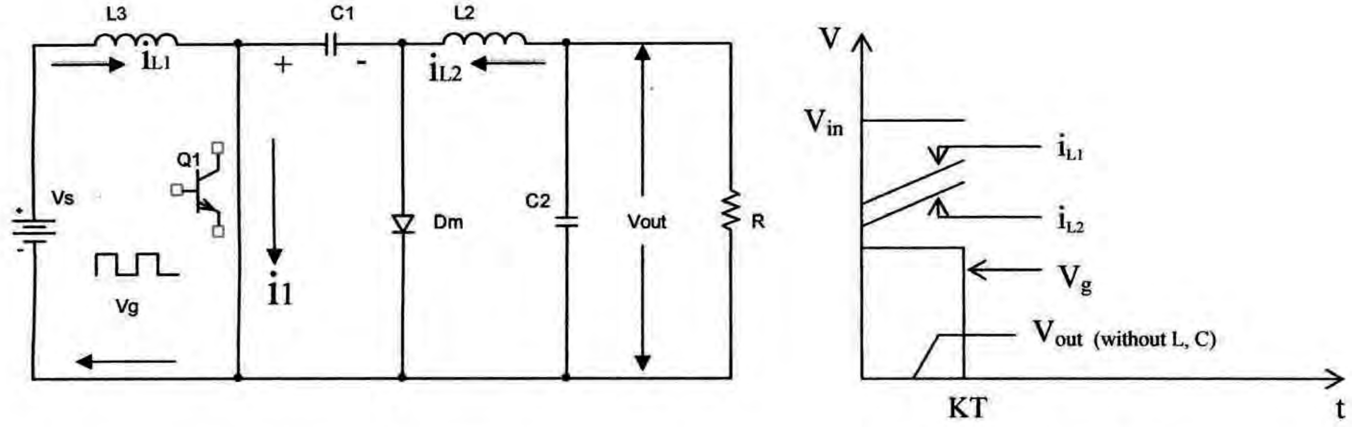
Ćuk converter is the modified form of Boost-Buck regulator having the capability to regulate the voltage in both buck and boost way. The operation can be explained with the help of Fig 2.2. In a Ćuk converter there are two modes of operation.

Mode 1 begins when transistor Q1 in turned on at t = 0. The current through inductor L1 rises. At the same time, the voltage of the capacitor C1 reverse biases diode D_m and turns it off. The capacitor discharges its energy to the circuit formed by C1, C2, L2 and the load.



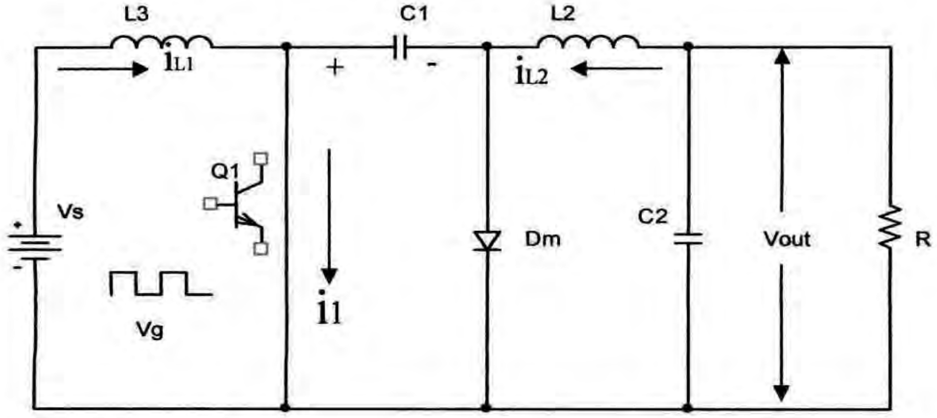
(a) Circuit diagram-Ćuk Converter

Waveform



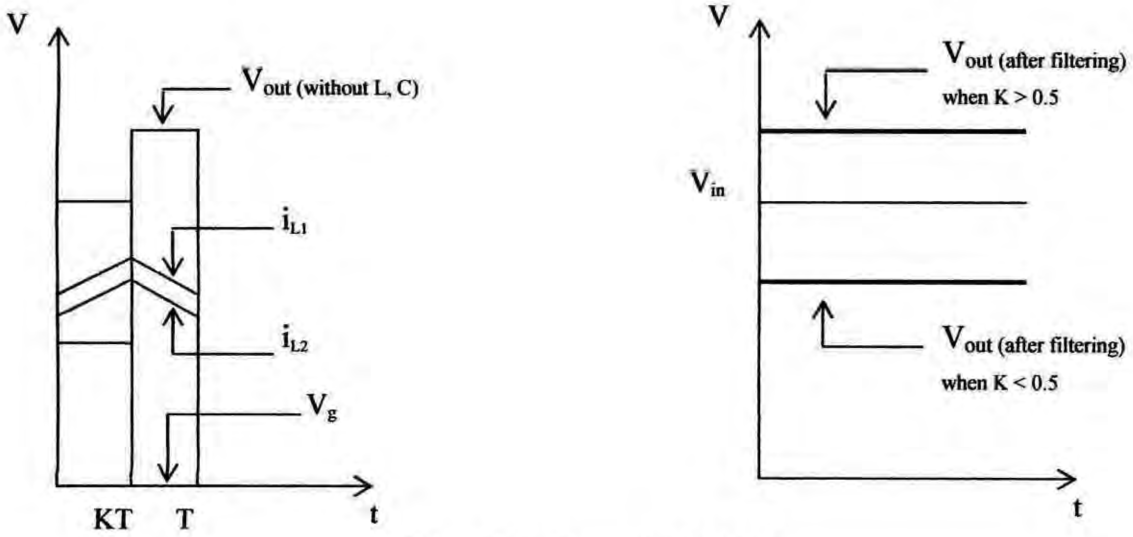
(b) Mode –1 (time = 0 to KT)

Waveform for Mode-1



(c) Mode –2 (time = KT to T)

Fig 2.2: Analysis of Ćuk Converter operation; (a) Circuit diagram and waveform, (b) Mode-1 of operation, (c) Mode-2 of operation. ……. (cont'd)



(d) Waveforms for Mode-2

Fig 2.2: Analysis of Ćuk Converter operation; (a) Circuit diagram and waveform, (b) Mode-1 of operation, (c) & (d) Mode-2 of operation.

Mode 2 begins when transistor Q1 is turned off at $t = t_1$. The capacitor C1 is charged from input supply and the energy stored in inductor L2 is transferred to the load. The diode D_m and transistor Q1 provide a synchronous switching action. The capacitor C1 is the medium for transferring energy from the source to the load.

Assuming that that current of inductor L1 rises linearly from I_{L11} to I_{L12} in time t_1,

$$V_s = L_1 \frac{I_{L12} - I_{L11}}{t_1} = L_1 \frac{\Delta I_1}{t_1}$$

Or

$$t_1 = \frac{\Delta I_1 L_1}{V_s}$$

And due to the charged capacitor C1, the inductor L1 current falls linearly from I_{L11} to I_{L12} in time t_2,

$$V_s - V_{c1} = \frac{-\Delta I_1 L_1}{t_2}$$

Or $$t_2 = \frac{-\Delta I_1 L_1}{V_s - V_{c1}}$$

Where V_{c1} is the average voltage of capacitor C1 and $\Delta I_1 = I_{L12} - I_{L11}$

From the above equations,

$$\Delta I_1 = \frac{V_s t_1}{L_1} = \frac{-(V_s - V_{c1})t_2}{L_1}$$

Substituting $t_1 = KT$ and $t_2 = (1-K)T$ the average voltage of capacitor C1 is V_{c1}.

$$V_{c1} = \frac{V_s}{1-K}$$

Assuming that the current of filter inductor L2 rises from I_{L21} to I_{L22} in time t_1.

$$V_{c1} + V_a = L_2 \frac{I_{L22} - I_{L21}}{t_1} = \frac{\Delta I_2}{t_1}$$

Or $$t_1 = \frac{\Delta I_2 L_2}{V_{c1} + V_a}$$

And the current of inductor L2 falls linearly from I_{L22} to I_{L21} in time t_2

$$V_a = -L_2 \frac{\Delta I_2}{t_2}$$

Or

$$t_2 = -L_{12} \frac{\Delta I_2}{V_a}$$

Where $\Delta I_2 = I_{L22} - I_{L21}$, From the above,

$$\Delta I_2 = \frac{(V_{c1} + V_a)t_1}{L_2} = \frac{-V_a t_2}{L_2}$$

Substituting $t_1 = KT$ and $t_2 = (1-K)T$ the average voltage of capacitor C1 is V_{c1}

$$V_{c1} = \frac{-V_a}{K}$$

Thus the value of output voltage can be found out as

$$V_a = \frac{-KV_s}{1-K}$$

Assuming a lossless circuit, $V_s I_s = -V_a I_a = V_s I_a K/(1-K)$ and the average input current

$$I_s = \frac{KI_a}{1 - K}$$

Resonant Inverter

A resonant inverter is a high frequency inverter used in many applications. Resonant switching topologies are the next generation of power conversion circuits, when compared to traditional pulse width modulation (PWM) topologies. Resonant-based supplies are more efficient than their PWM counterparts. This is due to the zero current and/or zero voltage transistor switching that is inherent in a resonant supply design.

This feature also provides an additional benefit of eliminating undesireable electromagnetic radiation normally associated with switching supplies (Fig 2.3).

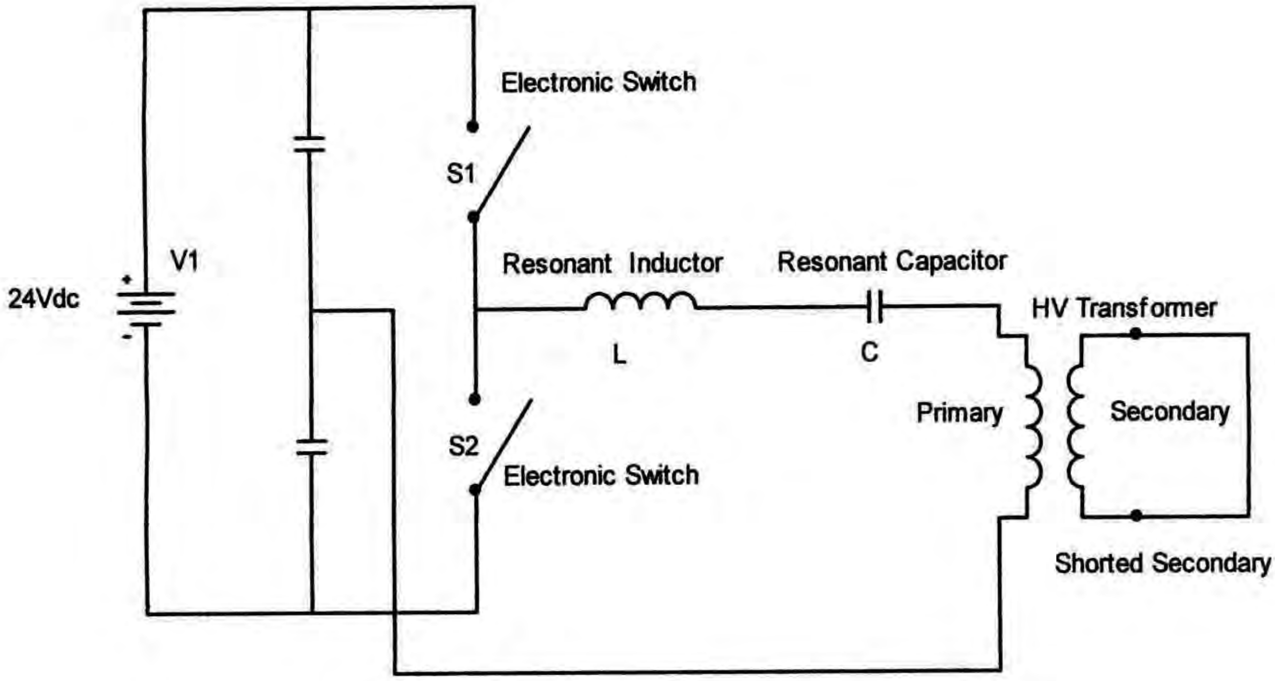
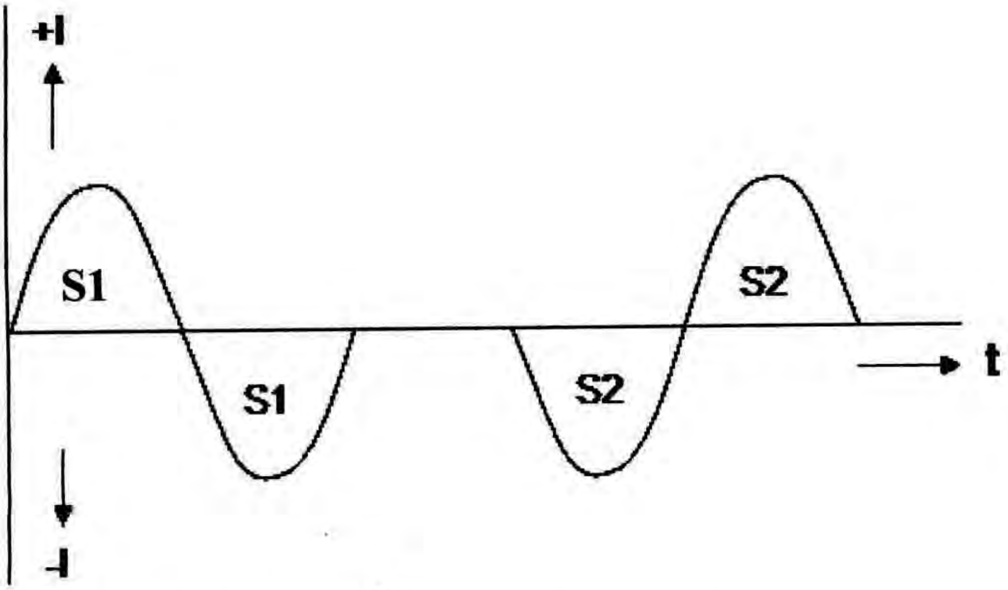


Fig 2.3(a): Resonant Inverter



(b)

Fig 2.3(b): Current wave shape of Resonant Inverter

$$\text{Where } I = V\sqrt{\frac{C}{L}} \quad \text{and} \quad f = \frac{1}{2\pi\sqrt{LC}}$$

2.3.1 Series Resonant Inverters

The series resonant inverters are based on resonant current oscillation. The resonating components and switching device are placed in series with the load to from an under damped circuit. The current though the switching devices falls to zero due to the natural characteristics of the circuit. If the switching element is a thyristor, it is said to be self commutated. This type of inverter produces a sinusoidal or near to sinusoidal wave at a high output frequency, ranging from 200 Hz to 100 kHz, and is commonly used in relatively fixed output applications (e.g. induction heating, sonar transmitter, fluorescent lighting, or ultrasonic generators). Due to the high switching frequency, the size of resonating components is small.

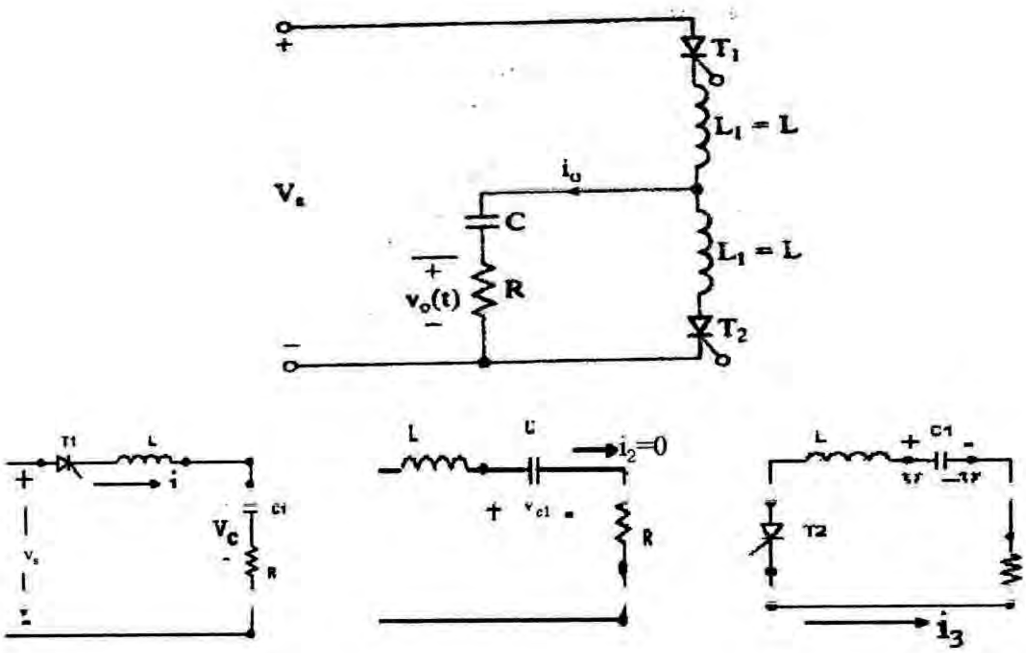
There are various configurations of series resonant, inverters, depending on the connections of the switching devices and load. The series inverters may be classified into two categories:

a. Series resonant inverters with unidirectional switching.

b. Series resonant inverters with bidirectional switches.

Figure 2.4 shows the circuit diagram of a simple series inverter using two unidirectional thyristor switches. When thyristor T_1 is fired a resonant pulse of current flows though the load and the current falls to zero at $t = t_{1m}$ and T_1 is self commutated. Firing of thyristor T_2 causes a reverse resonant current though the load and T_2 is also self commutated.

The circuit operation can be divided into three modes and the equivalent circuits are shown in following figure. The gating signals for thyristors and the waveforms for the load current and capacitor voltage are shown in Fig 2.5



Mode 1 Mode 2 Mode 3

Fig 2.4: Series resonant inverters with unidirectional switching

and Modes of operation of series resonant inverter

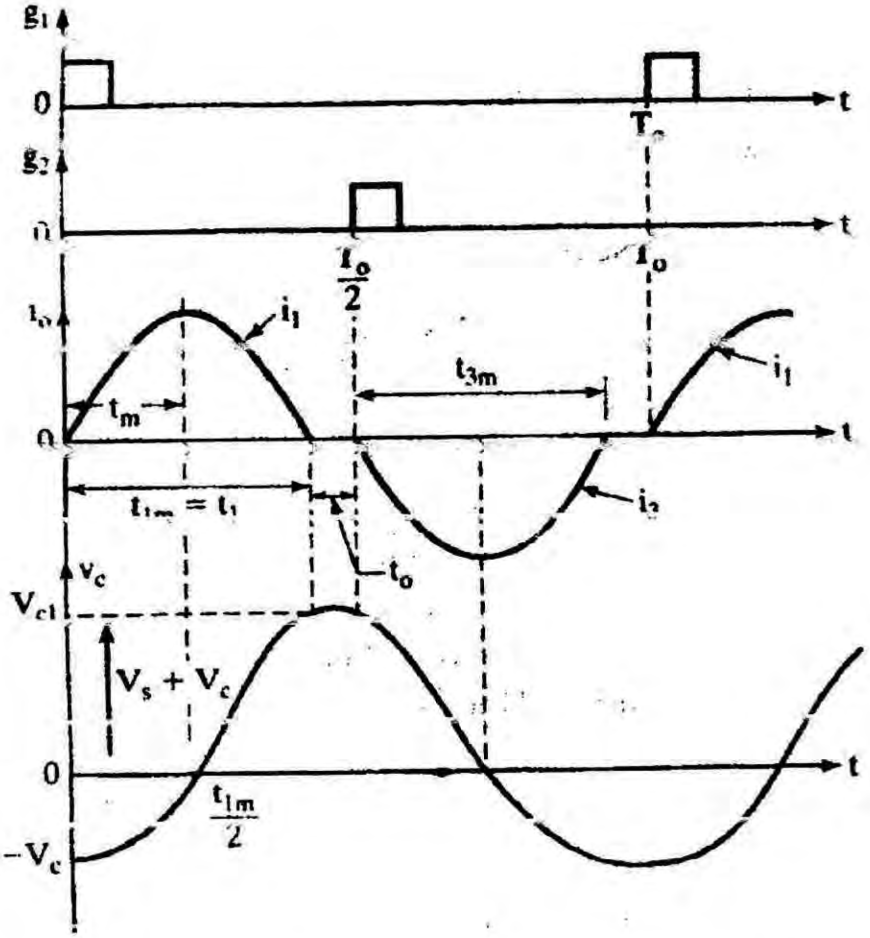


Fig 2.5: Gating signals for thyristors and the waveforms of Resonant Inverters with Unidirectional Switches

The series resonant circuit formed by L, C, and load (assumed resistive) must be underdamped, requiring

$$R^2 < \frac{4L}{C}$$

Mode 1. This mode begins when T_1 is fired and a resonant pulse of current flows though T_1 and the load (Fig 2.6). The instantaneous load current for this mode is described by

$$L\frac{di}{dt}+Ri_1+\frac{1}{C}\int i_1dt+v_{c1}(t=0)=V_S$$

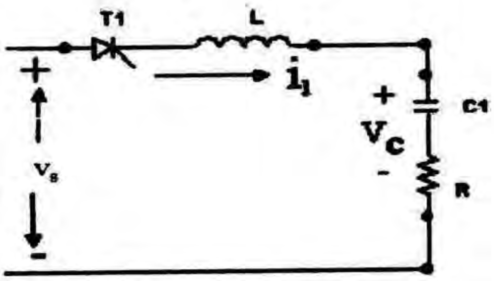


Fig 2.6: Mode I of operation

With initial conditions $i_1(t = 0) = 0$ and $v_{c1}(t = 0) = -V_c$, Because the circuit is underdamped, the solution of the above equation yields

$i_1(t)=A_1e^{-tR/2L}\sin\omega_r t$; Where ω_r is the resonant frequency and

$$\omega_r=\left(\frac{1}{LC}-\frac{R^2}{4L^2}\right)^{1/2}$$

The constant A_1 in the above equation can be evaluated from the initial condition:

$$\left.\frac{di_1}{dt}\right|_{t=0} = \frac{V_S+V_C}{\omega_r L} = A_1$$

and $i_1(t) = \frac{V_S+V_C}{\omega_r L}e^{-\alpha t}\sin\omega_r t$

Where $\alpha=\frac{R}{2L}$

The time t_m in the above equation when the current i(t) becomes maximum can be found from the condition

$$\frac{di_1}{dt}=0 \qquad \text{or} \qquad \omega_r e^{-\alpha t_m}\cos\omega_r t_m - \alpha e^{-\alpha t_m}\sin\omega_r t_m = 0$$

and this gives

$$t_m = \frac{1}{\omega_r}\tan^{-1}\frac{\omega_r}{\alpha}$$

The capacitor voltage can be found from

$$\begin{aligned} v_{c1}(t) &= \frac{1}{C}\int_0^t i_1(t)\,dt - V_C \\ &= -(V_S + V_C)e^{-\alpha t}(\alpha \sin \omega_r t + \omega_r \cos \omega_r t)\omega_r + V_S \end{aligned}$$

This mode is valid for $0 \le t \le t_{1m} (= \pi / \omega_r)$ and ends when $i_1(t)$ becomes zero at t_{1m}. At the end of this mode,

$$i_1(t=t_{1m})=0$$

and

$$v_{c1}(t=t_{1m}) = V_{C1} = (V_S + V_C)e^{-\alpha\pi/\omega_r} + V_S$$

Mode 2. During this mode thyristors T_1 and T_2 are off redefining the time origin, t = 0, at the beginning of this mode, (Fig 2.7) this mode is valid for $0 \le t \le t_{2m}$

$$i_2(t)=0, \quad v_{c2}(t)=V_{C1} \quad v_{c2}(t=t_{2m})=V_{C2}=V_{C1}$$

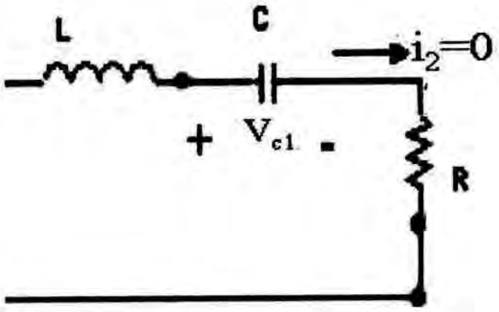


Fig 2.7: Mode 2 of operation

Mode 3. This mode begins when T_2 is switched on and a reverse resonant current flows though the load (Fig 2.8). Let us redefine the time origin t = 0, at the beginning of this mode the load current can be found from

$$L\frac{di_3}{dt} + R_{i3} + \frac{1}{C}\int i_3 dt + v_{c3}(t=0) = 0$$

with initial conditions $i_3(t=0)=0$ and $v_{c3}(t=0) = -V_{C2} = -V_{C1}$.

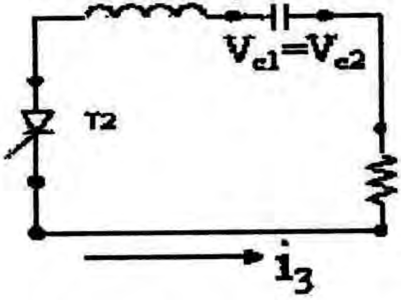


Fig 2.8: Mode 3 of operation

The solution of the above equation gives

$$i_3(t) = \frac{V_{C1}}{\omega_r L} e^{-\alpha t} \sin \omega_r t$$

The capacitor voltage can be found from

$$v_{c3}(t) = \frac{1}{C}\int_0^t i_3(t)\, dt - V_{C1}$$

$$= -V_{C1} e^{-\alpha t}(\alpha \sin \omega_r t + \omega_r \cos \omega_r t) / \omega_r$$

This mode is valid for $0 \le t \le t_{3m} = \pi / \omega_r$ and ends when *i₃t* becomes zero. At the end of this mode,

$$i_3(t=t_{3m})=0$$

and in the steady state,

$$v_{c3}(t=t_{3m}) = V_{C3} = V_C = V_{C1} e^{-\alpha\pi/\omega_r}$$

From the above equations,

$$V_C = V_S \frac{1+e^{-z}}{e^{z}-e^{-z}} = V_S \frac{e^{z}+1}{e^{2z}-1} = \frac{V_S}{e^{z}-1}$$

$$V_{C1} = V_S \frac{1+e^{z}}{e^{z}-e^{-z}} = V_S \frac{e^{z}(1+e^{z})}{e^{2z}-1} = \frac{V_S e^{z}}{e^{z}-1}$$

Where, $z=\alpha\pi/\omega_r$ substituting V_C from the above equations to V_S gives

$$V_S+V_C=V_{C1}$$

The load current $i_1(t)$ must be zero and T_1 must be turned of before T_2 is fired. Otherwise a short circuit condition results though the thyristors and dc supply. There fore the available off time t_{2m} (= t_{off}), know as the 'dead zone' must be greater than the turn off time of thyristors t_q,

$$\frac{\pi}{\omega_0} - \frac{\pi}{\omega_r} = t_{off} > t_q$$

Where ω_0 is the frequency of the output voltage in rads per second. This equation indicates that the maximum possible output frequency is limited to

$$f_0 \le f_{\max} = \frac{1}{2(t_q + \pi / \omega_r)}$$

The resonant inverter circuit in the above figure is simple; however, it gives the basic concept and describes the characteristic equations which can be applied to other types of resonant inverters. The power flow from the dc supply is discontinuous. The dc supply has a high peak current and would contain harmonics.

An improvement of the basic inverter can be made if inductors are closed coupled as shown in the following (Fig 2.9):

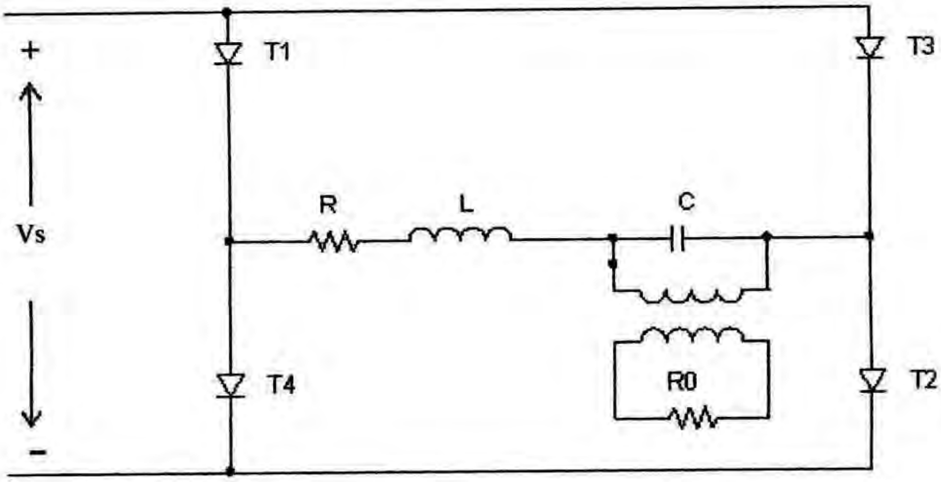


Fig 2.9: Full bridge series resonant inverter

When T_1 is fired and current $i_1(t)$ begins to rise the voltage across L_1 is positive with polarity as shown, the induced voltage on L_2 now adds to the voltage of C in reverse biasing T_2 and T_2 can be turned off. The result is that firing of one thyristor turns off the other ever before the load current reaches zero.

The drawback of high pulsed current from the dc supply can be overcome in a bridge configuration, as shown in Fig 2.9. where $L_1 = L_2$ and $C_1 = C_2$. The power is drawn from the dc source during both halfcycles of output voltage one half of the load current is supply by capacitor C_1 or C_2 and the other half by the dc source.

A full bridge inverter which allows higher output power(as shown above) when T_1 and T_2 are fired, a positive resonant current flows though the load and when T_3 and T_4 are fired, a negative load current flows. The supply current is continuous but pulsating.

The resonant frequency and available dead-zone depend on the load; and for this reason resonant inverters are most suitable for fixed load applications. The inverter load (or resistor R) could also be connected in parallel with the capacitor.

2.3.2 Series Resonant Inverters with Bidirectional switches

The performance of series inverters can be significantly improved by connecting an anti-parallel diode across a device as shown in Fig 2.10. When device Q_1 is fired a resonant pulse of current flows and Q_2 is self commutated at $t = t_1$. However, the resonant oscillation continues though diode D_1 until the current falls again to zero at the end of a cycle. The waveform for the load current and the conduction intervals of the power devices are also shown in Fig 2.11.

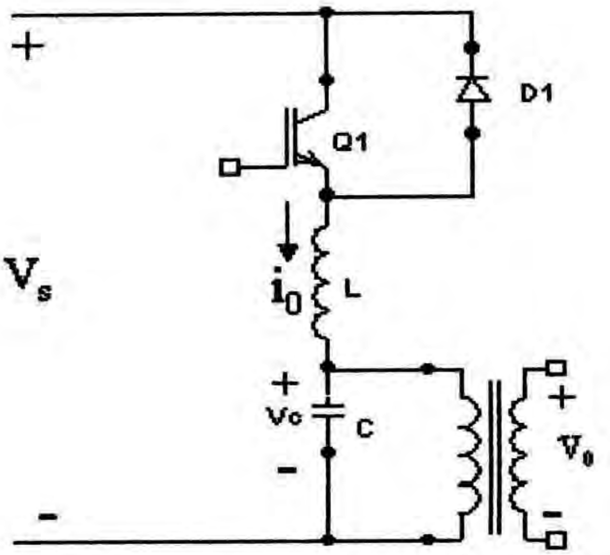


Fig 2.10: Series Resonant Inverters with bidirectional switch

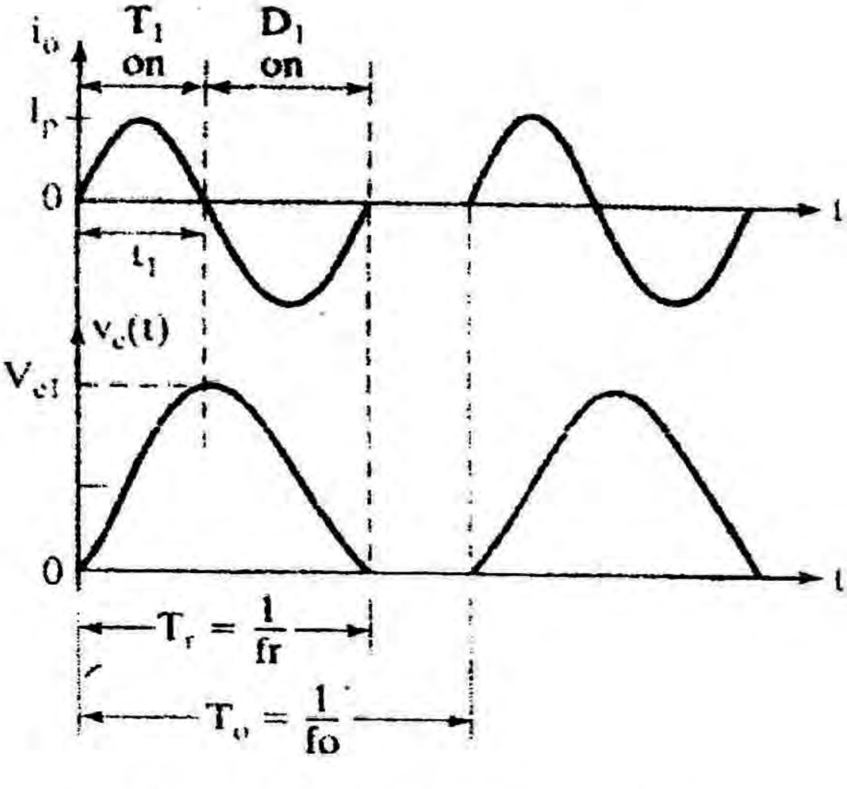


Fig 2.11: Waveforms of Series Resonant Inverter

If the conduction time of the diode is greater than the turn off time of the device, there is no need of a dead-zone and the output frequency f_0 is the same as the resonate frequency f_r is given by the relation,

$$f_0 = f_r = \frac{\omega_r}{2\pi}$$

Where, f_r is the resonating frequency of the series circuit. The minimum devices switching time t_s consists of delay time, rise time, fall time and storage time that $t_{sw}=t_d+t_r+t_f+t_s$. Thus , the maximum inverter frequency is given by

$$f_{S(\max)} = f_r = \frac{1}{2t_{sw}}$$

and f_0 should be less than $f_{s(\max)}$.

If the switching device is a thyristor and t_q is it's turn off time. Then maximum inverter frequency is given by

$$f_{S(\max)} = \frac{1}{2t_q}$$

The half bridge and the full-bridge configuration of inverters are shown Fig 2.12 and Fig 2.13. The inverters can be operated in non-overlapping and overlapping modes. In a non-overlapping mode the firing of a transistor device is delayed until the last current oscillation though a diode has been completed. In an overlapping mode, a device is fired while the current in the diode of the other part is still conducting as shown in the figure. Although overlapping operation increases the output frequency, the output power is increased.

The maximum frequency of the inverter is limited due to the turn off or commutation requirement of thyristors typically 12 to 20μs, whereas transistors require only a microsecond or less. The transistor inverter can operate at the resonant frequency.

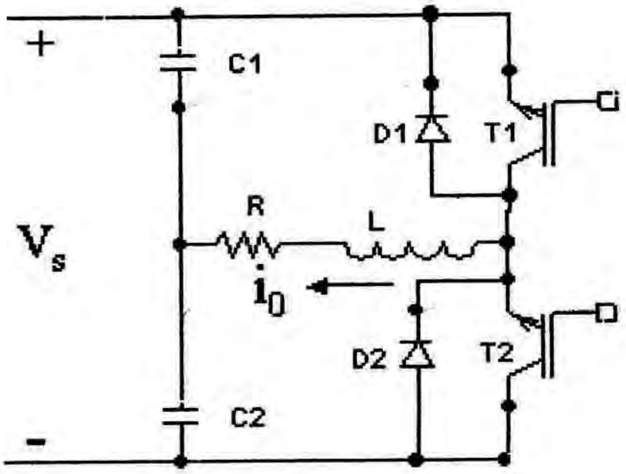


Fig 2.12(a): Circuit of Half-bridge series inverters with bidirectional switches

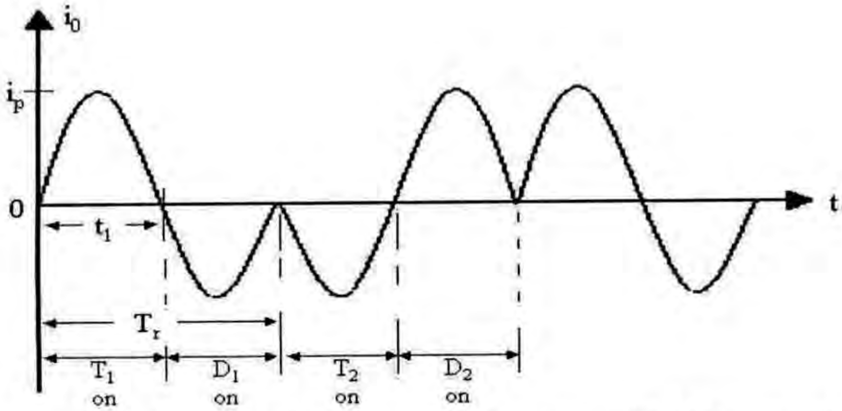
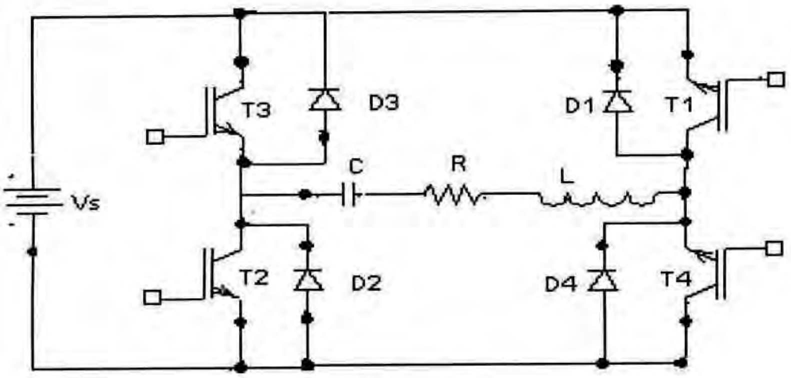
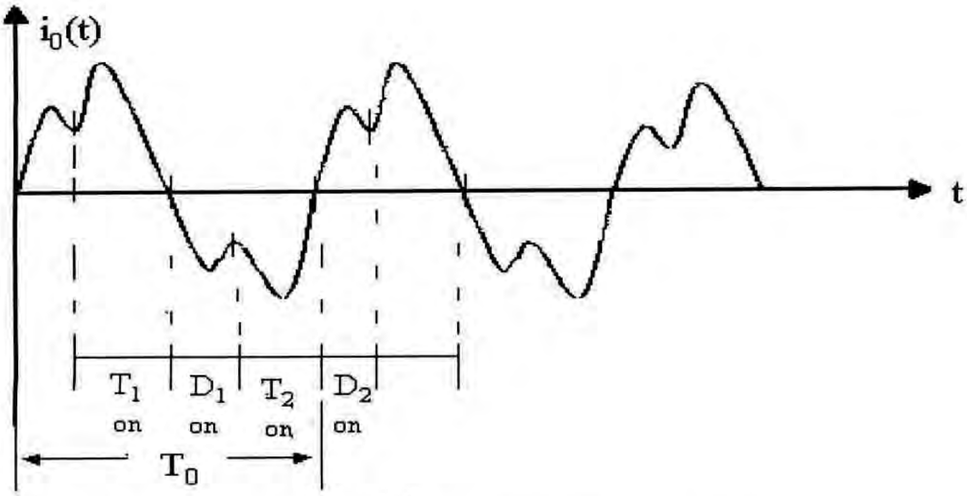


Fig 2.12(b) : Waveform of Half-bridge series inverters with bidirectional switches



(a)



(b)

Fig 2.13: Full-bridge series inverter with bidirectional switches

(a) Circuit (b) Waveform

2.3.3 Frequency Response of Series Resonant Inverters

It can be noticed from the waveforms of Figs 2.12(b) and 2.13(b) that varying the switching frequency f_s (= f_0) can vary the output voltage. The frequency response of the voltage gain exhibits the gain limitations against the frequency variations. There are three possible connections of the load resistance R in relations to the resonating components: (1) series (2) parallel and (3) series parallel combination.

In Fig 2.9, the load resistance R forms a series circuit with the resonating components L and C. The equivalent circuit is shown in Fig 2.14:

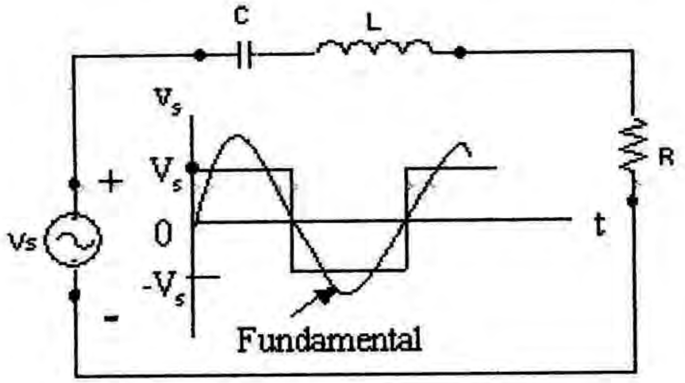


Fig 2.14: Series loaded circuit and input voltage

The voltage gain of the circuit is given by,

$$G(j\omega) = \frac{V_0}{V_i}(j\omega) = \frac{1}{1 + j\omega L/R - j/(\omega CR)}$$

Let $\omega_0 = 1/\sqrt{LC}$ be the resonant frequency, and $Q_s = \omega_0 L/R$ be the quality factor. Substituting L, C, R in terms of Q_s and ω_0, we get

$$G(j\omega) = \frac{v_0}{v_i}(j\omega) = \frac{1}{1 + jQ_S(\omega/\omega_0 - \omega_0/\omega)} = \frac{1}{1 + jQ_S(u - 1/u)}$$

Where, $u = \omega/\omega_0$.

The magnitude of G ($j\omega$) can be found from

$$|G(j\omega)| = \frac{1}{[1+Q_S{}^2(u-1/u)^2]^{1/2}}$$

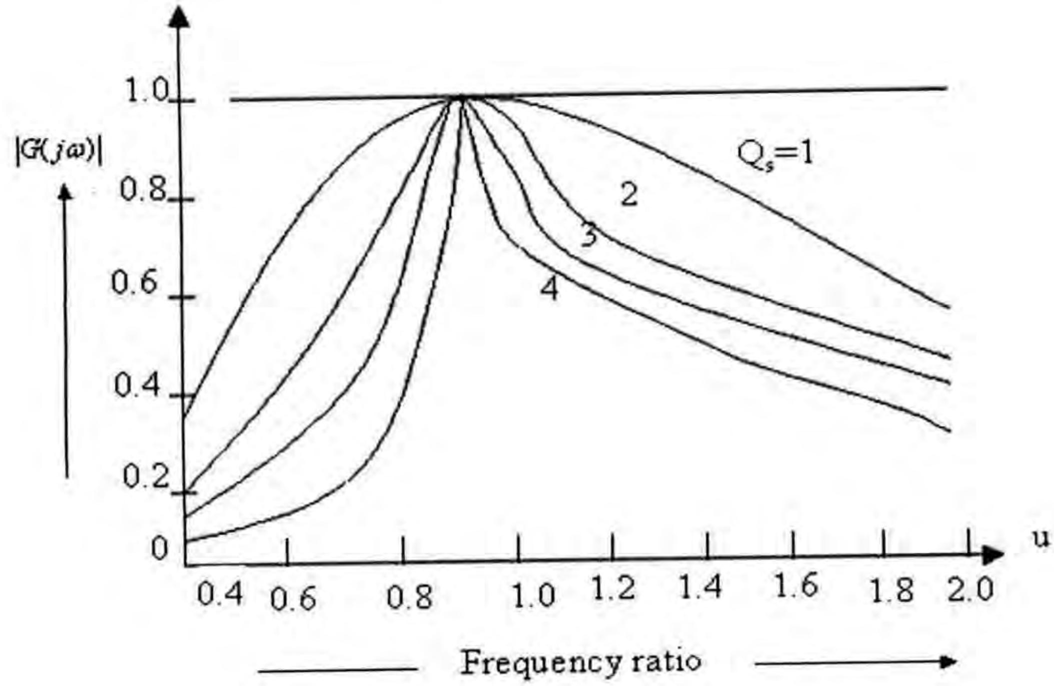


Fig 2.15: Frequency response of series loaded circuit

The above Fig (Fig 2.15) shows the magnitude plot of $|G(j\omega)|$ for $Q_s = 1$ to 4. For a continuous output voltage the switching frequency should be greater than the resonant frequency f_0. If the inverter operates near resonance and a short circuit occurs at the load, the current rises to a value especially at a high-load current. However the current can be controlled by raising the switching frequency. The current though the switching device decreases as the load current decreases, thereby having lower on-state conduction losses and a high efficiency at a partial load. The series inverter is most suitable for high voltage low-current applications. The maximum output occurs at resonance and the maximum gain for $u = 1$ is $|G(j\omega)|_{\max} = 1$

Under no-load conditions, R= ∞ and $Q_s = 0$. Thus the curve would simply be a horizontal line. That is for $Q_s = 1$, the characteristic has a poor selectivity and the output voltage changes significantly from no-load to full-load conditions, thereby yielding poor regulation. The resonant inverter is normally used in applications requiring only a fixed output voltage. However, some no- load regulations can be obtained by time ratio control at frequencies lower than the resonant (shown in the above figure). This type of control have two disadvantages: (1) it limits how far the operating frequency can be varied up and down from the resonant frequency, and (2) due to a low Q- factor, it requires a large change in frequency to realize a wide range of output voltage control.

2.3.4 Battery and Inverter System

In a stand alone alternate energy system battery and inverter are integral part of the system. If a gas or diesel generator is already in use, a battery and inverter subsystem should be an active consideration. This subsystem allows to achieve the following benefits:

a. AC power is available 24 hours a day with the flick of a switch or instantaneously as per design.
b. The generator can be run at convenient times for direct AC power and battery charging.
c. Generator operation is more efficient.
d. Energy costs are lower because generator run time is reduced.
e. Generator capacity is better utilized as a result of battery storage.

2.4 Design of Cûk Regulator fed Resonant Inverter

The design of Cûk Regulator fed Resonant Inverter with control circuitry as designed for the proposed operation of remote area telecom system is described in the following section.

2.4.1 Cûk converter

A number of DC-DC converter circuits are known that can increase or decrease the magnitude of the DC voltage and/or invert its polarity. Fig 2.16 illustrates a Ćuk converter used DC-DC converter circuit, along with it's conversion ratio. In this example, the switch can be realized using a power MOSFET or IGBT and a diode (Fig 2.17).

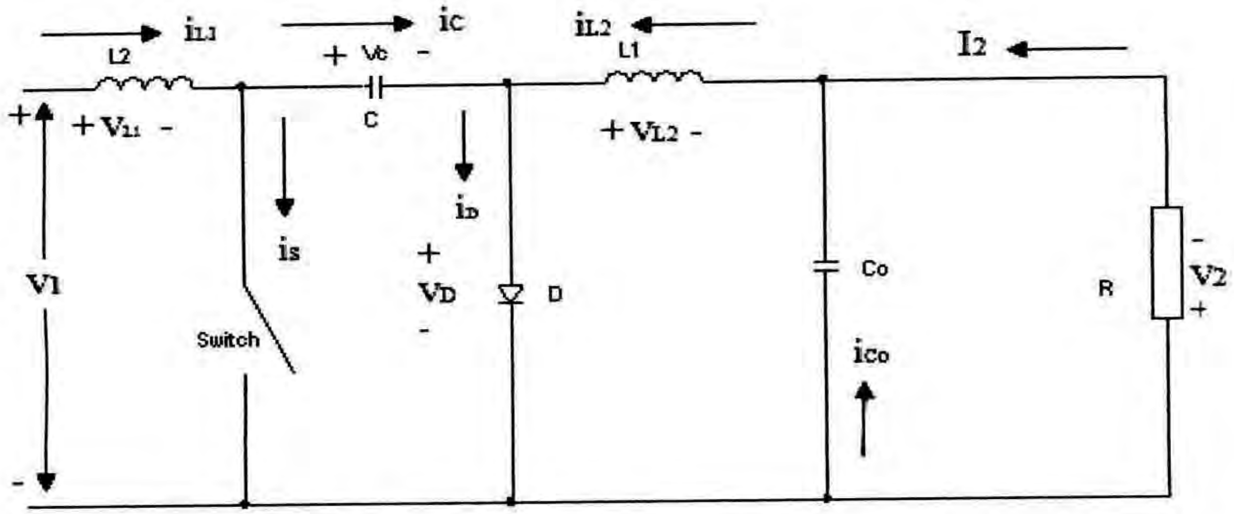


Fig 2.16: Ćuk (Boost and Buck) Converter using conventional switch

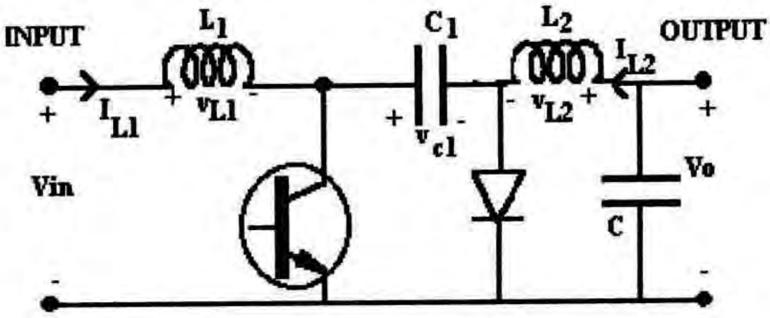


Fig 2.17: Ćuk (Boost and Buck) Converter using IGBT

The ideal conversion ratio M(D) of Ćuk converter is given by;

$$M(D) = \frac{V_0}{\mathrm{Vin}} = \frac{V_0}{\mathrm{Vc}} \cdot \frac{\mathrm{Vc}}{\mathrm{Vin}} = \frac{D}{1-D} \quad \text{.........} (1)$$

The Ćuk converter shown in Fig 2.16, consists of a dc input voltage source Vg, an input inductance L_1, controllable switch S, energy transfer capacitance C_1, diode D, filter inductance L_2, filter capacitance C and load resistance R. An important advantage of Ćuk topology is a continuous current at both the input and the output of the converter. Disadvantages of the Ćuk converter are a high number of reactive components and high current stresses on the switch, the diode and the capacitor.

The Ćuk regulator use only one transistor, employing only one stage conversion, and require inductors or capacitors for energy transfer. Due to current handling limitation of a single transistor, the output power of these regulators is small, typically tens of watts. At a higher current, the size of these components increases causing increased component losses. As a result the efficiency decreases.

It is clear from expression (1) that, if the duty cycle D of the converter is increased, the efficiency of the Ćuk converter increases, but after certain value of D, the efficiency again goes down, which is limited by the transistors current handling capability, component size and component losses. So that, single stage conversion is not sufficient enough to work with a better efficiency. In this research work, two stage conversion has been used for higher efficiency with reduced losses for high voltage gain (Fig 2.18 and 2.19) [23].

The output of the alternative power supply (24V dc) is fed to the input of the Ćuk converter. With 2-stage conversion 240V DC is available at the output of the Ćuk converter as shown in Fig 2.19 [24].

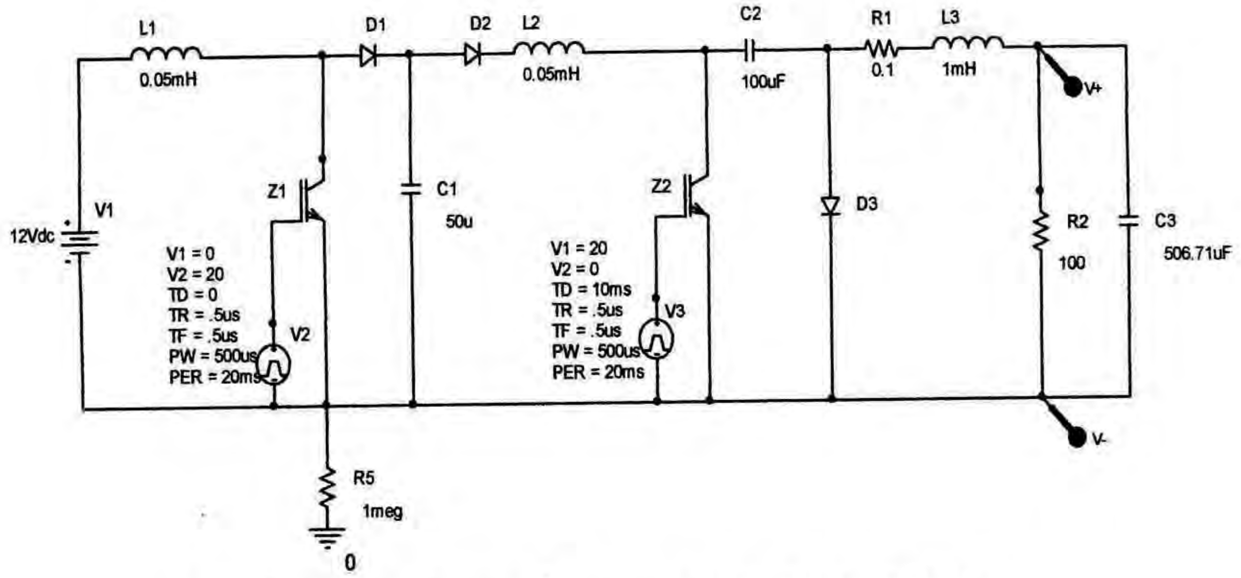


Fig 2.18: Practical 2-stage Ćuk converter circuit using IGBTs

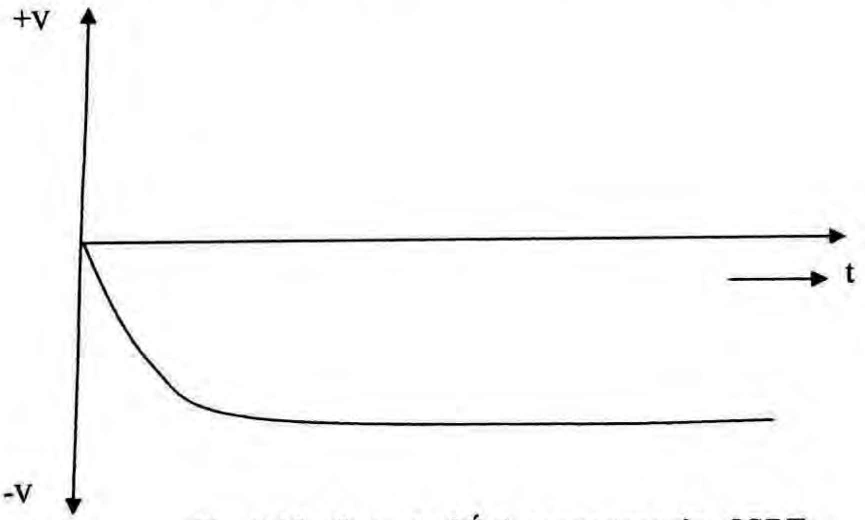


Fig 2.19: Output of Ćuk converter using IGBTs

2.4.2 Resonant Inverter

An inverter with a resonant circuit load is known as resonant inverter. Resonant inverters have many distinct advantages over conventional power converters. Due to the soft commutation of the switches, no turn-off loss or stress is present [27]. They are well suited for high power applications because they allow high frequency operation for equipment size/weight reduction without sacrificing conversion efficiency and imposing extra stress on the switches.

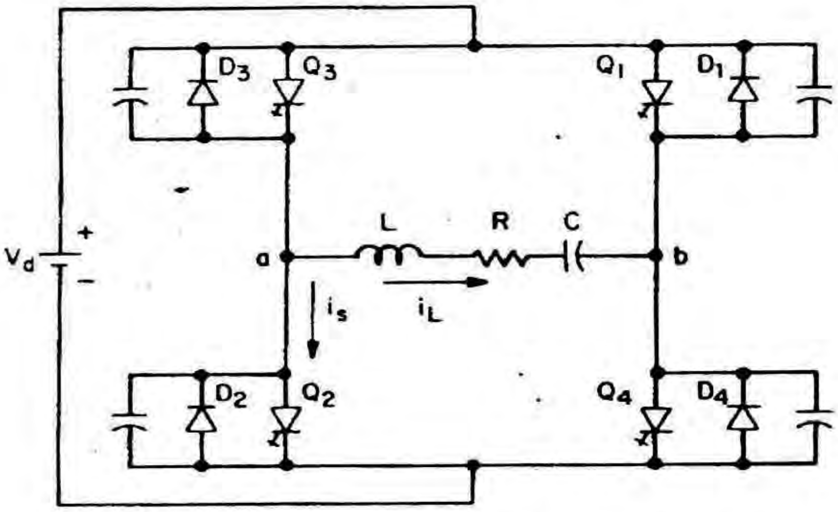


Fig 2.20(a): GTO bridge Resonant Inverter

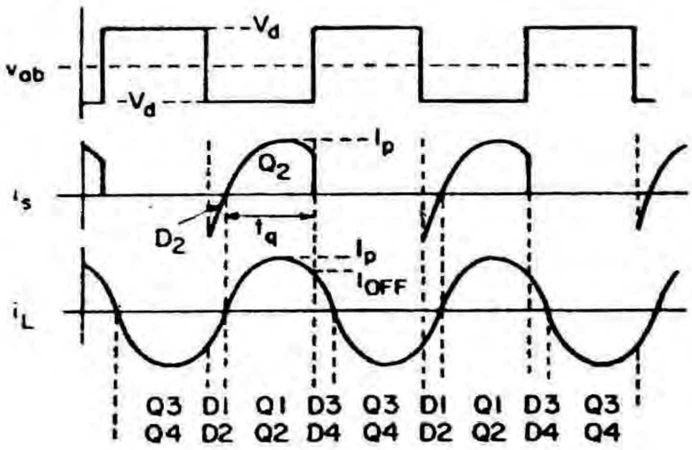


Fig 2.20(b): Inverter current and voltage waves for GTO bridge Resonant Inverter

Fig 2.20(a) shows a full bridge resonant inverter. A unique advantage of this type of inverter is that the device switching loss is eliminated and, therefore, the inverter can be operated at high frequency with high efficiency. Fig 2.20(b) shows the voltage and current waves where the load current harmonics are neglected. In an ordinary inverter, the capacitor energy is dumped into the snubber resistor at turn-on of the device, but here, the energy is absorbed in the main circuit. This types of snubber is called lossless snubber. If the load parameters vary, the natural resonance frequency will also vary [28]. Assuming the load inductance is much greater than the resonant inductor L, the equivalent circuit of the system for the duration of each resonant cycle reduces to that shown in the following Fig (Fig 2.21):

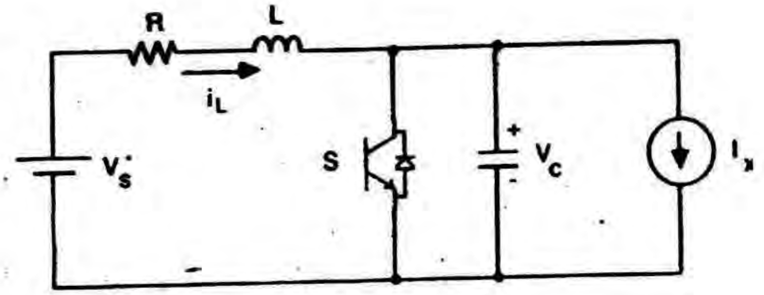


Fig 2.21: Equivalent circuit of resonant inverter

$$\text{Where } I = V\sqrt{\frac{C}{L}} \quad \text{and } f = \frac{1}{2\pi\sqrt{LC}}$$

The maximum resonant frequency is limited by the turn off times of thyristors or transistors. Resonant inverters allow limited regulation of the output voltage. The ZVS and ZCS converters are becoming increasingly popular because they are turned on and off at zero current or voltage, thereby eliminating switching losses. The resonant voltage pulses are produced at the input of the inverter, and the inverter devices are turned on and off at zero voltages.

The output of the Ćuk converter (240 V DC) is fed to the input of the resonant inverter. 230V AC with the wave shape shown in fig 2.23 is available at the output of the resonant inverter. The wave shape is approximately sinusoidal. Minor deviation is for the diodes and transistor conduction delay.

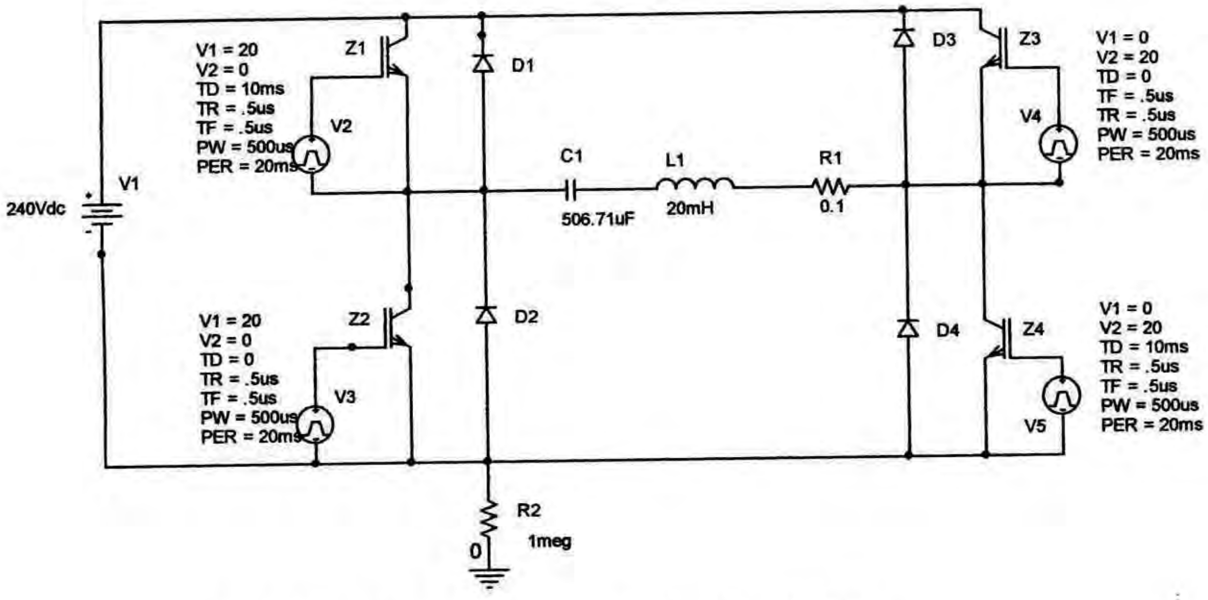


Fig 2.22: Resonant Inverter circuit using IGBTs

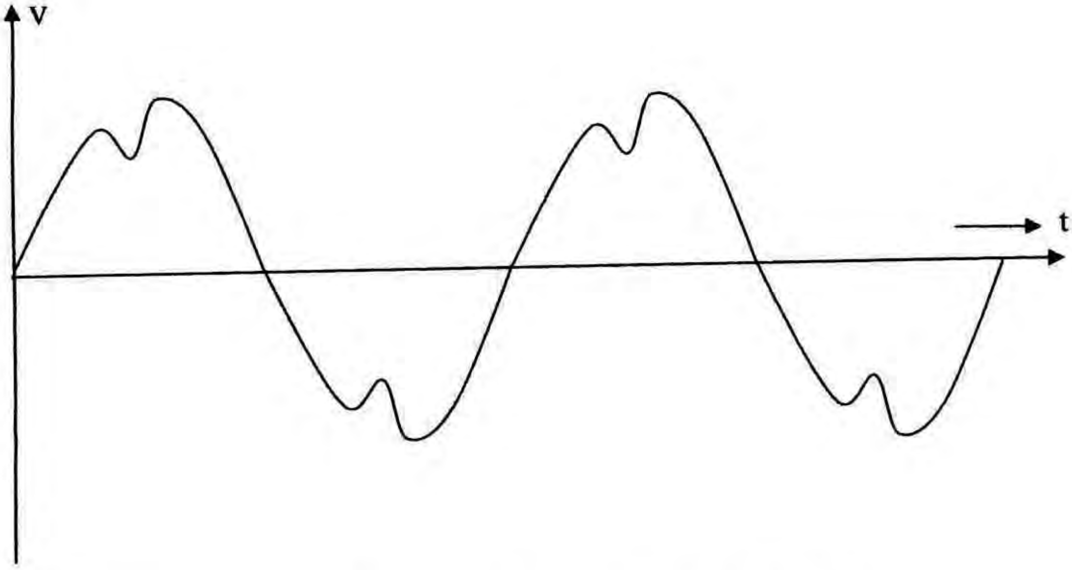


Fig 2.23: Wave shape of Resonant Inverter circuit using IGBTs

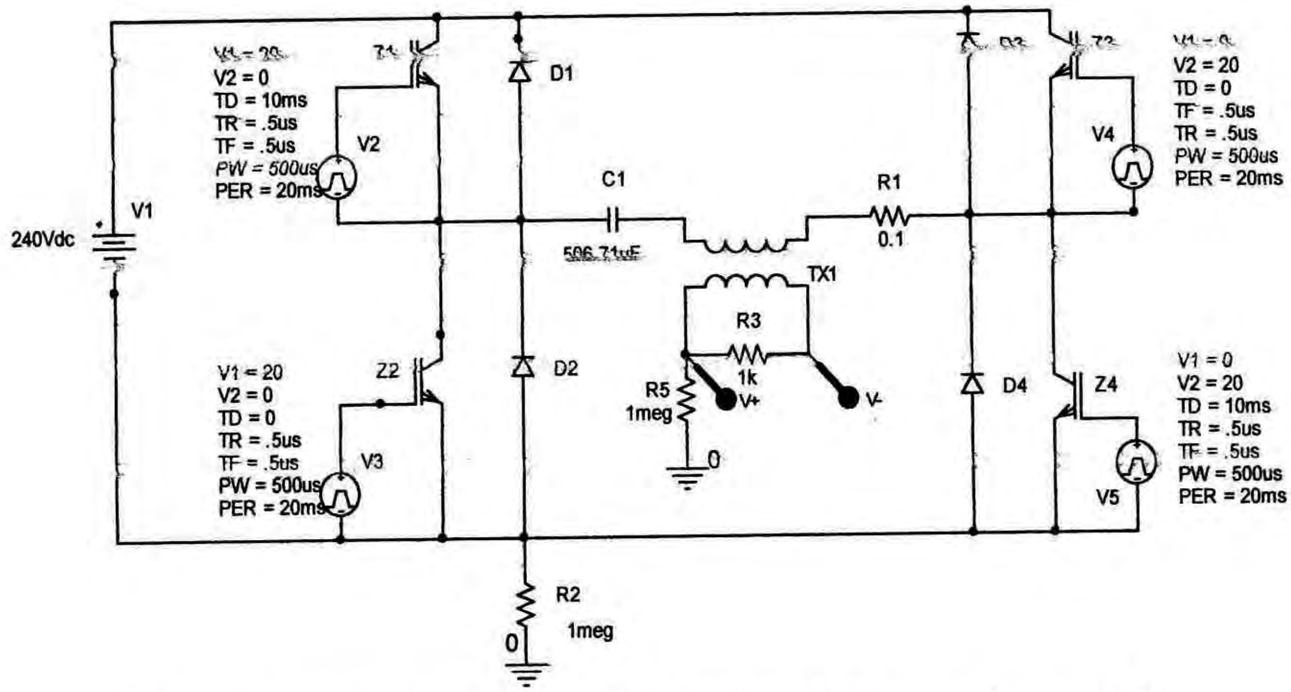
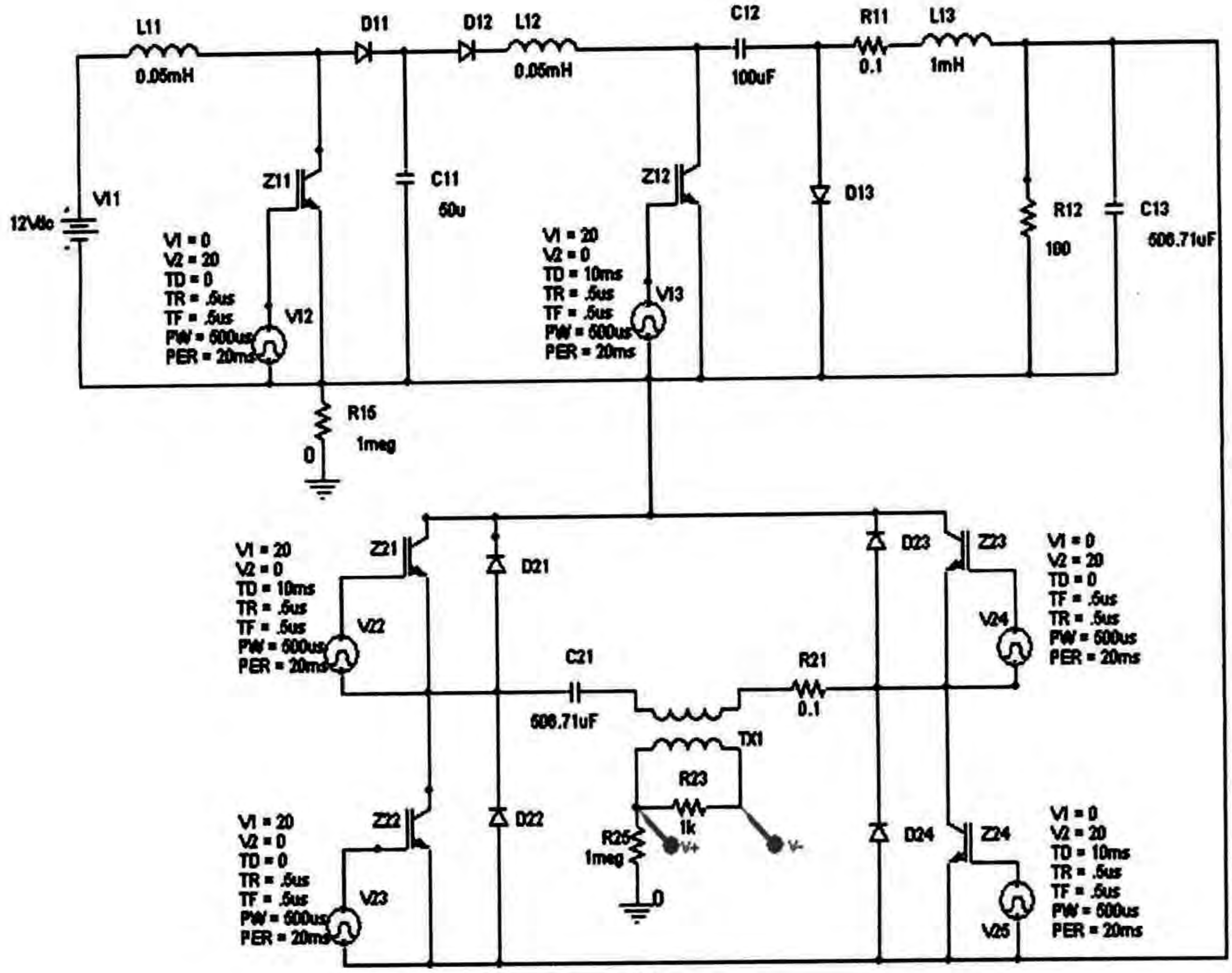


Fig 2.24: Resonant Inverter circuit using IGBTs (Inductor at the output is replaced by a transformer)

2.5 Conventional Ćuk Regulator Fed Resonant Inverter

When the resonant inverter is fed from the Ćuk converter the circuit is like the following Fig (Fig 2.25):



(a)

Fig 2.25: Conventional Ćuk Regulator Fed Resonant Inverter

Following investigations are carried out from a Conventional Ćuk Regulator Fed Resonant Inverter both for single stage and double stages:

a. Output voltage, Input voltage

b. Gate pulses

c. Efficiency

2.5.1 Efficiency variation with duty cycle

Variation of efficiency with duty cycle is shown in Fig.2.26 for single stage Ćuk converter. For assumed values of parasitic resistance and voltage drops of devices, the efficiency is maximum 98% at 0.6 duty cycle. Efficiency of the converter decreases after D = 0.6.

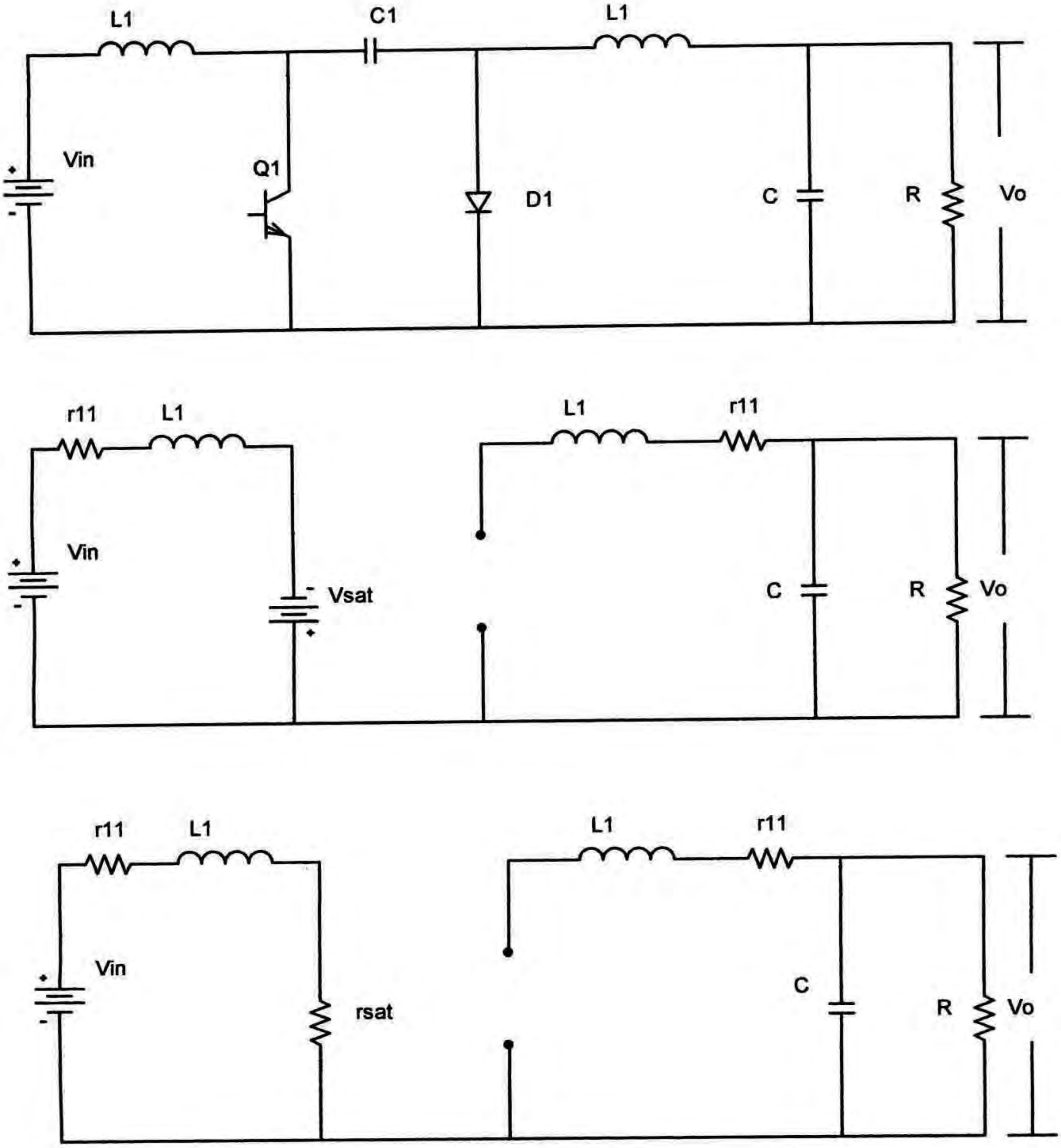


Fig 2.26: Single stage Ćuk converter operation (cont'd)

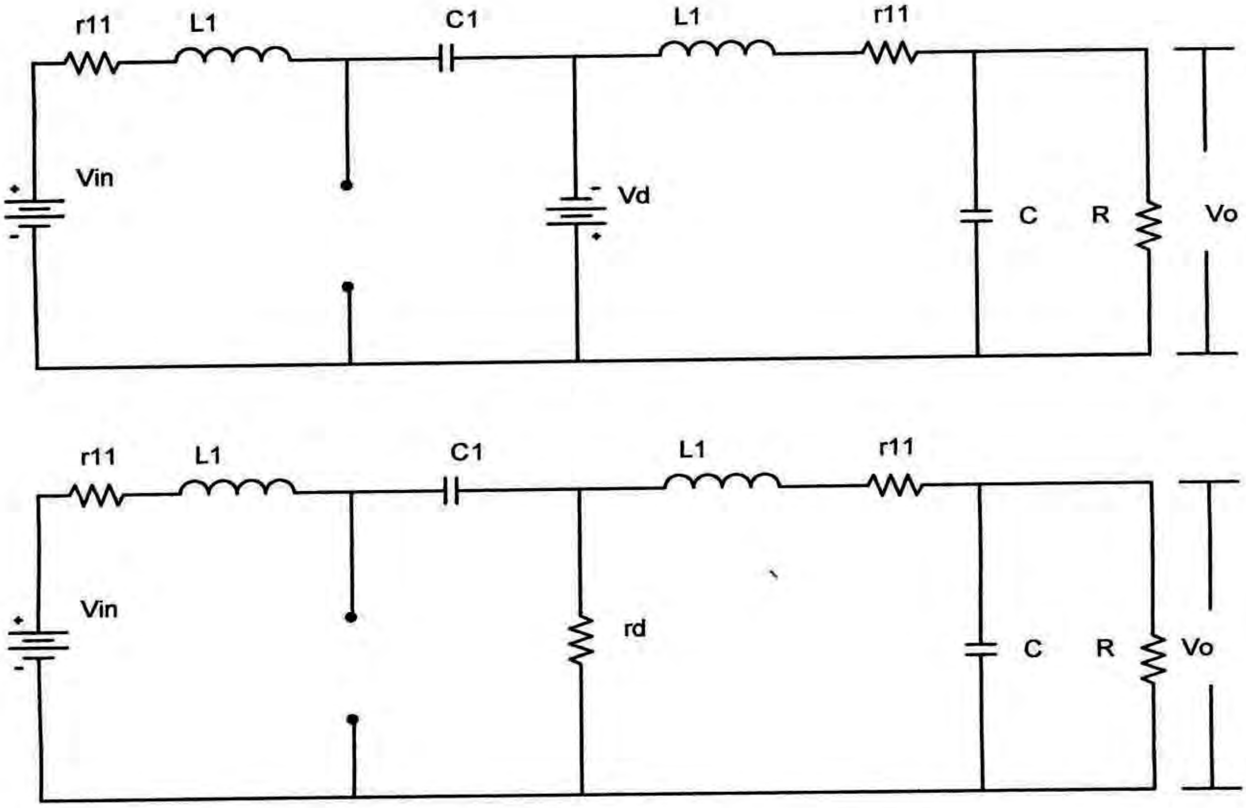


Fig 2.26: Single stage Ćuk converter operation

2.5.2 Efficiency for single stage Ćuk converter

From the Fig 2.26,
$r_1 = r_{l1} + r_{sat}$

and $r_2 = r_{l2} + r_d$

$$\text{Efficiency, } \eta = \frac{I_0^{\,2} R}{I_0^{\,2} R + I_{in}^{\,2} r_1 + I_0^{\,2} r_2}$$

$$= \frac{1}{1 + \frac{I_{in}^{\,2}}{I_0^{\,2}} \cdot \frac{r_1}{R} + \frac{r_2}{R}}$$

$$= \frac{1}{1 + \left(\frac{D}{1 - D}\right)^2 \cdot \alpha_1 + \alpha_2}$$

Where, $\alpha_1 = r_1/R$ and $\alpha_2 = r_2/R$

Now, r_{l1} and r_{l2} are chosen as 0.1Ω

$$\begin{aligned}
\alpha_1 &= r_1/R \\
&= (r_{l1} + r_{sat})/R\,; \qquad r_{sat} \approx 0.9 \text{ and } R = 300\Omega \\
\alpha_1 &= (0.1 + 0.9)/300 \\
&= 0.00333 \\
\alpha_2 &= r_2/R \\
&= (r_{l2} + r_d)/R\,; \qquad r_d \approx 0.9 \text{ and } R = 300\Omega \\
\alpha_2 &= (0.1 + 0.9)/300 \\
&= 0.00333
\end{aligned}$$

$$\text{Efficiency, } \eta = \frac{1}{1 + 0.00333\left(\dfrac{D}{1-D}\right)^2 + 0.00333}$$

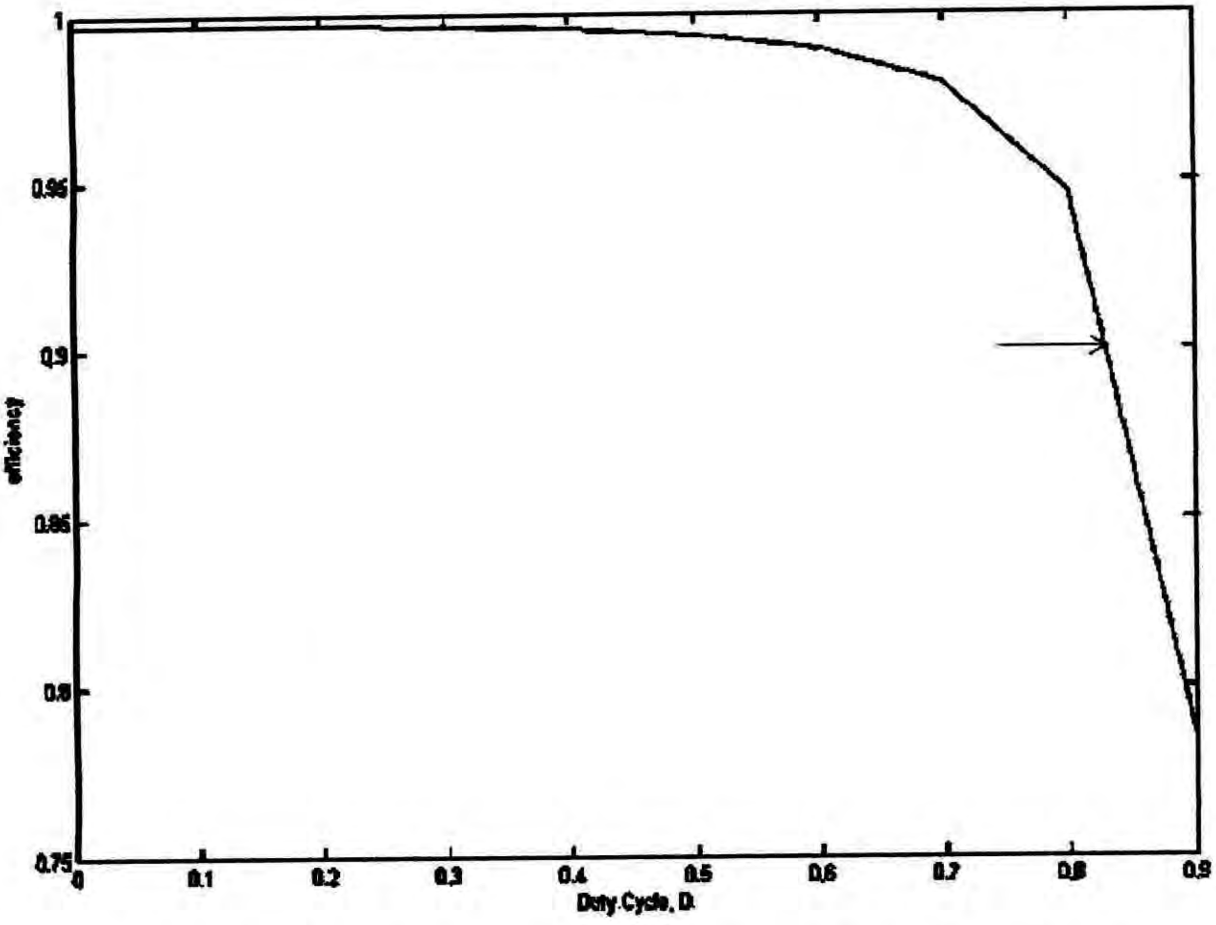


Fig 2.27: Efficiency, η Vs. Duty Cycle, D for single stage Ćuk converter

From the above curve (Fig 2.27) it is clear that for a single stage converter; the maximum efficiency practically attainable is 98.5%; where the value of $D = 0.6$. The input voltage is 24V DC.

The output will be $V_0 = 24 \times \frac{D}{1 - D}$

$$= 24 \times 0.6/0.4$$

$$= 36\text{ V}$$

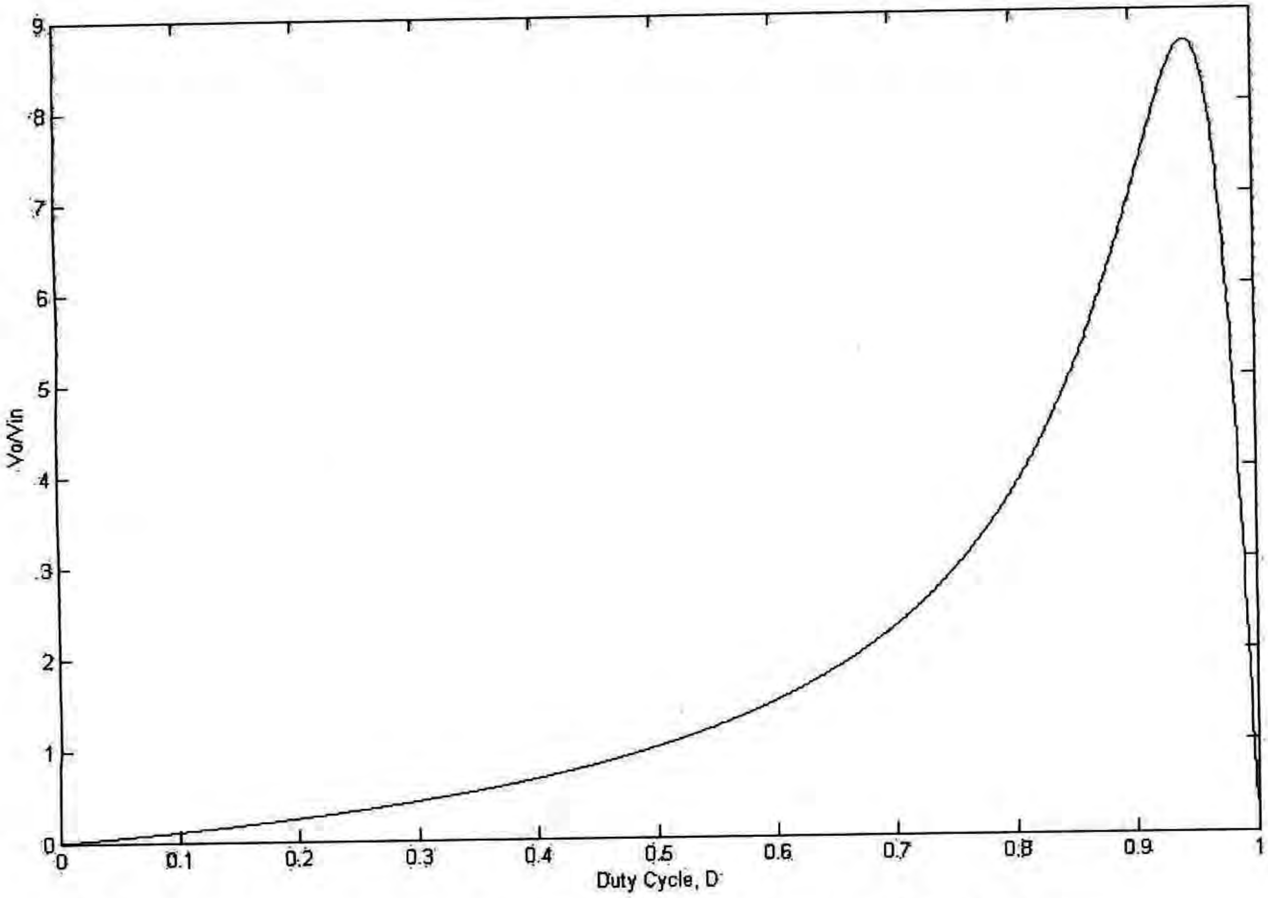


Fig 2.28: Voltage transfer function Vs. duty cycle V_0/Vin Vs. Duty Cycle, D for single stage Ćuk

2.5.3 Efficiency for double stage Ćuk converter

Efficiency, $\eta = \eta_1 \times \eta_2$

Again, $\eta = \dfrac{V_0 I_0}{V_{in} I_{in}}$

$$\frac{V_0}{V_{in}} = \eta \frac{I_{in}}{I_0}$$

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

$$\frac{V_0}{V_{in}} = \frac{1}{1 + 0.00333 \left(\frac{D}{1 - D}\right)^2 + 0.00333} \cdot \frac{D}{1 - D}$$

Voltage transfer function V_0/V_{in} with variation of duty cycle D for single stage converter is shown in Fig 2.28. Figure shows the V_0/V_{in} increases due to parasitic resistances and device voltage drops in practical circuit.

$$\eta = \frac{1}{1 + 0.00333 \left(\frac{D_1}{1 - D_1}\right)^2 + 0.00333} \times \frac{1}{1 + 0.00333 \left(\frac{D_2}{1 - D_2}\right)^2 + 0.00333}$$

If $D_1 = D_2$ then,

$$\eta = \left(\frac{1}{1 + 0.00333 \cdot \left(\frac{D}{1 - D}\right)^2 + 0.00333}\right)^2$$

Variation of efficiency of double stage converter is shown in Fig 2.29, which indicates that maximum efficiency of is 99% at D = 0.55. At 0.8 duty cycle, efficiency of single stage converter fall below 90%, whereas at D = 0.8 efficiency of double stage converter still remains above 95%.

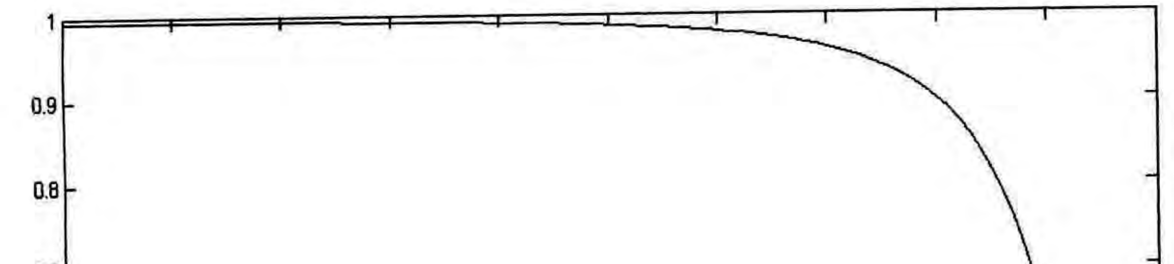


Fig 2.29: Efficiency, η Vs. Duty Cycle, D for double stages Ćuk converter

For double stage, taking the efficiency $\eta = 0.9$, from the efficiency curve, D = 0.8

Again,

$$\frac{I_0}{I_{in}} = \frac{I_{02}}{I_{in2}} \cdot \frac{I_{01}}{I_{in1}}$$

$I_{in2} = I_{01}$

$$\frac{I_0}{I_{in}} = \frac{I_{02}}{I_{in1}}$$

$$\frac{I_0}{I_{in}} = \frac{1 - D_1}{D_1} \cdot \frac{1 - D_2}{D_2}$$

If $D_1 = D_2$, then

$$\frac{I_0}{I_{in}} = \left(\frac{1 - D}{D} \right)^2$$

Again, $\eta = \frac{V_0 I_0}{V_{in} I_{in}}$

$$\frac{V_0}{V_{in}} = \eta \frac{I_{in}}{I_0}$$

$$= \eta \left(\frac{D}{1 - D} \right)^2$$

$$\frac{V_0}{V_{in}} = \left(\frac{D}{1 - D} \right)^2 \left(\frac{1}{1 + 0.00333 \cdot \left(\frac{D}{1 - D} \right)^2 + 0.00333} \right)^2$$

Taking D = 0.8 (from the curve),

$$\frac{V_0}{V_{in}} = \left(\frac{0.8}{1 - 0.8} \right)^2 \left(\frac{1}{1 + 0.00333 \cdot \left(\frac{0.8}{1 - 0.8} \right)^2 + 0.00333} \right)^2$$

$$\frac{V_0}{V_{in}} = 14$$

Or, $V_0 = 24 \times 14 = 336$ V

So, the output voltage can be easily obtainable as 230V or more keeping the efficiency of the converter more than 90%, which is the main reason why a double stage Ćuk converter is used in this thesis work.

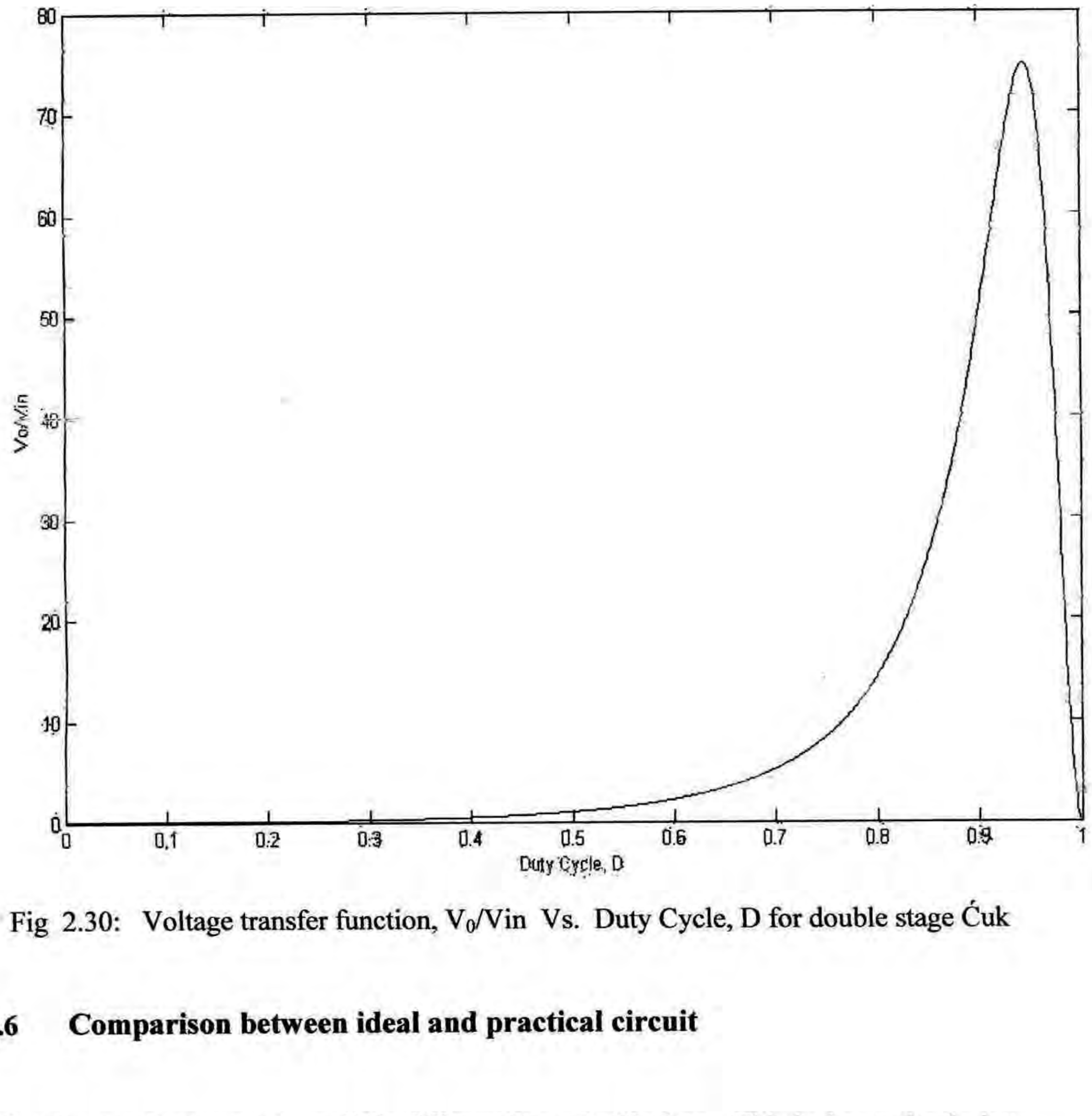


Fig 2.30: Voltage transfer function, V_0/Vin Vs. Duty Cycle, D for double stage Ćuk

2.6 Comparison between ideal and practical circuit

Often the practical circuits are little different from the ideal one. This is due to the design constraints parameter selection limitations. Following section examines the deviations of practical circuits from the ideal one for the single and double stage Ćuk converter.

2.6.1 Single stage Ćuk converter

Ideally, operation of a single stage Ćuk converter (theoretical) is like the following Fig (Fig 2.31):

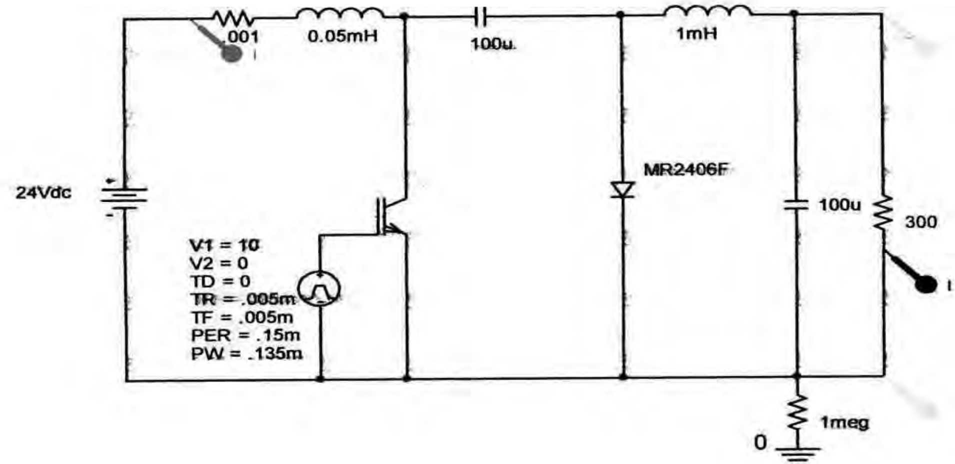
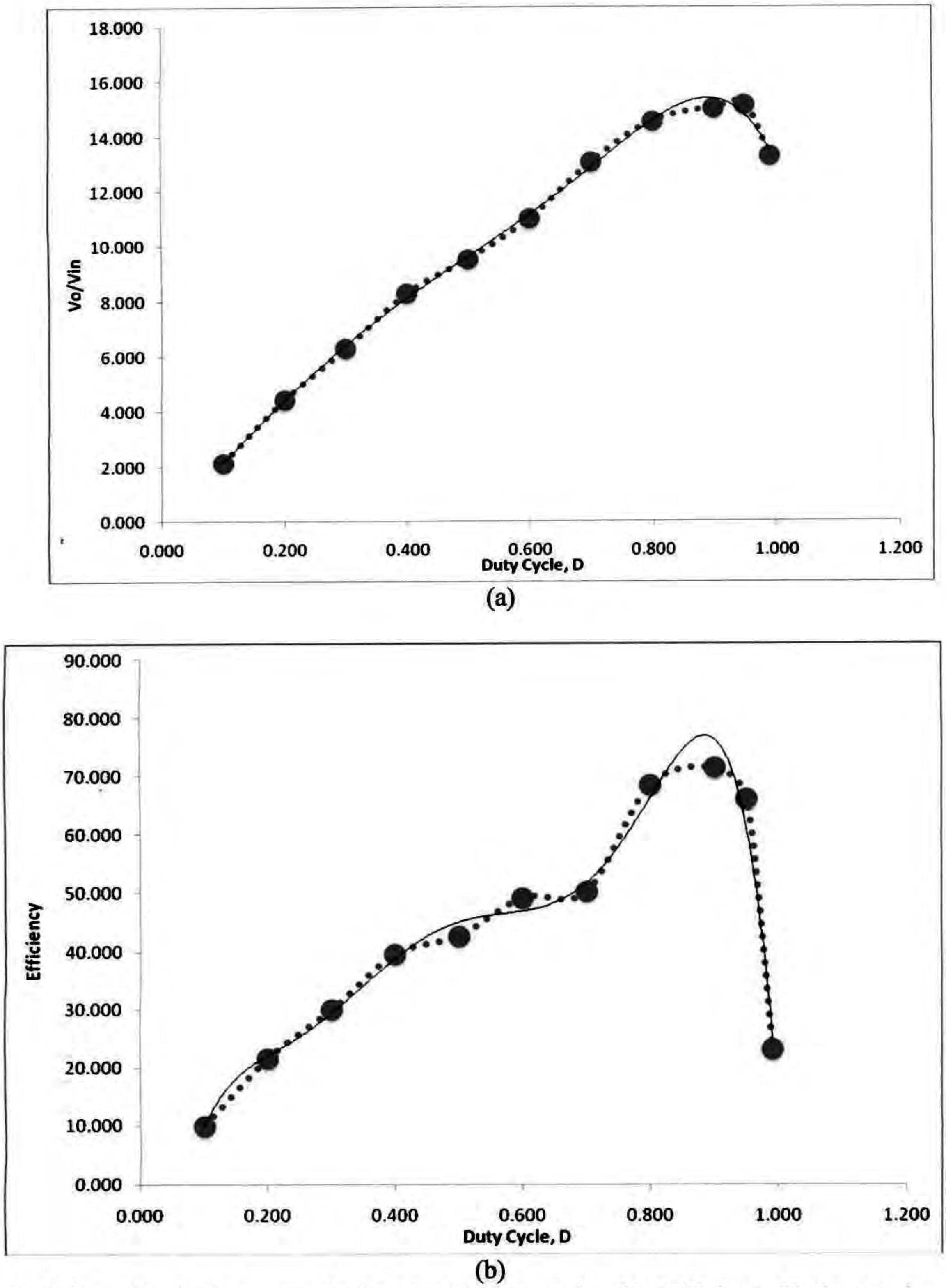


Fig 2.31: Operation of single stage Ćuk converter (Ideal case)

The simulation result and the wave shape is shown below:

D	I_{in}	V_0	I_0	V_0/V_{in}	$V_0I_0/V_{in}I_{in}$
0.1	3.82	52.25	0.174	2.177	9.92
0.2	7.295	106.73	0.355	4.45	21.64
0.3	10.62	151.5	0.5	6.31	30.01
0.4	13.97	199.6	0.665	8.31	39.59
0.5	17.11	229.26	0.764	9.55	42.65
0.6	19.76	264.55	0.881	11.02	49.16
0.7	27.21	313.79	1.045	13.07	50.21
0.8	24.76	349.44	1.165	14.56	68.5
0.9	25.38	361.13	1.204	15.05	71.38
0.95	27.77	363.66	1.21	15..15	66.02
0.99	61.168	319.47	1.065	13.31	23.176



(a)

(b)

Fig 2.32: (a) Voltage transfer function Vs duty cycle (b) Efficiency Vs duty cycle of a single stage Ćuk converter

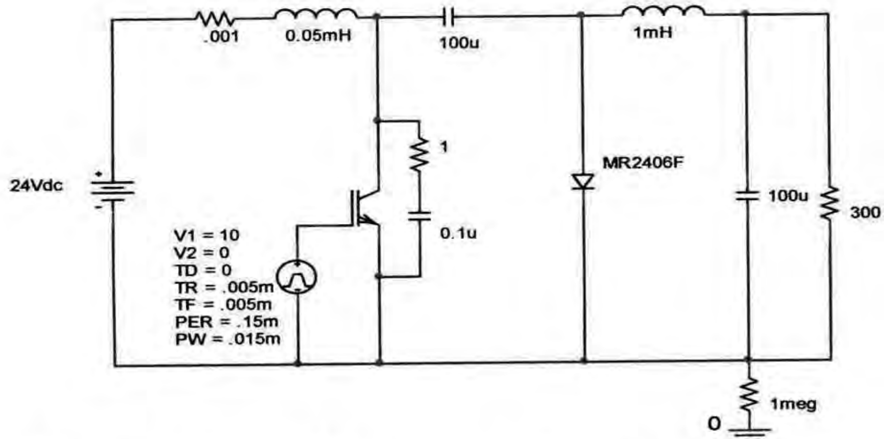


Fig 2.33: Single stage Ćuk converter using compensator circuit

D	I_{in}	V_0	I_0	V_0/V_{in}	$V_0I_0/V_{in}I_{in}$
0.1	4.26	46.36	0.154	1.93	7.0
0.2	7.79	91.25	0.306	3.8	14.83
0.3	11.8	136.65	0.455	5.69	21.95
0.4	15.7	185.5	0.618	7.73	30.42
0.5	19.78	213.2	0.71	8.88	31.88
0.6	25.47	244.3	0.814	10.18	32.53
0.7	26.39	279.12	0.93	11.63	40.98
0.8	38.45	349.66	1.165	14.57	44.16
0.9	41.75	434.68	1.45	18.11	62.9
0.95	41.4	394.73	1.35	16.44	53.6

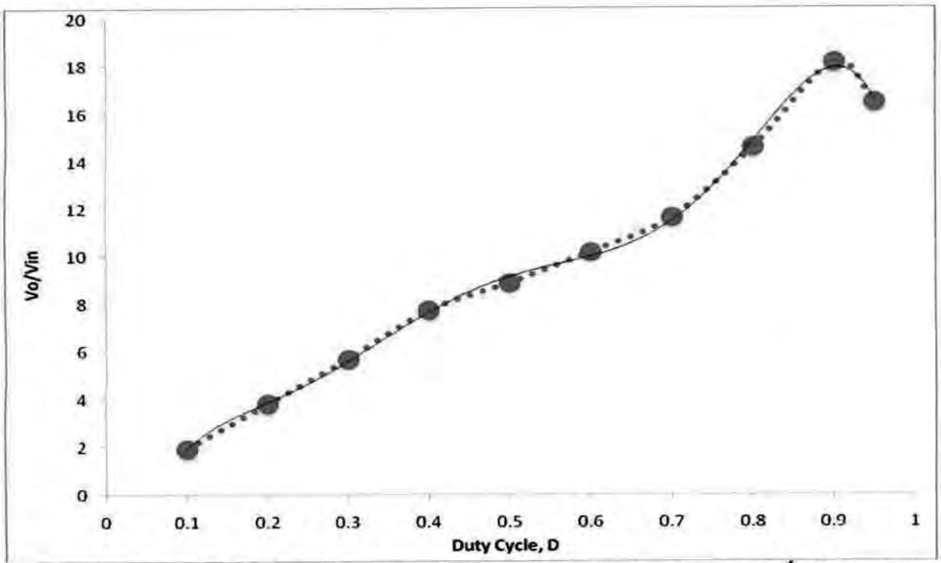
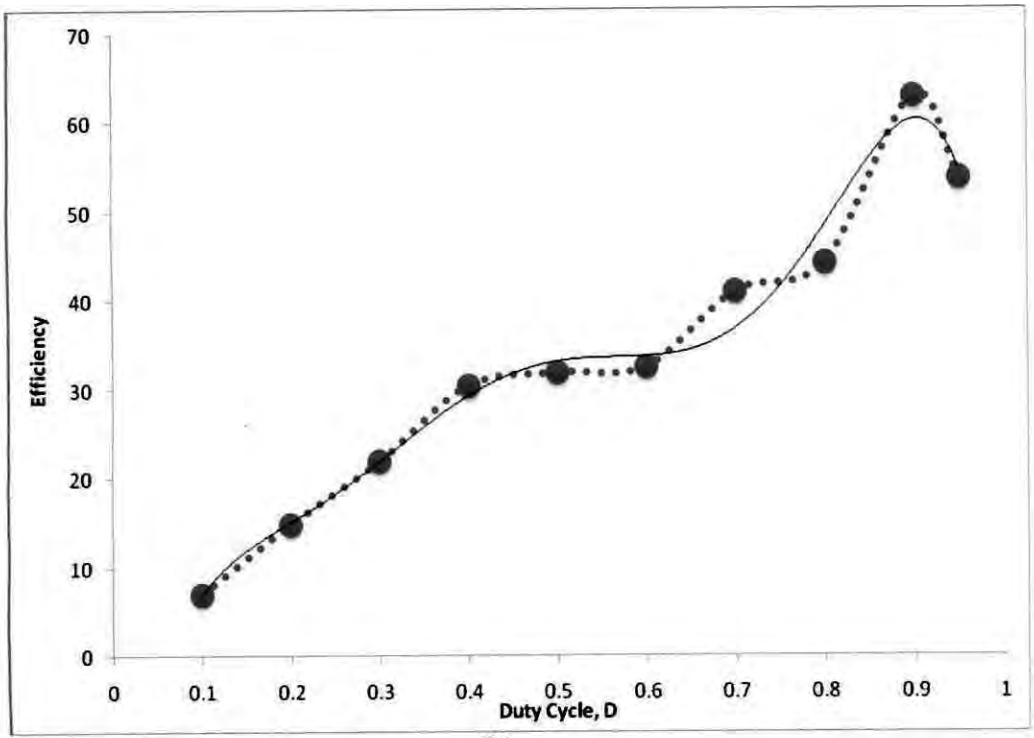


Fig 2.34(a): Voltage transfer function Vs duty cycle of a single stage Ćuk converter using compensator circuit



(b)

Fig 2.34(b): Efficiency Vs duty cycle of a single stage Ćuk converter using compensator circuit

But, for practical reasons the modified single stage Ćuk converter is like the following:

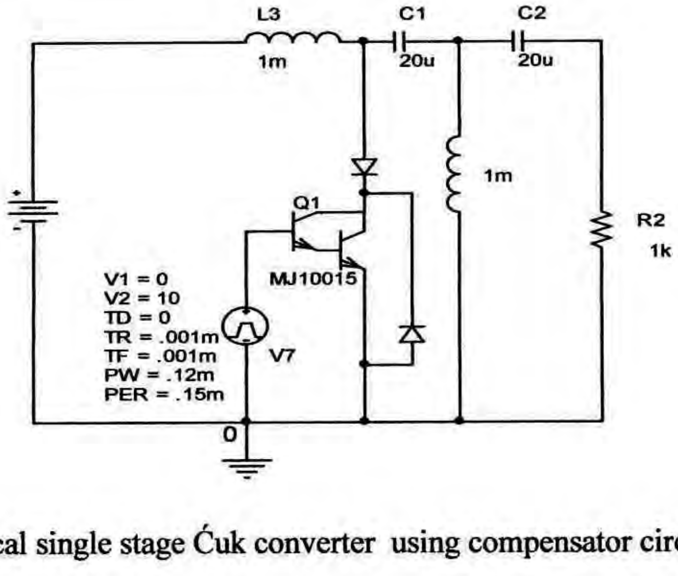


Fig 2.35: Practical single stage Ćuk converter using compensator circuit

2.6.2 Double stage Ćuk converter

Ideally, operation of a double stage Ćuk converter (theoretical) is like the following (Fig 2.36):

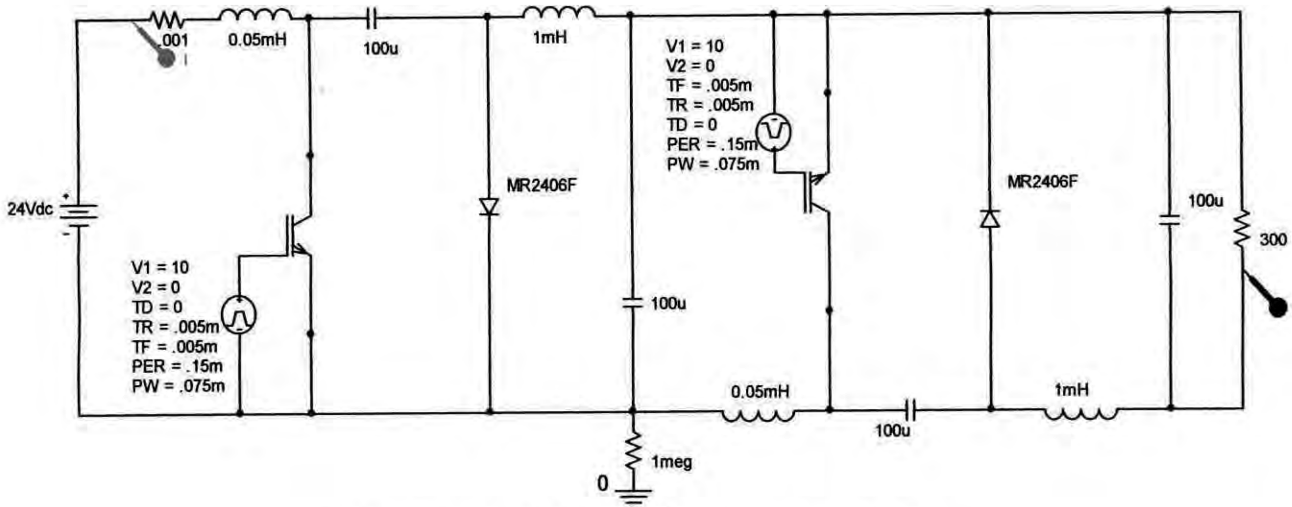
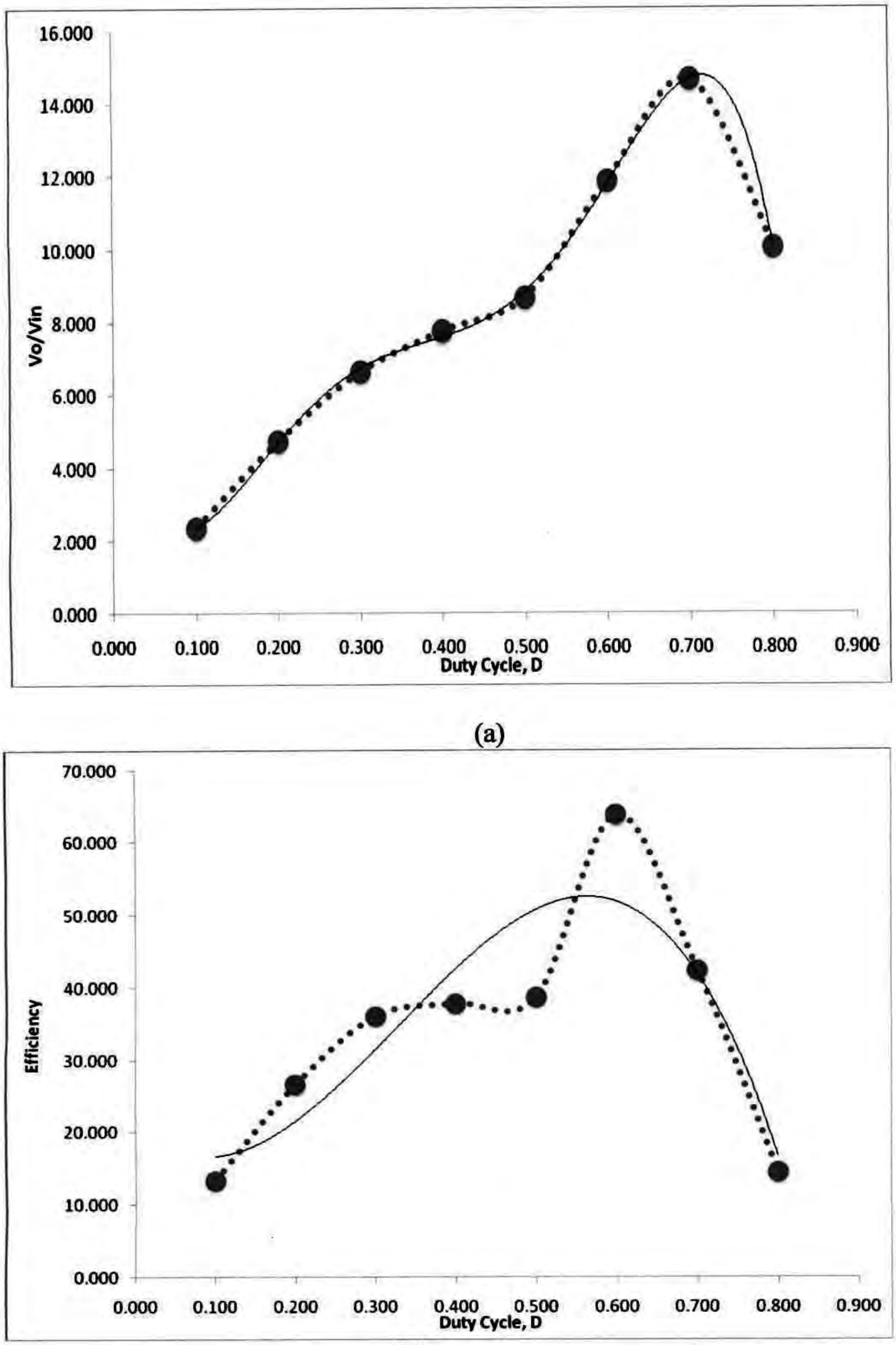


Fig 2.36: Double stage Ćuk converter circuit

The simulation result and the wave shape is shown below:

D	I_{in}	V_0	I_0	V_0/V_{in}	$V_0I_0/V_{in}I_{in}$
0.1	3.36	56.83	0.189	2.37	13.32
0.2	6.78	114.1	0.38	4.75	26.64
0.3	9.74	159.57	0.53	6.65	36.15
0.4	12.73	186.67	0.62	7.77	37.88
0.5	15.59	208.63	0.695	8.69	38.74
0.6	17.71	285.54	0.95	11.89	63.82
0.7	40.55	352.1	1.17	14.67	42.33
0.8	55.8	241.56	0.805	10.06	14.5
0.9	66.85	122.68	0.409	5.11	3.13



(a)

(b)

Fig 2.37: (a) Voltage transfer function Vs duty cycle (b) Efficiency Vs duty cycle of a double stage Ćuk converter.

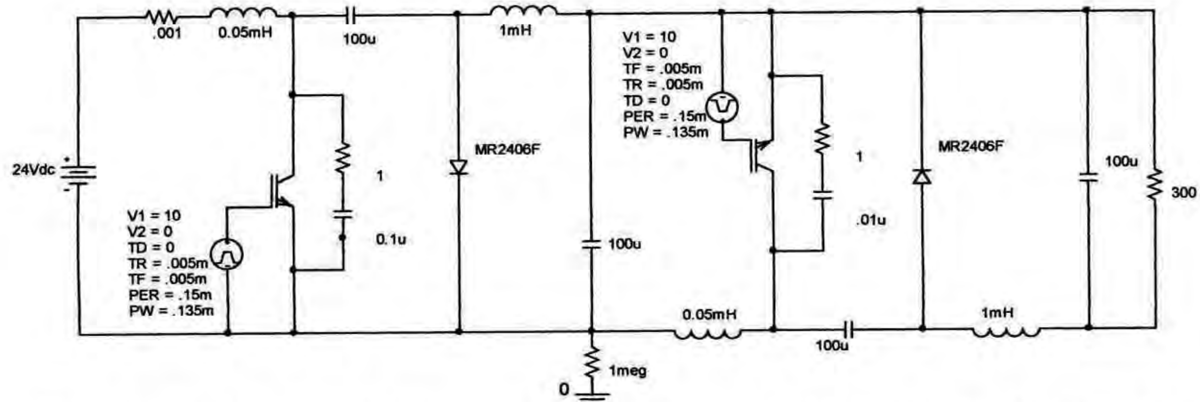


Fig 2.38: Double stage Ćuk converter using compensator circuit to get positive output

D	I_{in}	V_0	I_0	V_0/V_{in}	$V_0I_0/V_{in}I_{in}$
0.1	3.75	54.14	0.18	2.25	10.83
0.2	6.755	103.32	0.344	4.3	21.92
0.3	9.9	147.72	0.49	6.15	32.08
0.4	12.84	180.26	0.6	7.51	35.09
0.5	15.55	198.8	0.66	8.28	35.15
0.6	17.93	276.06	0.92	11.5	59.02
0.7	41.01	338.55	1.13	14.1	38.86
0.8	55.92	223.68	0.745	9.32	12.42
0.9	67.28	95.83	0.319	3.99	1.89

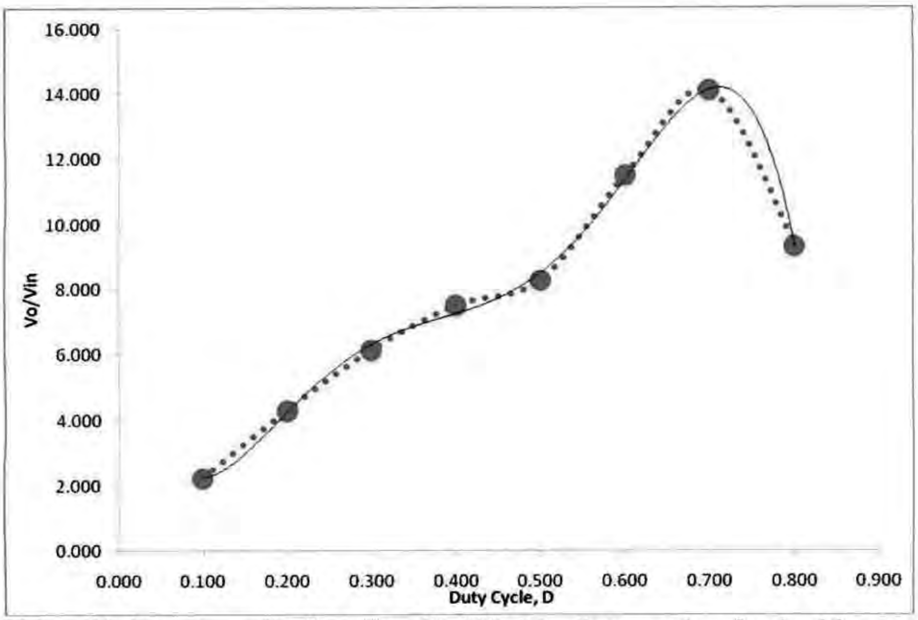


Fig 2.39(a): Voltage transfer function Vo/Vin Vs duty cycle of a double stage Ćuk converter using compensator circuit.

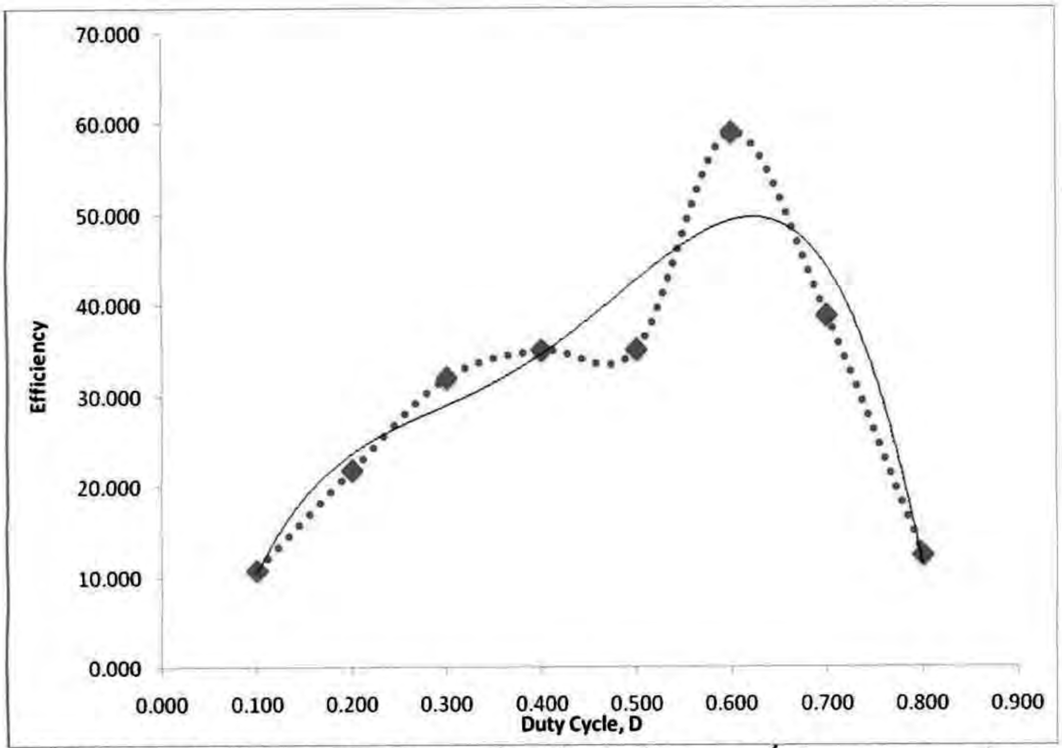


Fig 2.39(b): Efficiency Vs. duty cycle of a double stage Ćuk converter using compensator circuit.

But, for practical reasons the modified double stage Ćuk converter is like the following (Fig 2.40):

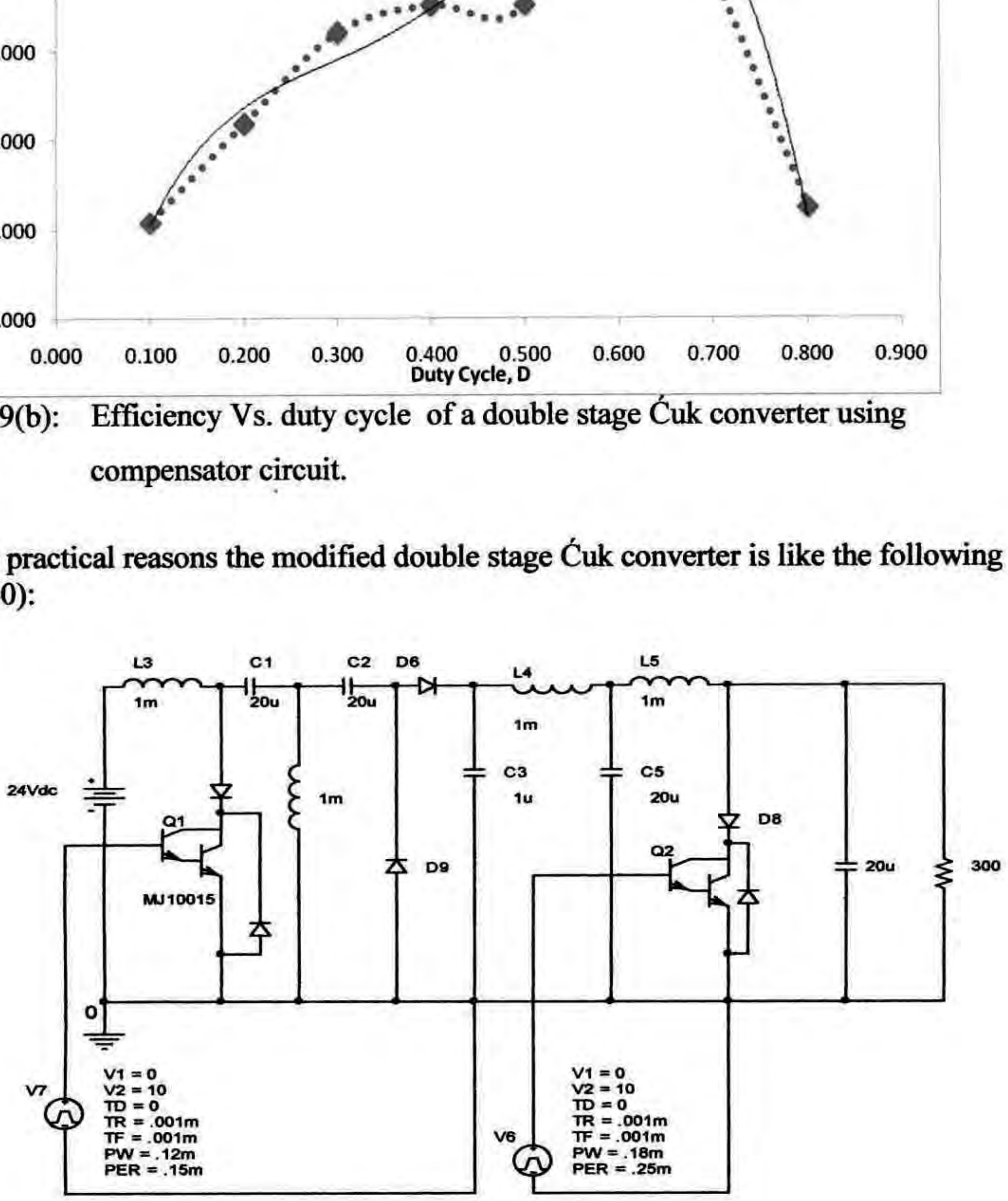


Fig 2.40: Modified double stage Ćuk converter

In a double stage converter, there is a tendency of dropping the output of the first stage when the second stage is cascaded with the first stage. A circuit called 'lift circuit' is used in between the first and second stage for compensation. Also, the output of a Ćuk converter is of opposite polarity of the input; but, by suitable component arrangement, the output is made as the same polarity of the input for the circuit shown above.

Resonant Inverter

Ideally a Resonant Inverter and its output wave shape should be as follows:

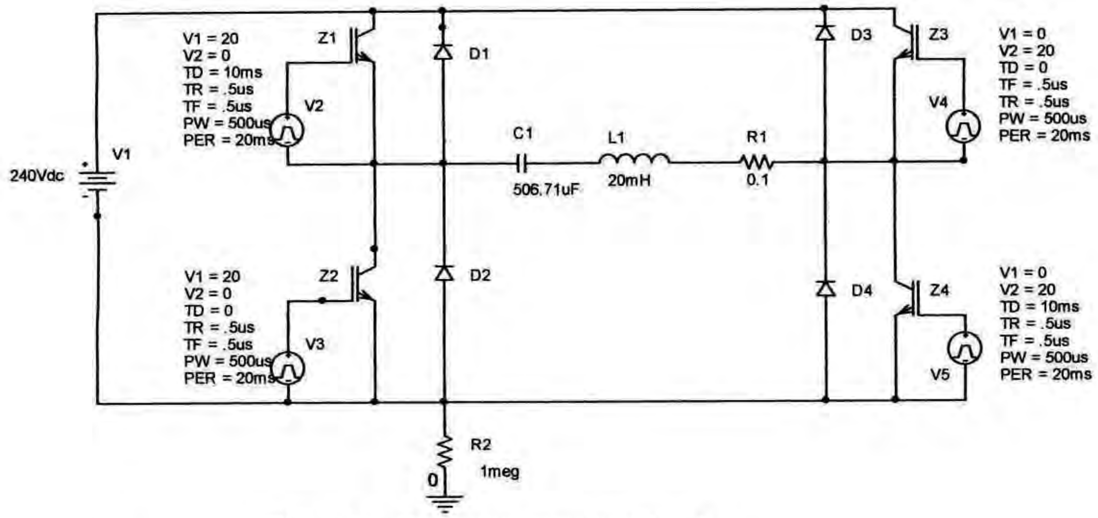


Fig 2.41: Resonant Inverter circuit

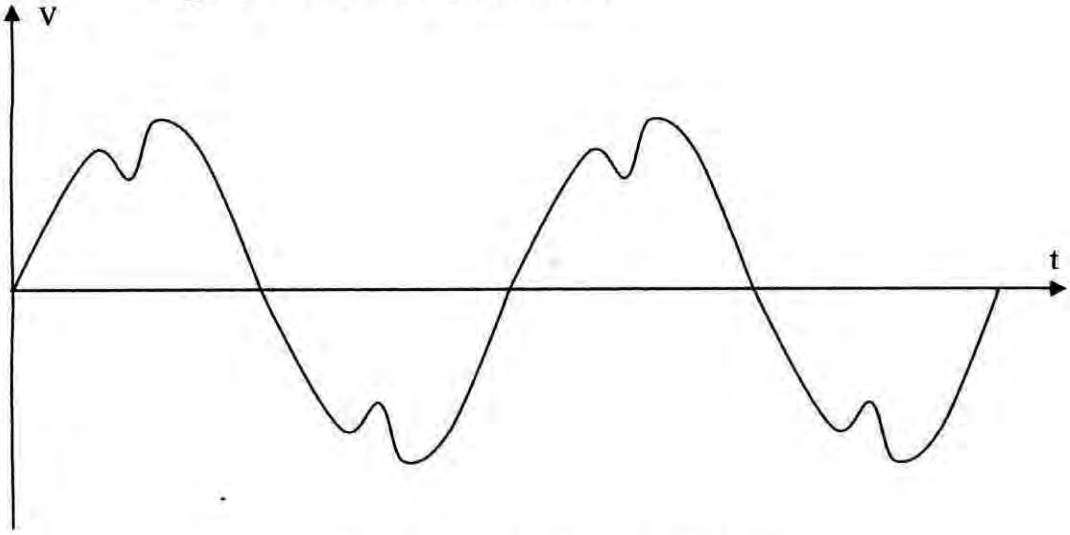


Fig 2.42: Wave shape of ideal Resonant Inverter circuit

2.7 Ćuk Converter fed Resonant Inverter

In the Ćuk Converter fed Resonant Inverter, the input selected for the Ćuk Converter is 24V DC as obtainable from the solar or other alternative source. Practical switches are replaced by IGBTs. Switching voltage for the IGBT is 20V. The output is taken from a 300Ω resistance.

The Resonant Inverter is fed from the Ćuk Converter. If the Ćuk Converter is not connected with the Resonant Inverter its output is about 220V DC; but when the Resonant Inverter is connected as a load to the Ćuk Converter its output drops to about 140V DC, and the output of the Resonant Inverter is about 100V AC. A modified Ćuk Regulator circuit is used to compensate for the drop. The components of the Resonant Inverter is so chosen to obtain the output frequency as 50Hz. The output impedance of the Resonant Inverter is taken as 300Ω.

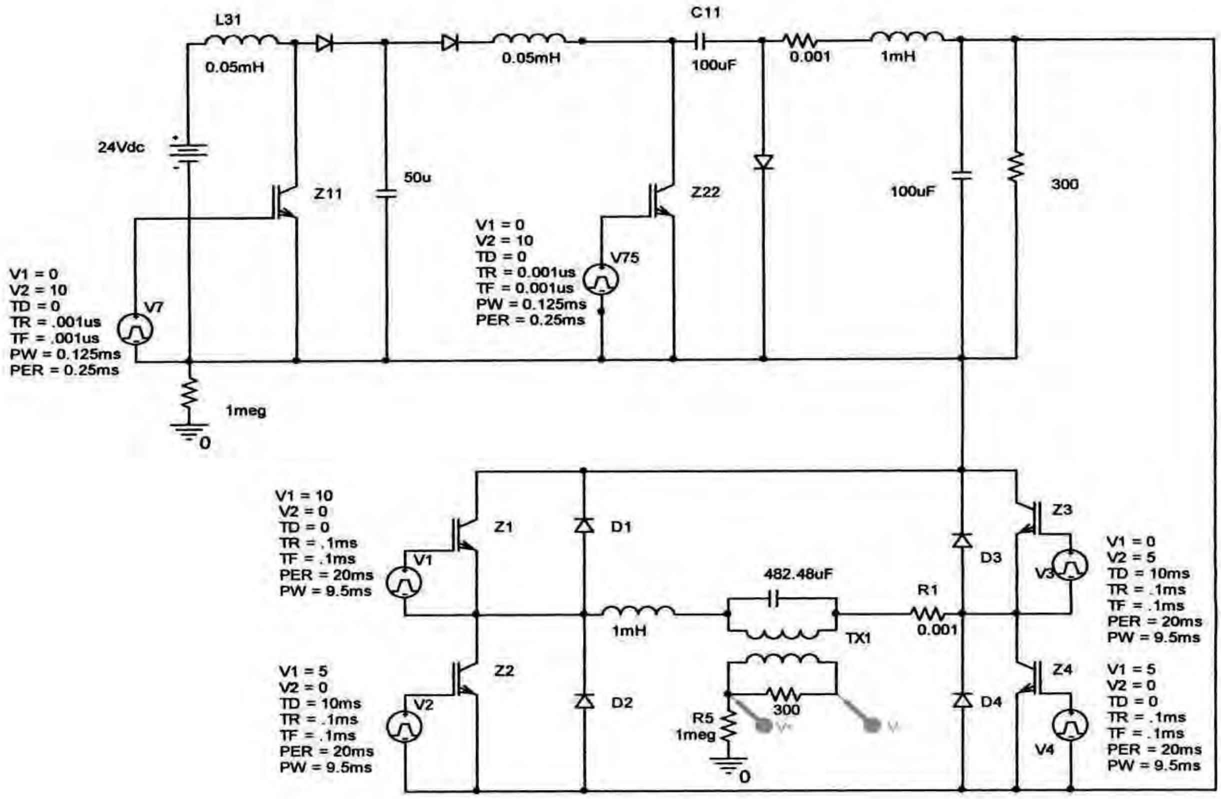


Fig 2.43: Ćuk Regulator fed Resonant Inverter

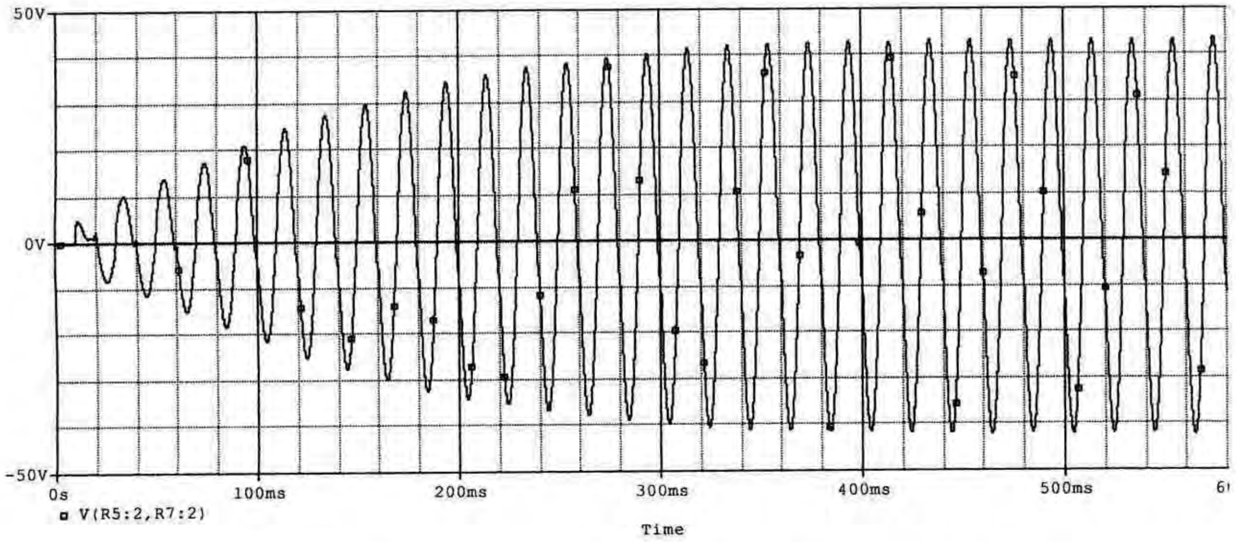


Fig 2.44: Wave shape of Cûk Regulator fed Resonant Inverter

The desired frequency 50Hz is attainable in the single stage Ćuk Regulator (Fig 2.44) but it will not provide 300V as required for the output of 300Ω load. So, double stage modified Ćuk Regulator is required to be used as in the next section.

2.7.1 Modified Ćuk Regulator fed Resonant Inverter (Using switch)

From the above Figs, it can be seen that single stage Cûk Regulator will not provide 300V output for 300Ω load. The next step is to use double stage modified Cûk Regulator given in the next Fig (Fig 2.45).

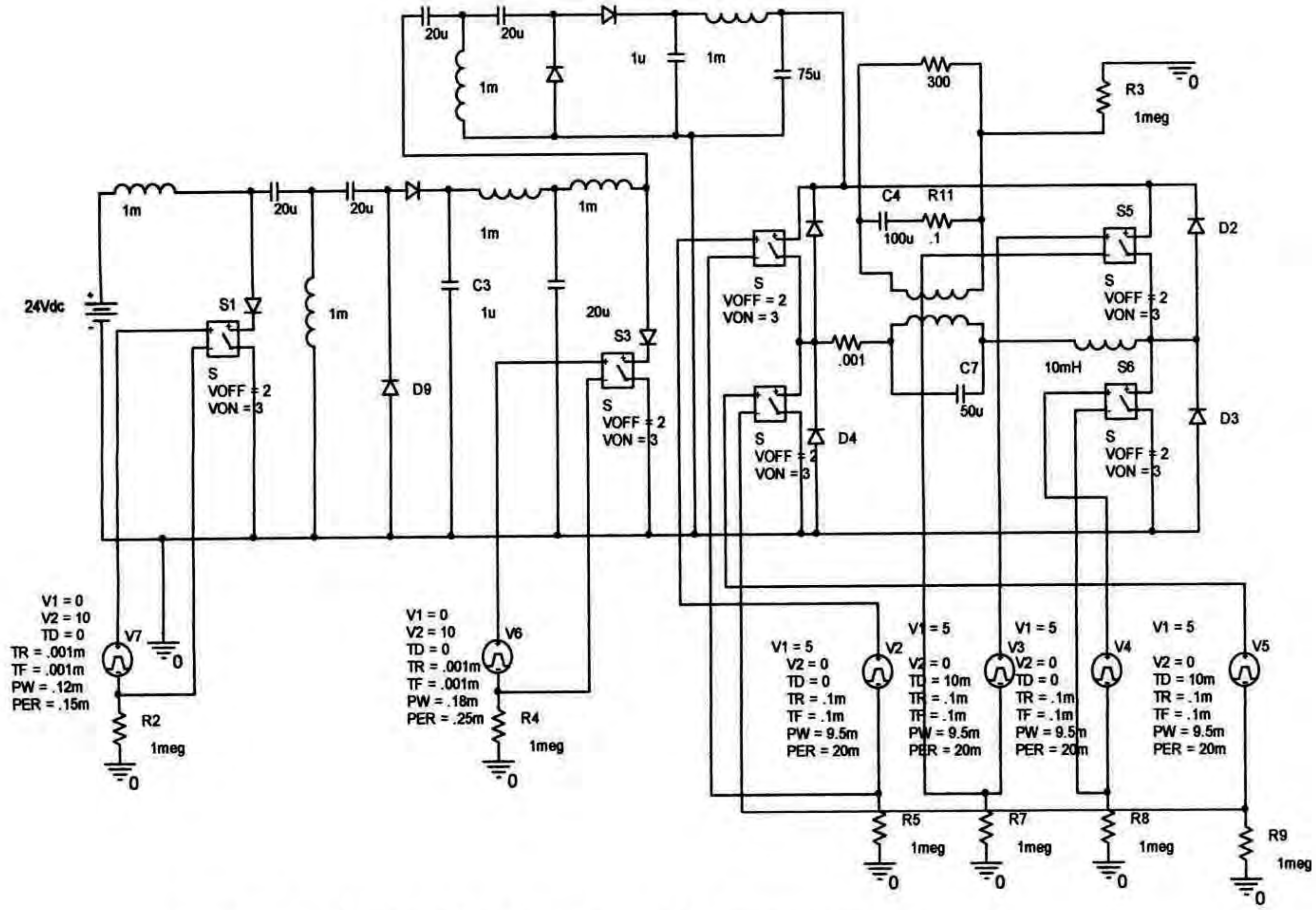


Fig 2.45: Modified Ćuk Regulator fed Resonant Inverter

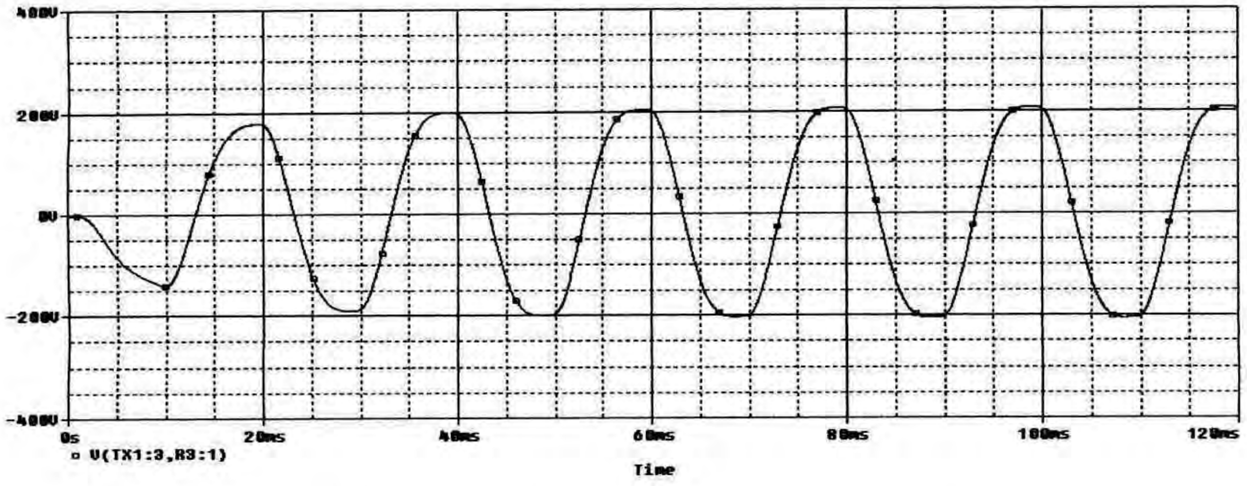


Fig 2.46: Output of modified Ćuk Regulator fed Resonant Inverter (Ideal switch implementation)

The modified Ćuk Regulator fed Resonant Inverter is like the following (Fig 2.45). It consists of a two stage Cûk Regulator, a lift circuit between the two stages of Cûk Regulator for compensating the voltage drop, a Resonant Inverter and another lift circuit between the Cûk Regulator and Resonant Inverter for complete compensation. Practical switches are used in this circuit instead of IGBTs for switching actions. The input is taken as 24V DC. The load in the output of the Resonant Inverter is 300Ω. The output wave shape in the Resonant inverter as taken in the 300Ω load is shown in Fig 2.46. From Fig 2.46, it is evident that the output voltage is 240V AC and frequency is 50Hz.

2.7.2 Modified Ćuk Regulator fed Resonant Inverter

The modified Ćuk Regulator fed Resonant Inverter is shown in Fig 2.47. In this circuit, the switches in the Cûk Regulator are replaced by Darlington pair and that of Resonant Inverter is replaced by IGBTs for practical considerations. Like the modified Ćuk Regulator fed Resonant Inverter, two lift circuits are used for compensation. The input is taken as 24V DC. The load in the output of the Resonant Inverter is 300Ω. The output wave shape in the Resonant inverter as taken in the 300Ω load is shown in Fig 2.48. From Fig 2.48, it is evident that the output voltage is 240V AC and frequency is 50Hz.

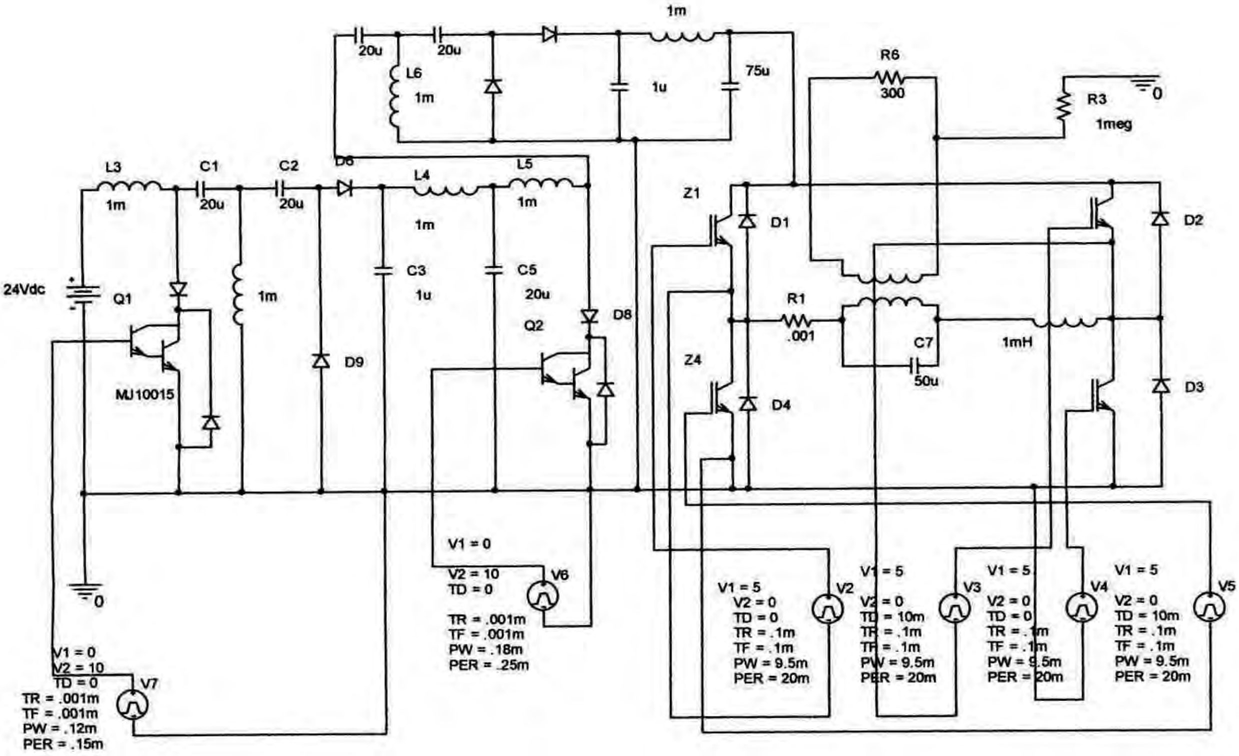


Fig 2.47: Modified Ćuk Regulator fed Resonant Inverter

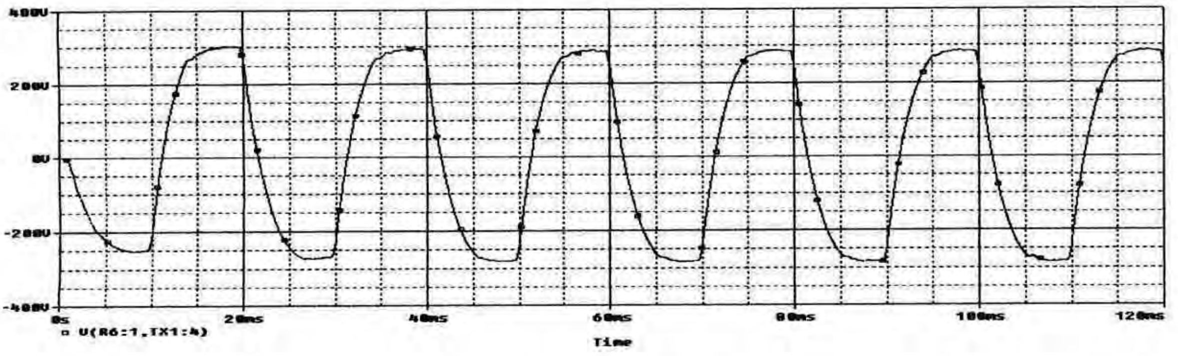


Fig 2.48: Output of modified Ćuk Regulator fed Resonant Inverter (Practical BJT switch implementation)

The deviation from the theoretical one is for the need of lift circuit for resonant inverter and other practical constraints.

2.7.3 Modified Ćuk Regulator fed Resonant Inverter using Switches and IGBTs

The switching action in the Ćuk Regulator is accomplished by two switches S_1 and S_2. The switching in the Resonant Inverter is accomplished by IGBTs. Two lift circuits like the modified Ćuk Regulator fed Resonant Inverter is also used for compensation. The input voltage is 24V DC and output impedance is 300Ω as shown in Fig 2.49. The wave shape for the modified Ćuk Regulator fed Resonant Inverter (practical IGBT switch implementation) is shown in Fig 2.50.

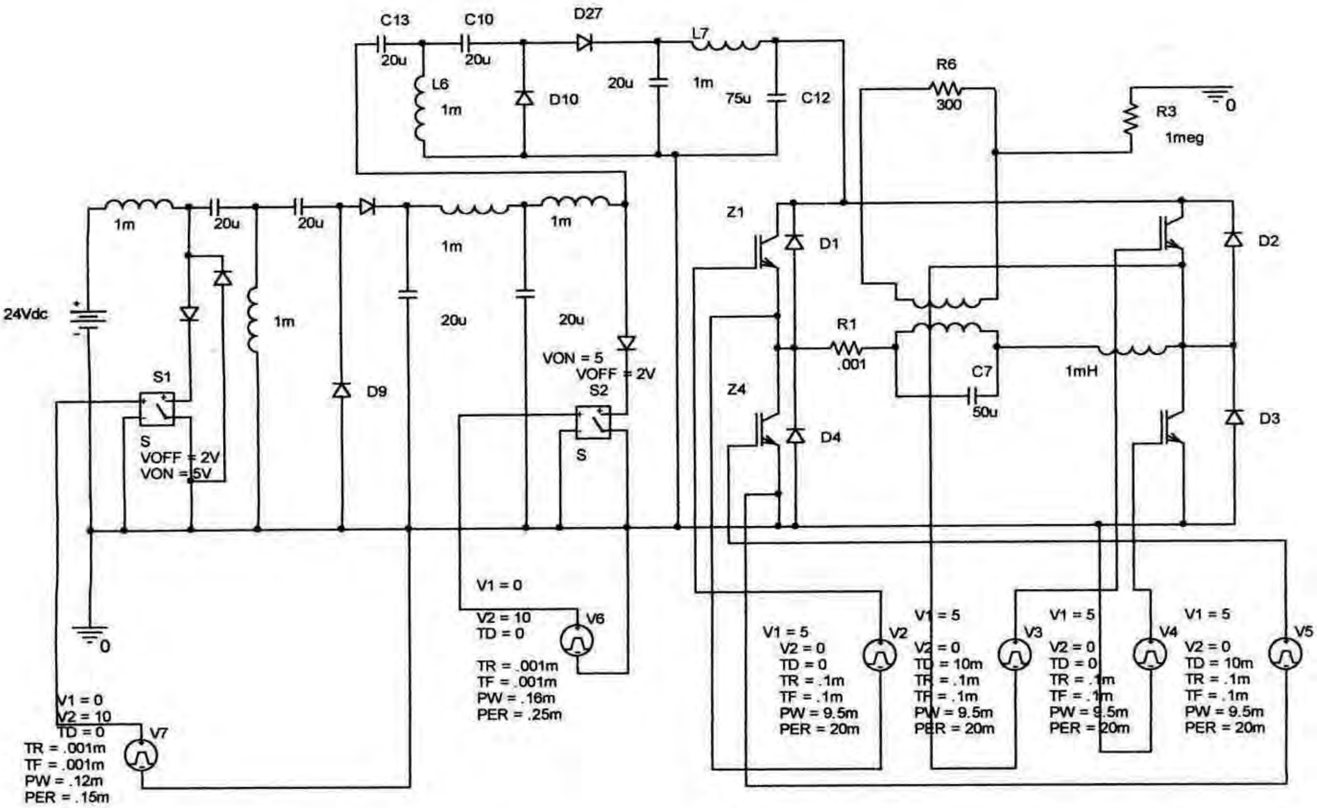


Fig 2.49: Modified Ćuk Regulator fed Resonant Inverter using Switches and IGBTs

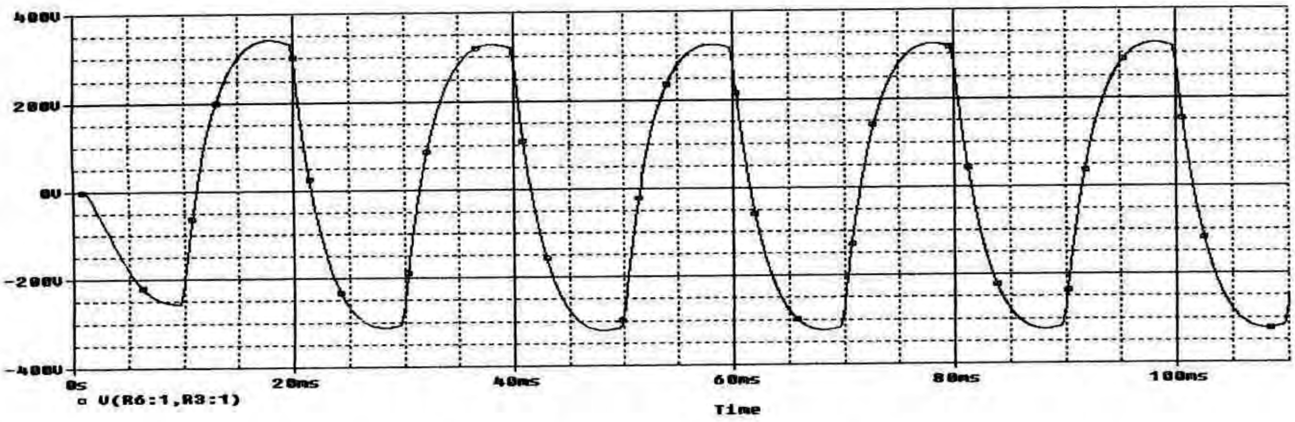


Fig 2.50: Wave shape of modified Ćuk Regulator fed Resonant Inverter (practical IGBT and switch implementation)

As seen from the wave shape of the modified Ćuk Regulator fed Resonant Inverter that the output frequency is 50Hz and the output voltage is 240V AC. The wave shape is a pure sine wave without distortion. The implementation of the circuit is simple and cheap.

2.8 Discussion on Results

The objective has been to design and analyze a power supply to the load is a 240V AC at 50Hz frequency from renewable energy sources such as solar system, fuel cell and microwind turbines etc. To attain the goal an approach was taken as shown in block diagram of Fig 2.51.

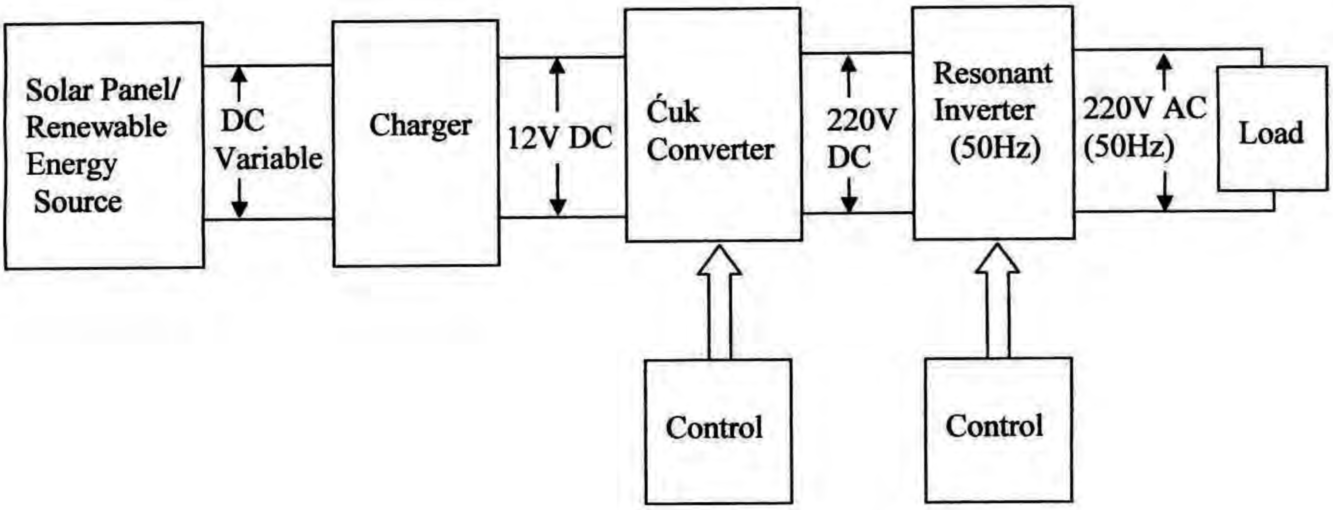


Fig 2.51: Block diagram of the proposed power supply

This Thesis presents a Ćuk DC-DC converter fed PWM resonant inverter for remote area communication apparatus. It has a resonant circuits on the ac side of the inverter. The current flowing in a switching device is a sum of the load current and the resonant current. The switching devices are controlled to be turned on and off at zero current by regulating the amplitude of the resonant current.

The maximum frequency of the zero current switching based inverter is as high as the resonant frequency, because a switching device can be turned on or off once in a resonant cycle. In the simulation works, IGBT's are used as switching devices, so that the resonant frequency f_R is designed to be 50Hz is given by,

$$f_R = \frac{1}{2\pi\sqrt{L_R C_R}} = 50Hz$$

The parameters are so chosen to obtain desired AC voltage to run conventional communication equipment designed for 230V, 50Hz or 60Hz. Step up DC-DC conversion has been achieved by duty cycle control of Ćuk converter topology. Ćuk topology is the efficient and light weight unit among all switch mode power supplies as they transfer energy capacitively. Ćuk converters have both voltage step down and voltage step up capability. In this work, the converter is used for step up operation. The output of Ćuk converter is fed to a resonant inverter circuit to obtain direct sinusoidal supply for communication equipment. Resonant inverters are soft switched inverters with very low switching loss and they are usually designed and operated at very high frequency. But in this thesis work the inverter is designed for 50Hz output.

2.8.1 The simulation circuits and results using Spice Simulation Software, are shown in previous section [36]. The results are obtained taking the following considerations into account:

a. To step-up the battery voltage, Ćuk Regulator is used; Boost Regulator could also have been used. But, experience shows that Boost Regulator is an unreliable regulator. It may malfunction at any time during operation.

b. 2-stage Ćuk Regulator has been used. The negative output of the Ćuk Regulator is made positive with suitable circuit configuration.

c. If a transformer would be used in the first stage of the circuit to step-up the voltage, the circuit would have to withstand high current, which would require heavy transformer. Calculation shows that the designed circuit has reduced the wire the wire size to at least $\frac{1}{25}$ times than it would be if a transformer was used.

d. It is shown that, the efficiency of a double stage converter is above 90%, which is more than the efficiency achievable by single stage Ćuk converter.

Chapter 3

Conclusions and Recommendations

3.1 Conclusions

Power crisis in the world has compelled mankind to think for alternative energy. But all the alternative sources have not yet been exploited. From many ongoing researches, it reveals that if all the alternative energy sources are exploited, the energy crisis of the world would be reduced to a great extent.

Many alternative energy technologies today are well developed and they are reliable and cost competitive with the conventional fuel generators. The cost of alternative energy technologies is on a falling trend and is expected to fall further as demand and production increases. There are many alternative sources of energy such as biomass, wind, solar, minihydro and tidal power. The most important advantage offered by alternative energy sources is their potential to provide sustainable electricity in areas not served by the conventional power grid. The growing demand of alternative energy technologies has resulted in a rapid growth in the need for power electronics. Most of the alternative energy technologies produce DC power, and hence power electronics and control equipment are required to convert the DC power into AC power.

The DC-DC converter is the first stage used in this research work. It facilitates to step-up the DC voltage level of the alternative energy source. For reliability and efficient operation Ćuk Regulator is used. Also the Ćuk Regulator provide continuous current at both input and output of the converter operation.

The Resonant Inverter converts the DC voltage into AC voltage. Resonant Inverters are more efficient than the PWM converter. It provides zero current and/or zero voltage transistor switching and thereby minimizes the switching losses. Though Resonant Inverter is a high frequency inverter, with special design in this work the output frequency is fixed at 50Hz. The component size is also kept sufficiently small; which has been the objective of this thesis work.

This Thesis work has proposed a DC-DC Ćuk converter and a Resonant Inverter for AC power applications. An alternative power source (Solar system, fuel cell, wind power etc.) at 12V or 24V DC is assumed to be available in remote areas. A power supply unit is designed and fabricated to provide conventional AC voltage at 50/60 Hz, so that the commercially available communication equipments may be used in remote installations without specially made customised modules.

With solid state switches used, due to absence of freewheeling path surge voltage appears across the switches. In this work snubbers are used to reduce voltage spikes across switches this purpose [37]. The input current is quite high; and further research is required to modify the circuitry to reduce the input current and increase efficiency. As a starting work to use the alternative energy directly in an efficient, reliable, light weight and cost effective way in the commercially available communication/electronic equipments, the Ćuk Converter fed Resonant Inverter show promising aspects. Investigation shows that the ratings of the component and their sufficiently smaller size even in 50Hz frequency, the design will be successful and would be commercially well accepted.

3.2 Limitations

a. The Ćuk converter uses high number of reactive components and high current stresses on the diode and the capacitor take place.

b. During simulation, the switch, diode and passive components are assumed ideal, i.e. linear in nature. But the nonlinearities or parasitic of practical devices and components may, however, greatly affect some performance parameters of DC-DC converters. This effect causes the efficiency of the circuit to decrease. However, with careful design the efficiency of the circuit can be kept above 90%; the illustration and details calculation with the wave shape taking the effect of parasitic components into account is shown in chapter 2.

c. Hard switching in a power circuit causes power losses. During turn-on and turn-off process, the power device has to withstand high voltage and current simultaneously, which results in high switching losses and stress. To avoid this problem, resonant inverter is used by which ZVS (Zero Voltage Switching) and ZCS (Zero Voltage Switching) is achieved [38].

d. In this research work, the output frequency of the resonant inverter is kept as 50Hz, which enable the size of the magnetic components to be reduced, and power density of the converter increased. However, resonant inverters have high peak values of voltage and current, leading to high conduction loss and higher V and I ratings requirements for the power devices [39].

3.3 Recommendations

a. The proposed Ćuk Converter fed Resonant Inverter may be implemented practically in laboratory and be made commercially available in future.

b. The drawbacks of using Ćuk Converter and Resonant Inverter can be minimized with further research.

References

[1] Pipattanasompom M., and Rahman S., "Information and Communication Technology Infrastructure and Its Distributed Generation Solutions in Remote Areas", Department of Electrical and Computer Engineering, Alexandria Research Institute, Virginia Tech, Alexandria, VA 22314, U.S.A

[2] Gregory J., "Financing Renewable Energy Projects," IT Publications, UK, 1997.

[3] Okoro O. I., and Madueme T.C., "Solar energy: a necessary investment in a developing economy", International Journal of Sustaunable Energy" Volume 25, Number 01/March 2006

[4] Cabraal A., "Accelerating Sustainable PV Market Development", World Bank, 1998.

[5] Mankins, J. C., "Space solar power - A fresh look" AIAA Space Programs and Technologies Conference, Huntsville, AL, Sept 26-28, 1995.

[6] Solar Energy International: "PHOTOVOLTAICS: Design and Installation Manual", New society Publishers, Gabriola Island, Canada .

[7] Mankins J. C., and Howell J., "Overview of the space solar power (SSP) Exploratory Research And Technology (SERT) program" ASME, IEEE, Intersociety Energy Conversion Engineering Conference and Exhibit (IECEC), 35th, Las Vegas, NV, July 24-28, 2000.

[8] Rashid M H.. and Rashid H. M. "SPICE FOR POWER ELECTRONICS AND ELECTRIC POWER", 2nd Edition, Taylor & Francis Group, New work.

[9] Moschopoulos G., and Jain P., "A study of ac-dc PWM full-bridge integrated converter topologies", Journal of Power Electronics, vol.1 no. 2

[10] Rashid M H., Power electronics, "Circuits, Devices and Applications", 3rd Edition, Prentice Hall of India Pvt limited, New Delhi.

[11] Middlebrook R. D., "Power Electronics: Topologies, Modeling and Measurement," IEEE International Symposium on Circuits and Systems, 1981 Record, Chicago, IL, April 27-29, 1981.

[12] Middlebrook R. D., and Slobodan Ćuk, "Modeling and Analysis Methods for DC to-DC Switching converters," IEEE International Semiconductor Power Converter Conference Record, , Lake Buena Vista, FL, USA, pp 90-111, 1977.

[13] Bedford B. D., and R. G. Hoft, "Principles of Inverter Circuits," Wiley; 1964.

[14] Gene W. Wester, "Low frequency Characterization of Switched DC-to-Dc Converter" A PhD Thesis of California Institute of Technology, May 1972.

[15] Bose B. K., " Introduction to Power Electronics," University of Tennessee, Published in 1992.

[16] Ned Mohan, Undeland Tore M., and Willium P. Robbins, "Power Electronics- Converters, Applications, and Design, "John Wiley and Sons Inc., Second Edition, pp 161-195, and 669-695, 1995.

[17] Veffer H., "High current, Low inductance GTO and IGBT Snubber Capacitors," Siemens Components, pp 81-85, June 1990.

[18] Severns K. P , and Bloom G. E., "Modern DC-to-DC Switched Mode Power Converter Circuits," Van Nostrand Reinholdd Company, Ins., New York, USA, 1983.

[19] Unitrode, "Switching Regulated Power Supply Design Seminar Manual," Unitrode Corporation, USA, 1986.

[20] Dewan S. B., and Straughen A. , " Power Semiconductor Device and Circuits," Wiley-Interscience, 1975.

[21] Hnatek E. R., "Design of Solid State-state Power Supplies," Van Nostrand Reinholdd; 1971.

[22] Pressman Abrahan I., "Switching and Linear Power Supply," Power Converter Design, vol. I and vol. II, Hayden; 1977.

[23] Slobodan Ćuk, "A New Zero Ripple Switching DC-to-DC Converter," IEEE Power Electronics Specialist Conference Record, Atlanta, CA, USA, pp 12-32, 1980

[24] Shi-Ping Hsu, Art Brown, Loman Rensink, and R. D. Middlebrook, "Modeling and Analysis of Switching DC-to-DC Converters in Constant Frequency Current-Programmed Mode," IEEE Power Electronics Specialist Conference Record, Atlanta, San Diago, CA, USA, pp 284-301, 1979.

[25] Middlebrook R. D., and Slobodan Ćuk, "A New Optimum Topology Switching DC -DC converter," IEEE Power Electronics Conference Record, Palo Alto, CA, USA, pp 170-179, 1977.

[26] Loman Rensink, Art Brown, Shi-Ping Hsu, and Slobodan Ćuk, "Design of a Kilo-Watt Off-line Switcher Using a Ćuk Converter," Powercon 6, the Sixth National Solid-State Power Conversion Conference held in May 2-4, in Miami Beach, FL, 1979.

[27] Loman Rensink, "Switching Regulator Configurations and Circuit Realizations," California Institute of Technology, December 1979.

[28] Hunt W. T. , Jr., and Robert Stein, "Static Electromagnetic Devices, Allyn and Bacon; 1984.

[29] Slobodan Ćuk, "Basics of Switched Mode Power Conversion: Topologies, Magnetics and Control."

[30] Slobodan Ćuk, "Switching DC-to-DC Converter with Zero Input or Output Current Ripple," IEEE Industry Applications Society Annual Meeting, 1978 Record, Toronto, ONT, USA, pp 1131-1146, October 1-5, 1978.

[31] Slobodan Ćuk, "Discontinuous Inductor Current Mode in the Optimum Topology Switching Converter," IEEE Power Electronics Specialist Conference, 1978 Record, pp 105-123, Syracuse, NY, June 13-15, 1978.

[32] Rashid M. H., "Power Electronics Circuits, Device, and Applications," Prentice Hall of India Private Limited, Third Edition, pp 166-221, 2004.

[33] Forsyth A. J., and Mollov S. V., "Modeling and Control of DC-DC Converters," Power Engineering Journal, vol. 12, No. 5, pp 229-236, 1988.

[34] Sevems R. P., and Bloom G. E., "Modern DC-to-DC Switch Mode Power Converter Circuits," New DC-to-DC Switch Mode Power Converter Circuits," New York: Van Nostrand Reinhold, 1983.

[35] Chung H. S. H., "Design and Analysis of a Switched-capacitor-based Step-up DC/DC Converter with Continuous Input current," IEEE Transaction on Circuits and Systems I: Fundamental Theory and Applications, vol. 46, No. 6, pp 722-730, 1999.

[36] OrCAD 9.1 Software, 1985-1999, OrCAD Inc., USA.

[37] Rashid M. H., " Power Electronics Handbook," Academic Press, An Imprint of Elsevier, San Diago, California, Chapter 13 and 15, 2004.

[38] Sen P. C., "Power Electronics," Tata McGraw-Hill Publishing Company Ltd., India, pp 588-614, 1987.

[39] Mealing J. M.(Jr), "A Coherent Approach to the Design of switching Mode DC Regulators," IEEE Conference Record, IGA, pp. 177-185, October1967.

[40] Mitchell D. M., "DC-DC Switching Regulator," New York: McGraw-Hill, Chapter 2 and 4, 1988.