ANALYSIS OF A NEW FOUR QUADRANT SWITCH MODE DC-DC CONVERTER.

By

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BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY (BUET)

DECEMBER 2011

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A thesis submitted
to
the Department of Electrical and Electronic Engineering in partial fulfillment for the degree of
Master of Science in Electrical and Electronic Engineering

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING

The thesis titled "**AN ANALYSIS OF A NEW FOUR QUADRANT SWITCH MODE DC-DC CONVERTER**".

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Roll no. : 100606102P, Session : October 2006

has been accepted as satisfactory in partial fulfilment of the requirement for the degree of Master of Science in Electrical and Electronic Engineering on December 26, 2011.

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Candidate's Declaration

I hereby declare that this thesis has been prepared in partial fulfillment of the requirement for the degree of **Master of Science in Electrical and Electronic Engineering** at the **Bangladesh University of Engineering and Technology (BUET),** Dhaka and has not been submitted anywhere else for any other degree.

Signature of Candidate

26.12.2011

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Mohammad Mazharul Islam
Student No. 100606102P
EEE,BUET, Dhaka

Dedicated

to

My parents

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Abbreviations

V_{in} = The input voltage

V_a = The average output voltage

ΔV_c = Peak-to-peak ripple voltage of the capacitor.

V_{st} = peak of the saw tooth waveform

$V_{control}$ = peak of the control waveform

T_{ON} = Turn on time.

T_{OFF} = Turn off time.

T = T_{ON} + T_{OFF}.= Time period

D = Duty cycle = T_{ON} / T.

I_a = The average load current

f = Switching frequency

L = Inductor

C = Filter capacitance

ΔI = Peak-to-peak ripple current of the inductor.

Acknowledgement

All praises goes to **Almighty** to bless me the knowledge and ability to do the present study. My indebt gratitude must be to the most benevolent and merciful for everything what I have accepted from him.

It is the greatest pleasure to acknowledge my deepest gratitude to my supervisor **Dr. Mohammad Ali Choudhury,** Professor, Department of Electrical and Electronic Engineering, Bangladesh University of Engineering and Technology (BUET), Dhaka, for his continuous guidance, benevolence cooperation, valuable suggestions, and continual encouragement at all stages of the study.

I would like to express my sincere thanks and regards to all of my faculty members of the department especially the thesis examination committee members **Professor Dr. Saifur Rahman**, professor and head of the Department of Electrical and Electronic Engineering, Bangladesh University of Engineering and Technology (BUET) and **Dr. Mohammad Jahangir Alam**, professor, Department of Electrical and Electronic Engineering, Bangladesh University of Engineering and Technology (BUET), Dhaka, and **Dr. Md. Ashraful Hoque** Professor, Department of Electrical and Electronic Engineering, Islamic University of Technology (IUT), Gazipur. for critically reviewing the manuscript and for valuable suggestions for improvement of thesis.

I wish to convey my sincere thanks to all of my well wishers for their constant encouragement, sympathetic co-operation and mental support as well as backing at all stages of my thesis work.

Words would be simple and worthless for showing my heartily appreciation to my family. My family is the crypt of my all muse, ethics and values. My little effort to this study is just a reflection of that.

Finally, I also express my thanks to librarian and all staffs of the Department of Electrical and Electronic Engineering, BUET, for their cordial help and assistance. And embedded respect, of course, to the sample families for whom this research has been undertaken.

Mohammad Mazharul Islam

December, 2011

Abstract

In this thesis, two separate switch mode converters with voltage lift circuits with two sources and complex gate pulse control has been investigated. To reduce the number of supplies to one and ease the control signals, differential connection of Luo forward and Luo reverse two quadrant choppers have been proposed and investigated.

A new topology has emerged out of the research to provide four quadrant operation of a high frequency dc-dc converter having one supply source and easy gate pulse control. This new topology has been developed out of switching dc-dc converters with voltage lift circuits; its operational range is wide at high conversion efficiency, whereas, the present four quadrant switching dc-dc converters' conversion efficiency decreases around the operation of a particular duty cycle.

In previous work two separate switch mode dc-dc converters with voltage lift circuits, one working in two quadrant forward mode and the other working in two quadrant reverse mode have been switched by complex gate pulses to obtain the four quadrant dc-dc operation. Two sources are necessary for such circuit. Combining the two circuits to have single source topology would result in mal-operation due to overlapping switches. In this research differential connection of the load at the output of the two converters fed by same source has been investigated as per claimed of previous work. But the converter did not perform as four quadrant chopper because the reverse Luo converter does not work as it has been claimed.

It is found in simulation that these two source converters do not operate as claimed and they cannot be combined in any way to operate in four quadrants as a single power conversion circuit. It was therefore, necessitated separate method to obtain SMPS based Buck-Boost single four quadrant DC-DC converter.

The result is a single source topology switched by conventional ON/OFF duty cycle control as used in other high power chopper circuits. The combined topology has been analyzed and studied by spice simulation.

Chapter-1

ITRODUCTION

Power quality is the quality of voltage and current. It is an important consideration in industries and commercial applications. Power quality problems commonly faced are transients, sags, swells, surges, outages, harmonics, and impulses. Among these voltage sags and extended under voltages have negative impact on industrial productivity, and could be the most important type of power quality variation for many industrial and commercial customers. It is necessary that some converters are to be used to improve the quality power supply. Power semiconductor devices are making it possible for utilities to use a variety of power control equipment to raise power quality levels to meet the requirements

The DC– DC converter, also known as chopper, is a converter which transforms a D.C. The average value of a chopper's output voltage can be modified between zero and the full feeding voltage, using the "Pulse Width Modulation (PWM)" principle of constant frequency pulses. There are schemes of chopper operating in one to four quadrants. The H bridge converters are widely utilized in adjustable electrical drives with d.c. motors. An arm of this bridge is obtained by series connection of two controllable power switches. Each switch has an antiparallel diode, called "free-wheeling diode". The two switches of an arm structure work anti-phase.

Several types of converter are available which operate in single or two quadrants. There are more than 500 topologies of DC/DC converters. A common DC/DC converter family tree is shown in Figure 1.1.

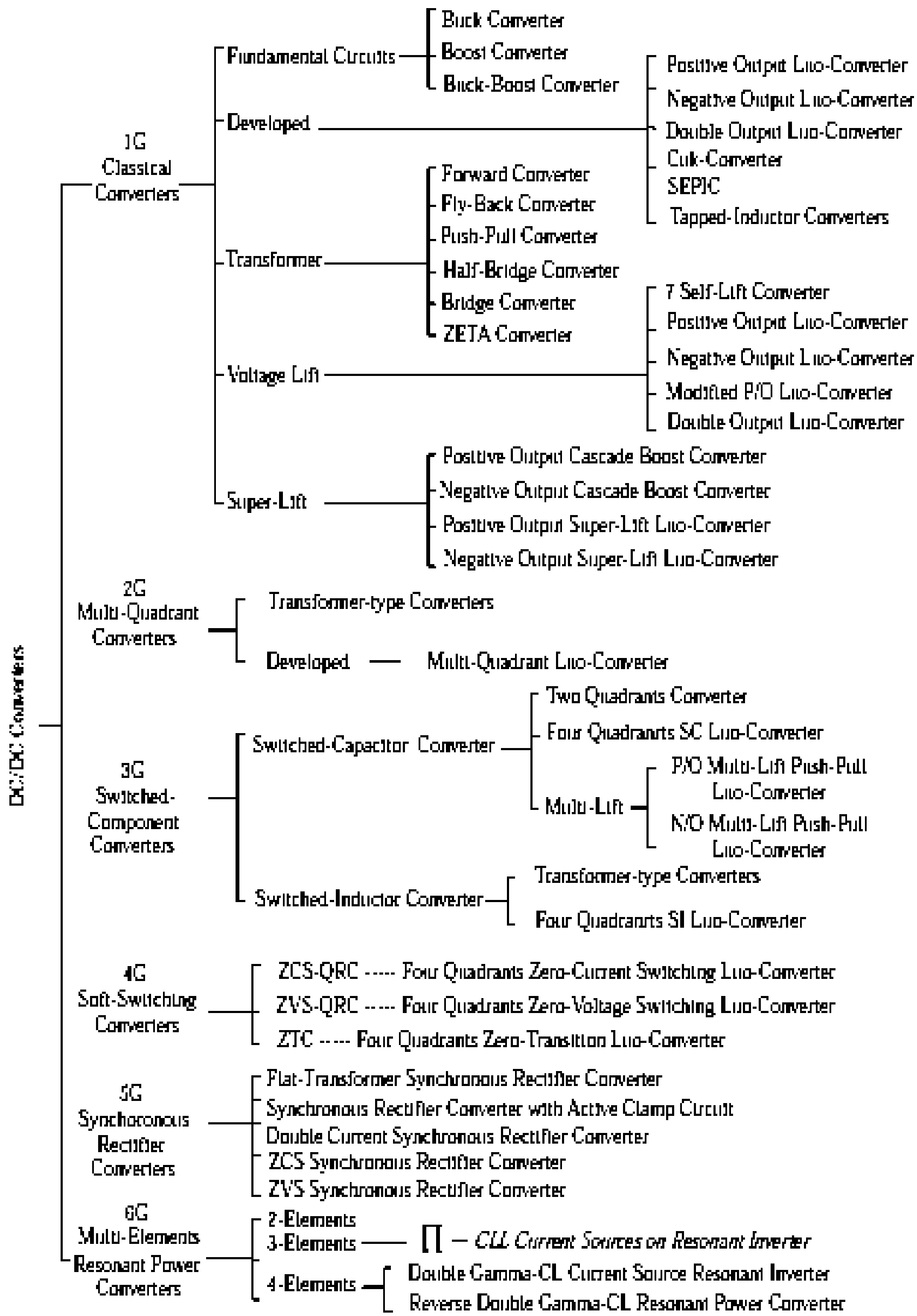


Figure 1.1: - DC/DC converter family Tree.

One such converter is Lou converter. The author investigated and suggested that combined circuit of four quadrant converter is possible. But compact and fully FOUR QUADRANT SWITCH MODE DC-DC CONVERTER is still unavailable. This work is a continuation of previous research to develop a NEW FOUR QUADRANT SWITCH MODE DC-DC CONVERTER with improved performance.

1. BACKGROUND OF SWITCH MODE DC- DC CONVERTERS (SMPS) [1-2, 23-24, 30-33, 38-39]:

Conventional switch mode dc-dc converters (SMPS) operate either in single quadrant or in two quadrants [1-2]. A switch mode DC-DC power supply is switched at very high frequency. Conversion of both step down and step up dc with insignificant filter size having facility of feed back regulation by on/off high frequency switching is possible in an SMPS. Usually SMPSs are used in dc-dc conversion for their light weight, high efficiency and isolated multiple outputs with and without voltage regulation. Uses of SMPSs are now universal in space power applications, computers, TV and industrial units. SMPSs have advantages of being low cost, compact, self regulating and self protected.

A simple DC-DC SMPS consists of a rectifier fed directly from line voltage, a filter and a static switch. The SMPS is switched by control circuitry at a very high frequency to step down or step up dc voltage by on/off ratio (duty cycle) control. The filter and the feedback circuit are the other components of a DC-DC SMPS. Figure-1.2 shows the block diagram of a DC-DC SMPS.

Main components of a dc-dc SMPS are:

1. Power circuit
2. Control circuit
3. Magnetic circuit.

The control circuit of an SMPS generates high frequency gate pulses for the switching device to control the dc. Switching is performed in multiple pulse width modulation (PWM) fashion according to feedback error signal from the load to serve two purposes,

1. Produce high frequency switching signal.

2. Control on / off period of switching signal to maintain constant voltage across the load.

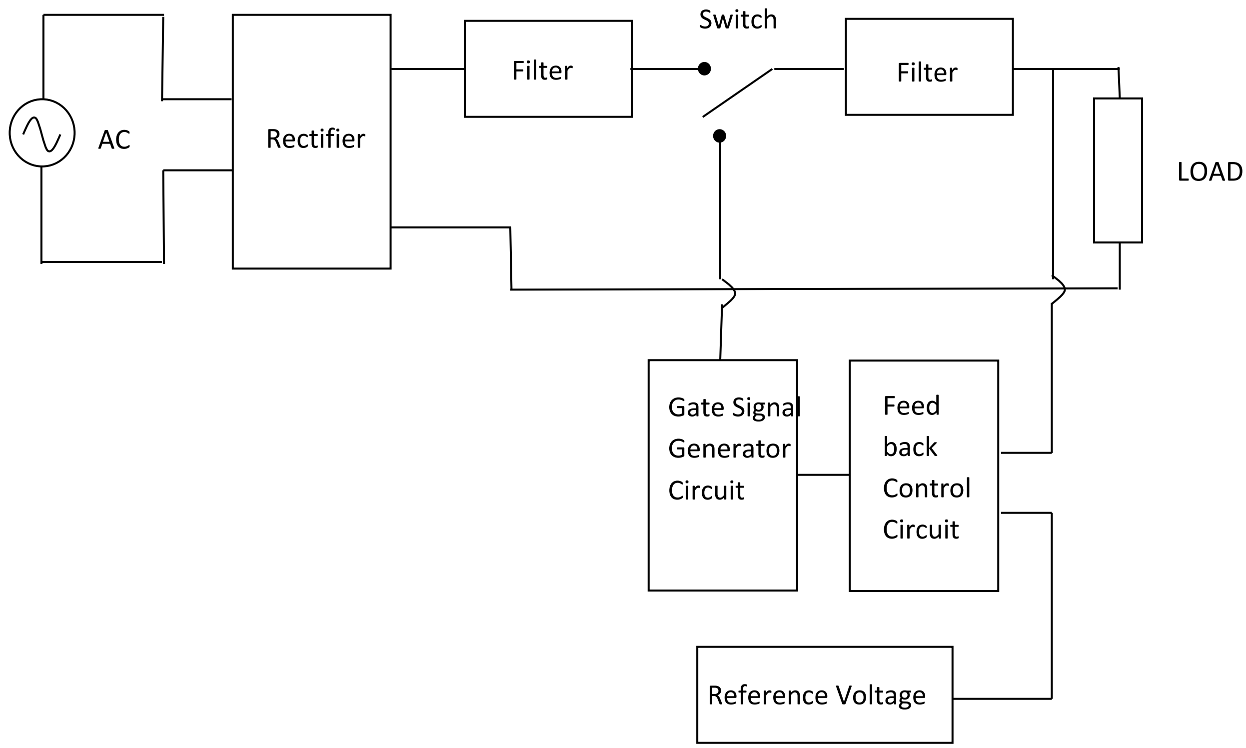


Figure-1.2: Block Diagram of SMPS.

High frequency switching reduces filter requirements at the input/output sides of the converter. Simplest PWM control uses multiple pulse modulations generated by comparing a dc with a high frequency carrier triangular wave.

Switching regulators are commonly available as integrated circuits. The designer can select the switching frequency by choosing the value of RC to set oscillator frequency. As a rule of thumb to maximize the efficiency, the oscillator period should be about 100 times longer than the transistor switching time; for example, if a transistor has a switching time of 0.5 µs, the oscillator period would be 50 µs, which gives the maximum oscillator frequency of 20 KHz. The limitation is due to the switching loss in the transistor. The transistor switching loss increases with the switching frequency and as a result the efficiency decreases. In addition, the core loss of inductor limits the high frequency operation.

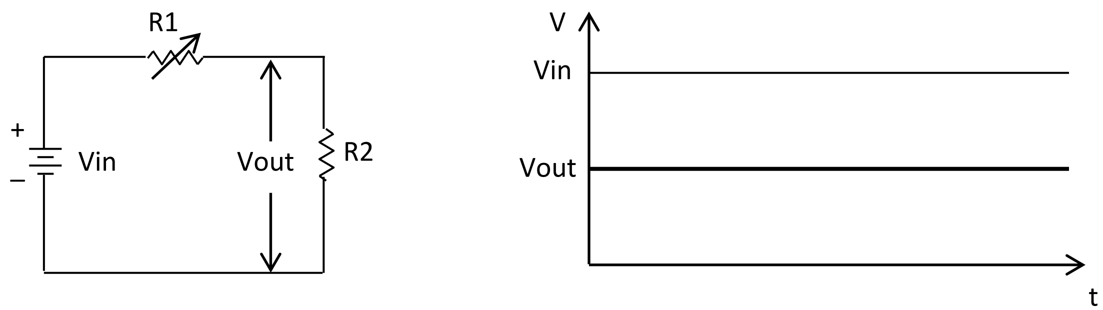


Figure-1.3: Linear (dissipative) power conversion circuit.

Figure-1.3 illustrates the circuit of a linear power conversion. Here power is controlled by a series linear element; either a resister or a transistor is used in the linear mode. The total load current passes through the series linear element. In this circuit greater the difference between the input and the output voltage, more is the power lost in the controlling device. Linear power conversion is dissipative and hence is inefficient. The efficiency range is typically 30 to 60% for linear regulators.

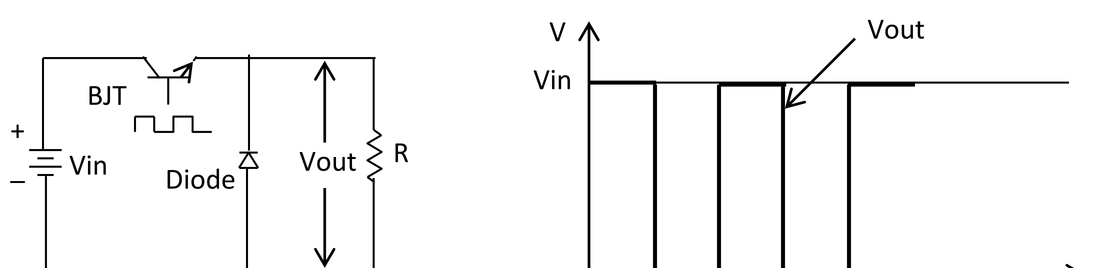


Figure-1.4: Switch mode (non dissipative) power conversion circuit.

The circuit of Figure-1.4 illustrates basic principle of a dc-dc switch mode power conversion. The controlling device is a switch. By controlling the ratio of the time intervals spent in on and off positions (defined as duty ratio), the power flow to the load can be controlled in an efficient way. Ideally this method is 100% efficient. In practice, the efficiency is reduced as the switch is non-ideal and losses occur in power circuits.

The dc voltage to the load can be controlled by controlling the duty cycle of the rectangular waveform supplied to the base or gate of the switching device. When the switch is fully on, it has only a small saturation voltage across it. In the off condition the current through the device is zero.

The output of the switch mode power conversion control (Figure-1.4) is not pure dc. This type of output is applicable in cases such as oven heating without proper filtration. If constant dc is required, then output of SMPS has to be smoothed out by the addition of a low-pass filter. Switches are required as basic components for efficient electric power conversion and control. Inductors and capacitors are used to smooth the pulsating dc originating from the switching action.

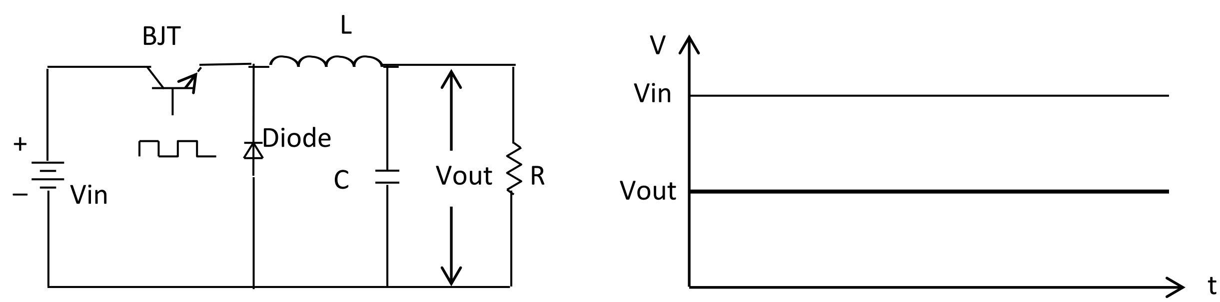


Figure-1.5: Typical switch mode power conversion circuit.

Although the conversion would be 100% efficient in the ideal case of lossless components (Figure-1.5), in practice all components are loss. Thus, efficiency is reduced. Hence, one of the prime objectives in switch mode power conversion is to realize conversion with the least number of components having better efficiency and reliability.

1.2 TYPES OF DC-DC CONVERTERS

There are four basic topologies of switching regulators:

a. Buck converter

b. Boost converter

c. Buck-Boost converter r and

d. Ĉuk converter.

1.2.1 BUCK CONVERTER [14 -16, 20, 26]

In Buck converters, output voltage is regulated and is less than the input voltage, hence the name "Buck". The circuit diagram is shown in Figure-1.6, the circuit operations can be divided into two modes. Mode 1 begins when transistor Q_1 is switched on at t = 0. The input current rises and flows through inductor L, capacitor C and load resistor R. Mode 2 begins when transistor Q_1 is switched off at $t = t_1$. The freewheeling diode D_m conducts due to energy stored in the inductor and the inductor current continuous to flow through L, C, load, and diode D_m. The inductor current falls until transistor is switched on again in the next cycle.

The voltage across the inductor L, is in general,

$$e_L = L\frac{di}{dt} \qquad (1.1)$$

Assuming that the inductor current rises linearly from I_1 to I_2 in time t1,

$$V_s - V_a = L\frac{I_2 - I_1}{t_1} = L\frac{\Delta I}{t_1} \qquad (1.2)$$

or

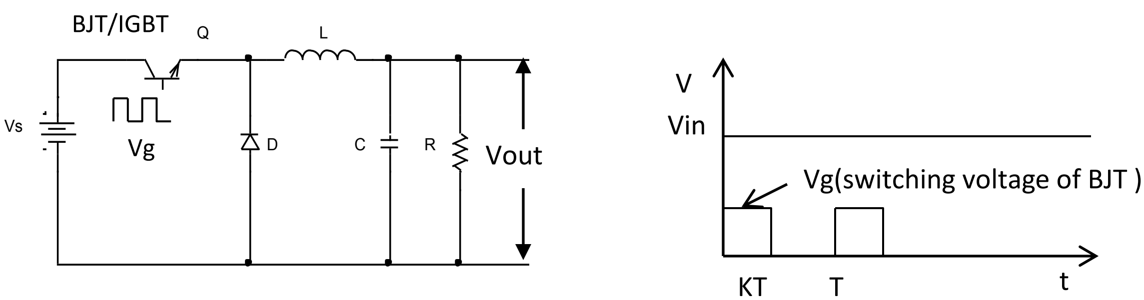
$$t_1 = \frac{L\Delta I}{V_s - V_a} \qquad (1.3)$$

And the inductor current falls linearly from I_2 to I_1 in time t_2,

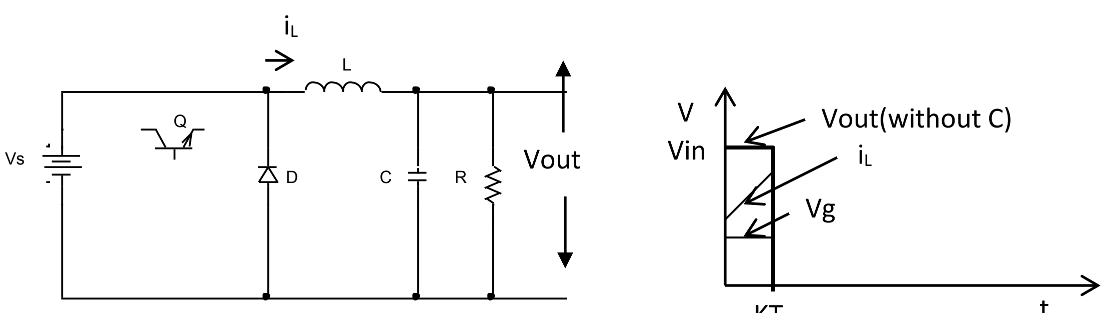
$$-V_a = L\frac{\Delta I}{t_2} \tag{1.4}$$

or

$$t_2 = \frac{\Delta I L}{V_a} \tag{1.5}$$

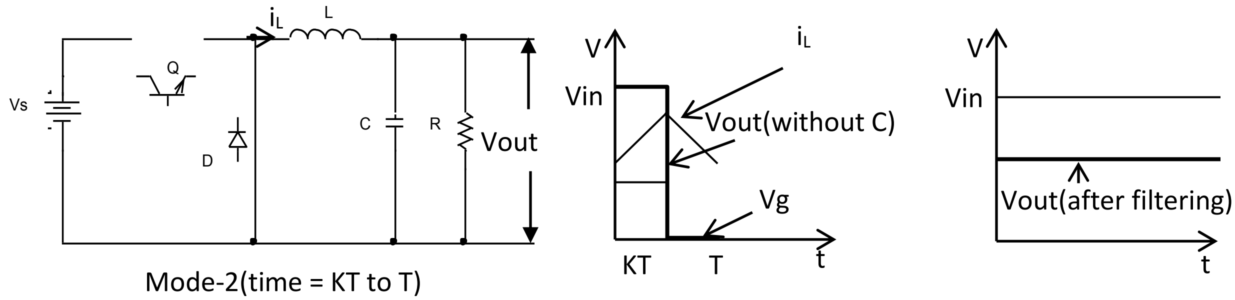


(a) Circuit diagram



Mode-1(time = 0 to KT)

(b) Equivalent circuits



(c) Equivalent circuits (d) Wave forms

Figure-1.6: Buck converter with continuous i_L.

Where $\Delta I = I_2 - I_1$ is the peak to peak ripple current of the inductor L. equating the value of ΔI in equations-(1.2) and (1.4) we get,

$$\Delta I = \frac{(V_s - V_a)t_1}{L} = \frac{V_a t_2}{L} \tag{1.6}$$

Substituting $t_1 = KT$ and $t_2 = (1-K)T$ yields the average output voltage as

$$V_a = V_s \frac{t_1}{T} = KV_s \tag{1.7}$$

From equation (1.7) it is seen that output voltage V_a is less than the input voltage V_s since K is less than 1.

1.2.2 BOOST CONVERTER [14-15, 16, 19]

In Boost converters, the output voltage is greater than the input voltage, hence the name "Boost". The circuit diagram is shown in Figure-1.7, the circuit operations can be divided into two modes. Mode 1 begins when transistor Q_1 is switched on at $t = 0$. The input current rises and flows through inductor L and transistor Q_1. Mode 2 begins when transistor Q_1 is switched off at $t = t_1$. The current which was flowing through the transistor would now flow through L, C, load and diode D_m. The inductor current falls until transistor Q_1 is turned on again in the next cycle. The energy stored in inductor L is transferred to the load.

Assuming that the inductor current rises linearly from I_1 to I_2 in time t1,

$$V_s = L\frac{I_2 - I_1}{t_1} = L\frac{\Delta I}{t_1} \tag{1.8}$$

or

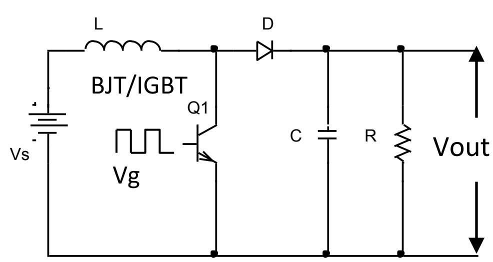
$$t_1 = \frac{L\Delta I}{V_s} \tag{1.9}$$

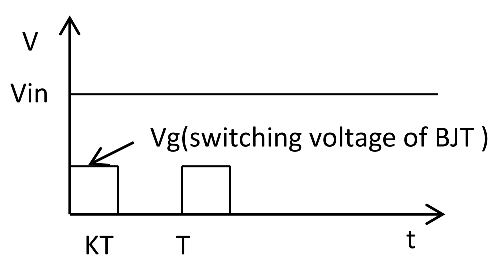
And the inductor current falls linearly from I_2 to I_1 in time t_2,

$$V_s - V_a = -L\frac{\Delta I}{t_2} \tag{1.10}$$

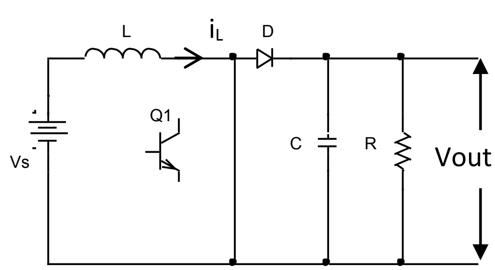
or

$$t_2 = \frac{\Delta I L}{V_a - V_s} \tag{1.11}$$

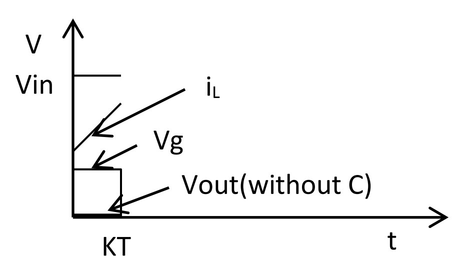




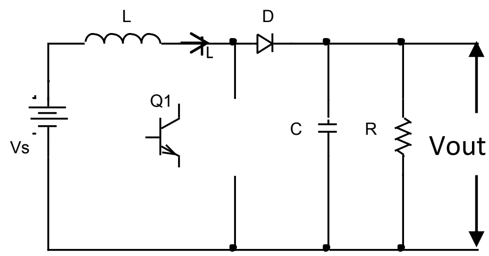
(a) Circuit diagram



Mode-1(time = 0 to KT)

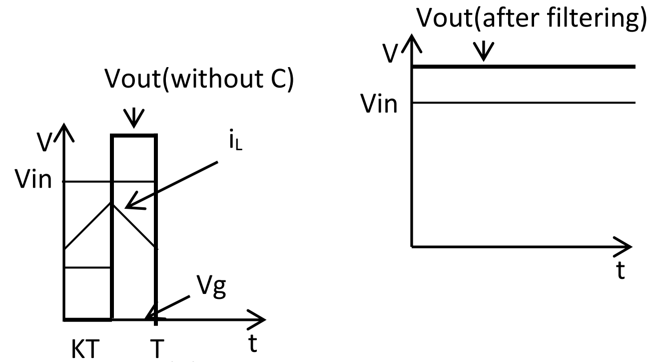


(b) Equivalent circuits



Mode-2(time = KT to T)

(c) Equivalent circuits



(d) Wave forms

Figure-1.7: Boost converter with continuous i_L.

Where $\Delta I = I_2 - I_1$ is the peak to peak ripple current of the inductor L. From equations- (1.8) and (1.10) we get

$$\Delta I = \frac{V_s t_1}{L} = \frac{(V_a - V_s)t_2}{L} \qquad (1.12)$$

Substituting t_1 = KT and t_2 = (1-K)T yields the average output voltage,

$$V_a = V_s \frac{T}{t_2} = \frac{V_s}{1 - K} \qquad (1.13)$$

From equation (1.13) it is seen that output V_a is greater than the input V_s since K is less than 1.

1.2.3 BUCK- BOOST CONVERTER [14, 16, 19-20, 38, 41]

Buck converters can step-down and boost converters can step-up dc voltages individually. The Buck-Boost converter in which the inductor is grounded can perform either of these two conversions. The output voltage polarity is opposite to input voltage and as a result the converter is also known as an *inverting* converter.

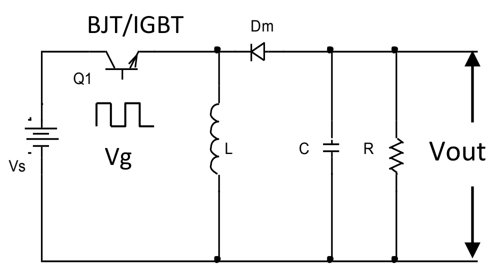
Operation of the Buck-Boost converter can be explained with the help of Figure-1.8. During mode 1, transistor Q_1 is turned on and diode D_m is reversed biased. The input current which rises flows through inductor L and transistor Q_1. During mode 2, transistor Q_1 is switched off and the current, which was flowing through inductor L, would flow through L, C, D_m and the load. The energy stored in inductor L would be transferred to the load and the inductor current would fall until transistor Q_1 is switched on again in the next cycle.

Assuming that the inductor current rises linearly from I_1 to I_2 in time t1,

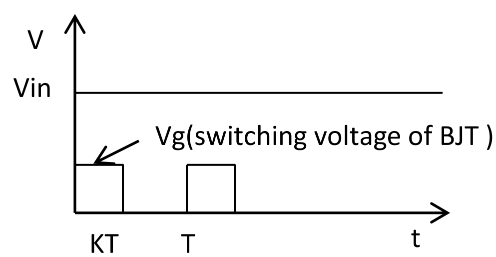
$$V_s = L\frac{I_2 - I_1}{t_1} = L\frac{\Delta I}{t_1} \tag{1.14}$$

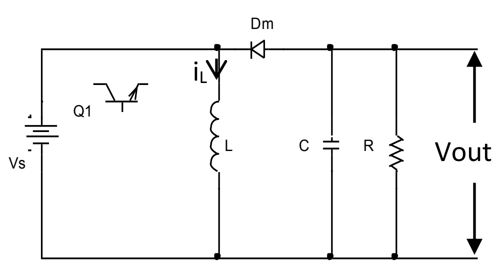
or

$$t_1 = \frac{L\Delta I}{V_s} \tag{1.15}$$



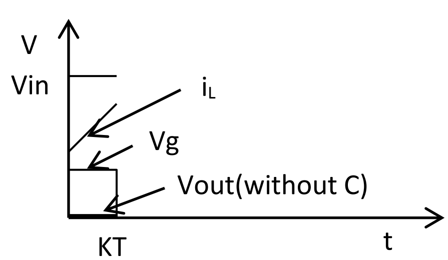
(a) Circuit diagram

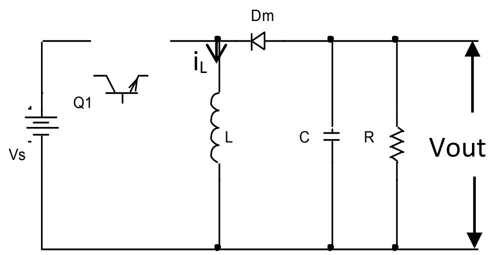




Mode-1(time = 0 to KT)

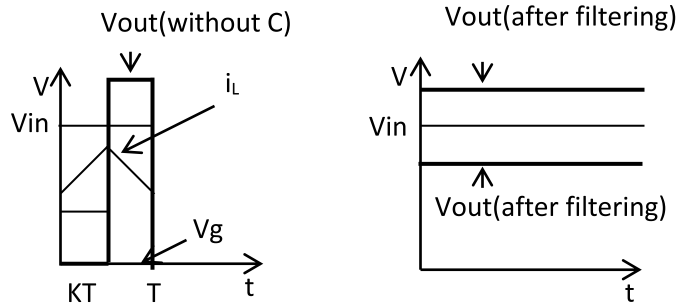
(b) Equivalent circuits





Mode-2(time = KT to T)

(c) Equivalent circuits



(d) Wave forms

Figure-1.8: Buck-Boost converter with continuous i_L.

And the inductor current falls linearly from I_2 to I_1 in time t_2,

$$V_a = -L\frac{\Delta I}{t_2} \tag{1.16}$$

or

$$t_2 = \frac{-\Delta I L}{V_a} \tag{1.17}$$

Where $\Delta I = I_2 - I_1$ is the peak to peak ripple current of the inductor L. From equations- (1.14) and (1.16) we get

$$\Delta I = \frac{V_s t_1}{L} = \frac{-V_a t_2}{L} \tag{1.18}$$

Substituting t_1 = KT and t_2 = (1-K)T yields the average output voltage,

$$V_a = \frac{-V_s K}{1-K} \tag{1.19}$$

From equation (1.19) it is seen that output V_a is greater than input V_s, when K is greater than 0.5 and output V_a is less than input V_s, when K is less than 0.5.

1.2.4 ĈuK CONVERTER [15, 16, 33-38, 41]

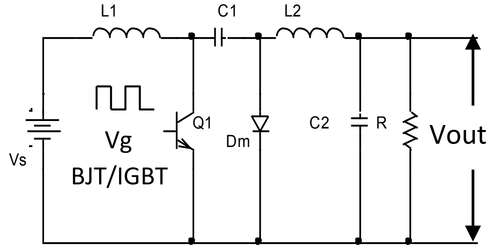
It is the modified form of Buck-Boost converter having the capability to regulate input voltage in both buck and boost way. The operation can be explained with the help of Figure-1.9. Mode 1 begins when transistor Q_1 is turned on at t = 0. The current through inductor L_1 rises. At the same time, the voltage of the capacitor C_1 reverse biases diode Dm and turns it off. The capacitor discharges its energy to the circuit formed by C_1, C_2, load and L_2. Mode 2 begins when transistor Q_1 is turned off at $t = t_1$. The capacitor C_1 is charged from input supply and the energy stored in the inductor L_2 is transferred to the load. The diode D_m and transistor Q_1 provide a synchronous switching action. The capacitor C_1 is the media for transferring energy from the source to the load.

Assuming that the current of inductor L_1 rises linearly from I_{L11} to I_{L12} in time t_1,

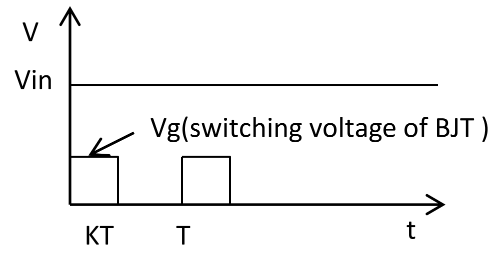
$$V_s = L_1 \frac{I_{L12} - I_{L11}}{t_1} = L_1 \frac{\Delta I_1}{t_1} \qquad (1.20)$$

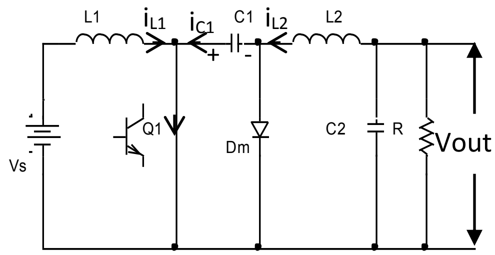
or

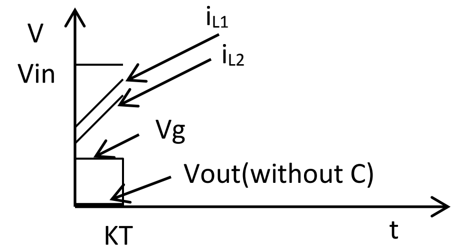
$$t_1 = \frac{L_1 \Delta I_1}{V_s} \qquad (1.21)$$



(a) Circuit diagram

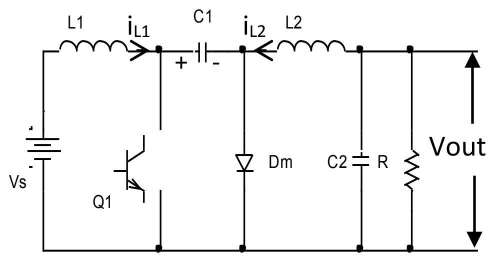




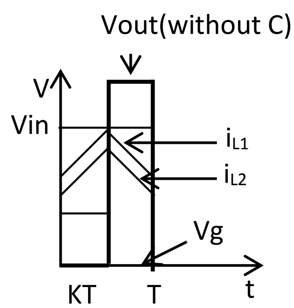


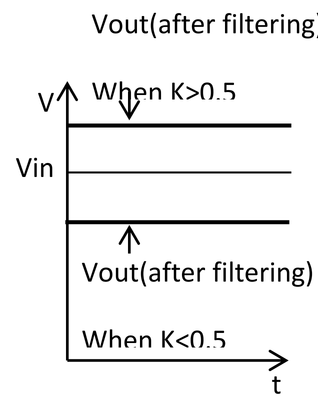
Mode-1(time=0 to KT)

(b) Equivalent circuits



Mode-2(time=KT to T)





(c) Equivalent circuits

(d) Wave forms

Figure-1.9: Ĉuk converter with continuous i_L.

And due to the charged capacitor C_1, the inductor L_1 current falls linearly from I_{L12} to I_{L11} in time t_2,

$$V_s - V_{c1} = -L_1 \frac{\Delta I_1}{t_2} \tag{1.22}$$

or

$$t_2 = \frac{-\Delta I_1 L_1}{V_s - V_{c1}} \tag{1.23}$$

Where V_{c1} is the average voltage of capacitor C_1 and $\Delta I_1 = I_{L12} - I_{L11}$ is the peak to peak ripple current of the inductor L_1. From equations (1.20) and (1.22),

$$\Delta I_1 = \frac{V_s t_1}{L_1} = \frac{-(V_s - V_{c1})t_2}{L_1} \quad (1.24)$$

Substituting t_1 = KT and t_2 = (1-K)T yields the average voltage of capacitor C_1 is V_{c1}.

$$V_{c1} = \frac{V_s}{1-K} \quad (1.25)$$

Assuming that the current of inductor L_2 rises linearly from I_{L21} to I_{L22} in time t_1,

$$V_{c1} + V_a = L_2 \frac{I_{L22} - I_{L21}}{t_1} = L_2 \frac{\Delta I_2}{t_1} \quad (1.26)$$

or

$$t_1 = \frac{L_2 \Delta I_2}{V_{c1} + V_a} \quad (1.27)$$

And the current of inductor L_2 falls linearly from I_{L22} to I_{L21} in time t_2,

$$V_a = -L_2 \frac{\Delta I_2}{t_2} \quad (1.28)$$

or

$$t_2 = \frac{-\Delta I_2 L_2}{V_a} \quad (1.29)$$

$\Delta I_2 = I_{L22} - I_{L21}$ is the peak to peak ripple current of the inductor L_2. From equations (1.26) and (1.28),

$$\Delta I_2 = \frac{-V_a t_2}{L_2} = \frac{(V_{c1} + V_a)t_1}{L_2} \quad (1.30)$$

Substituting t_1 = KT and t_2 = (1-K)T yields the average voltage of capacitor C_1 is V_{c1}.

$$V_{c1} = \frac{-V_a}{K} \quad (1.31)$$

Equating equations (1.25) and (1.31) we can find the average output voltage as

$$V_a = \frac{-KV_S}{1-K} \tag{1.32}$$

From equation (1.32) it is seen that output V_a is greater than input V_s, when K is greater than 0.5 and output V_a is less than input V_s, when K is less than 0.5.

1.2.5 ADVANTAGES OF AN SMPS [1-2, 14-17, 20-24, 27, 38 -41]:

Switch mode power supplies have following advantageous features:

* Isolation between the source and the load
* High power density for reduction of size and weight
* Controlled direction of power flow
* High conversion efficiency
* Input and output waveforms with low total harmonic distortion for small filters
* Controlled power factor if the source is an ac voltage.

1.3 DC CHOPPERS [1-2, 14-17, 20-24, 27, 38 -41]**:**

Basic SMPS circuits are single quadrant choppers that operate at very high frequency. Choppers are the circuits that convert fixed DC voltage to constant or variable DC voltage or pulse-width–modulated (PWM) AC voltage.

1.3.1 MULTIPLE QUADRANT OPRATION

A DC motor can run in forward running or reverse running. During the forward starting process its armature voltage and armature current are both positive. We usually call this forward motoring operation or quadrant I operation. During the forward braking process its armature voltage is still positive and its armature current is negative. This state is called the forward regenerating operation or quadrant II operation. Analogously, during the reverse starting process the DC motor armature voltage and current are both negative. This reverse motoring operation is called the quadrant III operation.

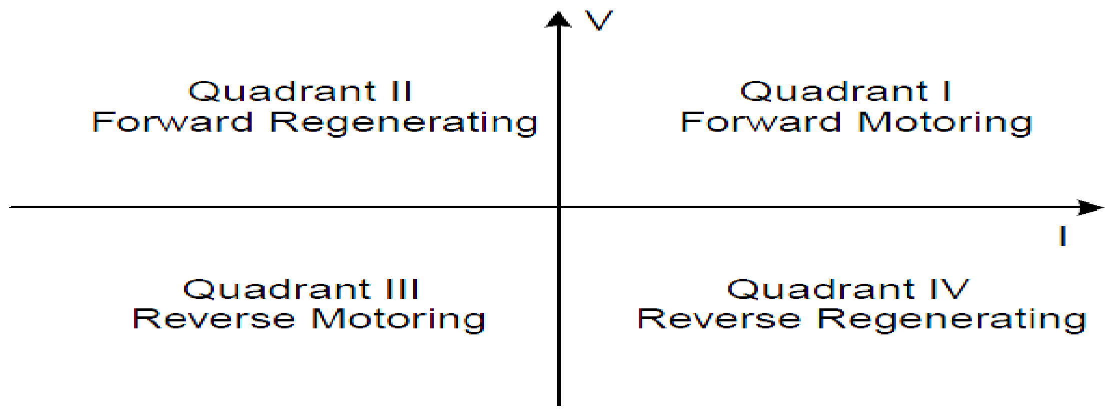


Figure-1.10: Four Quadrant Operation.

During reverse braking process its armature voltage is still negative and its armature current is positive. This state is called the reverse regenerating operation quadrant IV operation. Referring to the DC motor operation states. The classifications of DC-DC choppers according to Vo-Io position in X-Y co-ordinates are as follows:

Quadrant I operation: forward motoring, voltage is positive, current is positive; (+Vo +Io).

Quadrant II operation: forward regenerating, voltage is positive, current is negative; (+Vo -Io).

Quadrant III operation: reverse motoring, voltage is negative, current is negative; (-Vo -Io).

Quadrant IV operation: reverse regenerating, voltage is negative, current is positive; (-Vo +Io).

The operation status is shown in the Figure 1.10. Choppers can convert a fixed DC voltage into various other voltages. The corresponding chopper is usually named according to its quadrant operation chopper, e.g., the first quadrant chopper or "A"-type chopper. In the following description we use the symbols V_{in} as the fixed voltage, V_p the chopped voltage, and V_O the output voltage.

1.3.2 THE QUADRANT-ONE CHOPPER.

The one-quadrant chopper is also called "A"-type chopper and its circuit diagram is shown in Figure 1.11a and corresponding waveforms are shown in Figure 1.11b. The switch S can be some semiconductor devices such as BJT, IGBT, and MOSFET. Assuming all parts are ideal components, the output voltage is calculated by the formula, (1.33)

$$V_o = \frac{t_{on}}{T} V_{in} = kV_{in} \tag{1.33}$$

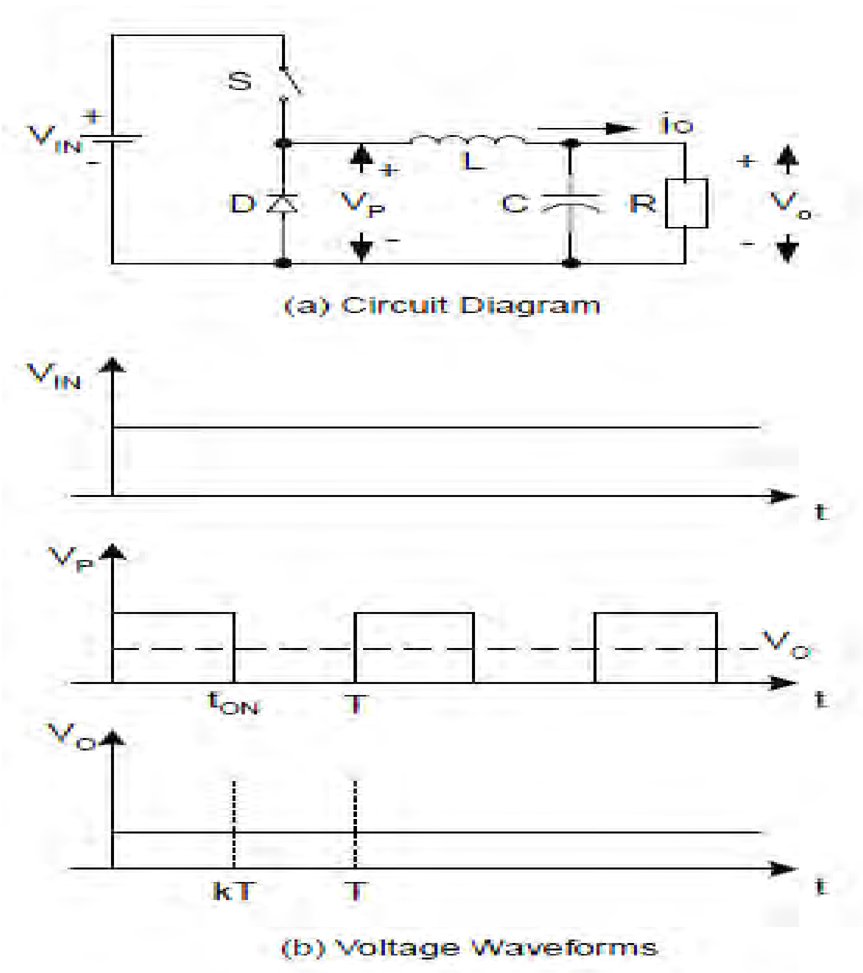


FIGURE 1.11: The Quadrant One Chopper.

Where T is the repeating period T = 1/f, f is the chopping frequency, t_{on} is the switch-on time, k is the conduction duty cycle k = t_{on}/T.

1.3.3 THE QUADRANT- TWO CHOPPER.

The two-quadrant chopper is the called "B"-type chopper and the circuit diagram and corresponding waveforms are shown in Figure 1.12a and b. The output voltage can be calculated by the formula,(1.34)

$$V_o = \frac{t_{off}}{T} V_{in} = (1-k)V_{in} \quad (1.34)$$

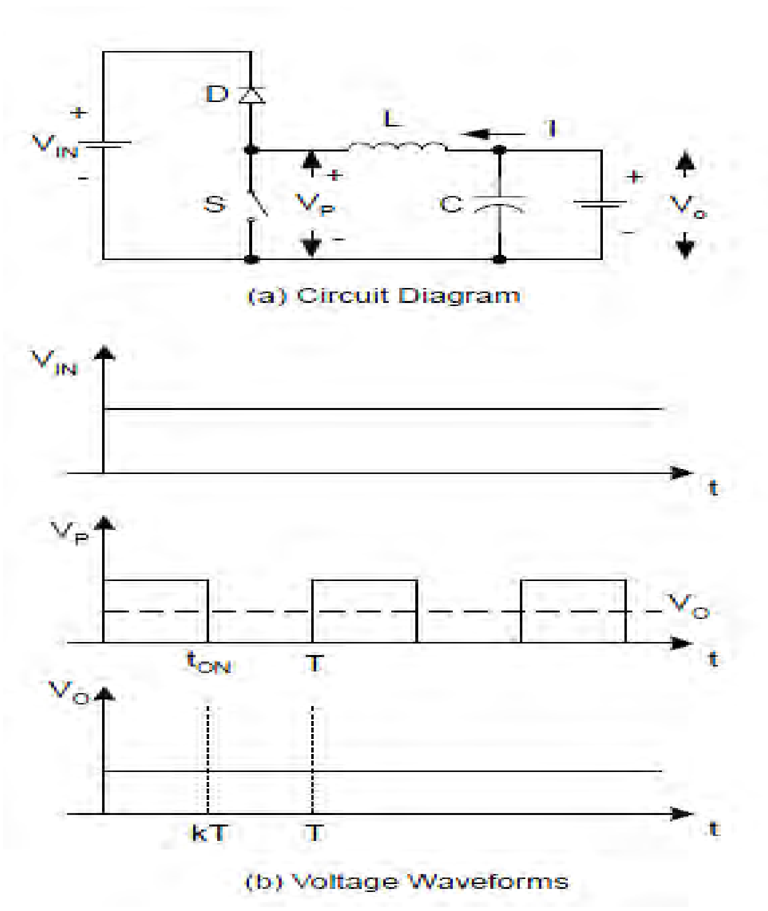


FIGURE 1.12: The Quadrant Two Chopper.

Where T is the repeating period T = 1/f, f is the chopping frequency, toff is the switch-off time toff = T – ton, and k is the conduction duty cycle k = ton/T.

1.3.4 THE QUADRANT- THREE CHOPPER

The three-quadrant chopper and corresponding waveforms are shown in Figure 1.13a and b. All voltage polarity is defined in the figure. The output voltage (absolute value) can be calculated by the formula (1.35)

$$V_o = \frac{t_{on}}{T} V_{in} = -kV_{in} \tag{1.35}$$

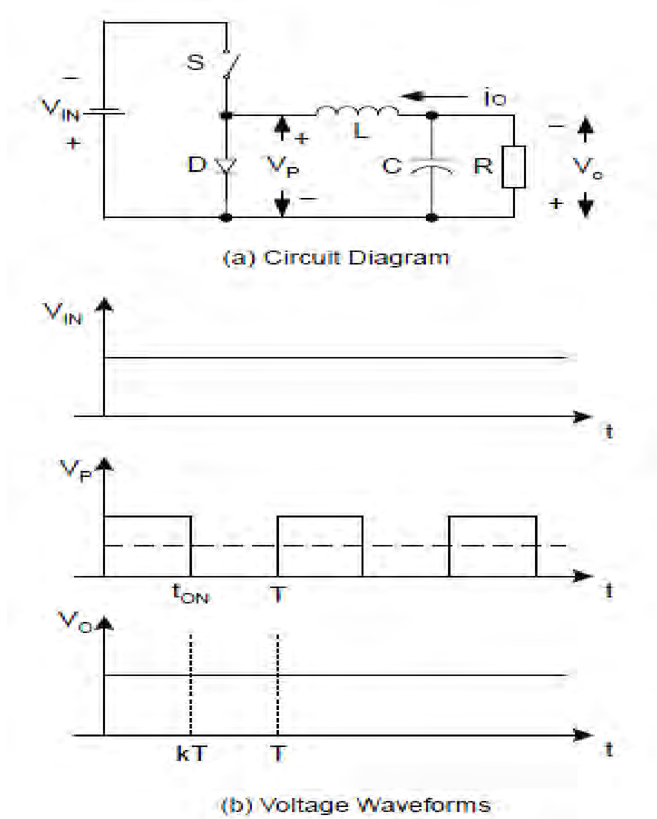


FIGURE 1.13: The Quadrant Three Chopper.

Where t_{on} is the switch-on time, and k is the conduction duty cycle $k = t_{on}/T$.

1.3.5 THE QUADRANT -FOUR CHOPPER

The four-quadrant chopper and corresponding waveforms are shown in Figure 1.14a and b. All voltage polarity is defined in the figure. The output voltage (absolute value) can be calculated by the formula (1.36).

$$Vo = \frac{t_{off}}{T} V_{in} = -(1-k)V_{in} \tag{1.36}$$

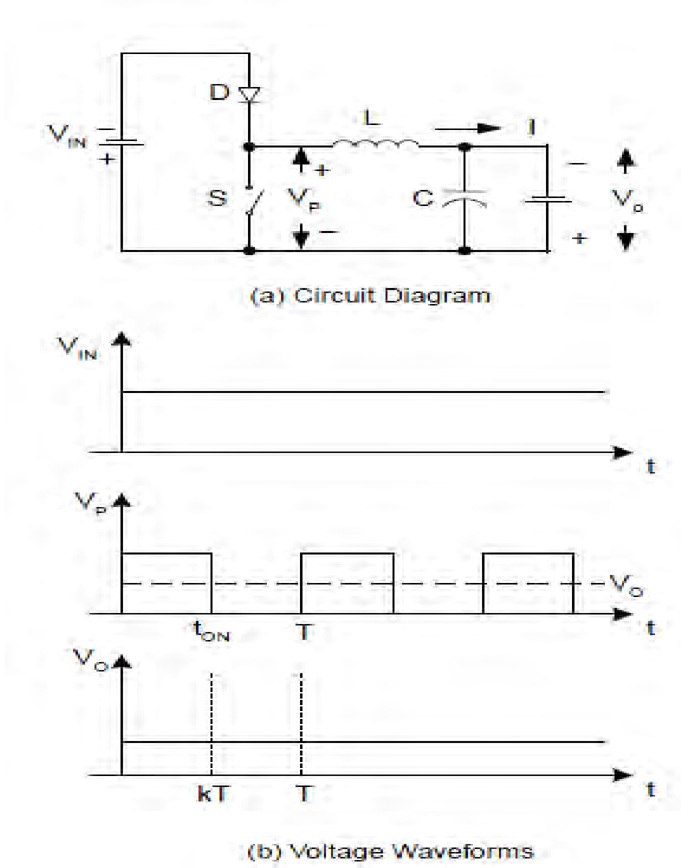


FIGURE 1.14: The Quadrant Four Chopper.

Where t_{off} is the switch-off time $t_{off} = T - t_{on}$, time, and k is the conduction duty cycle $k = t_{on}/T$.

1.3.6 THE ONE AND TWO QUADRANT CHOPPER

The one and two quadrant chopper is shown in Figure 1.15. Dual quadrant operation is usually requested in the system with two voltage sources V1 and V2. Assume that the condition V1 > V2, and the inductor L is an ideal component. During quadrant I operation, S1 and D2 work, and S2 and D1 are idle. Vice versa, during quadrant II operation, S2 and D1 work, and S1 and D2 are idle. The relation between the two voltage sources can be calculated by the formula,(1.37)

$$V_2 = \begin{cases} kV_1 & \text{QI Operation} \\ (1-k)V_1 & \text{QII Operation} \end{cases} \tag{1.37}$$

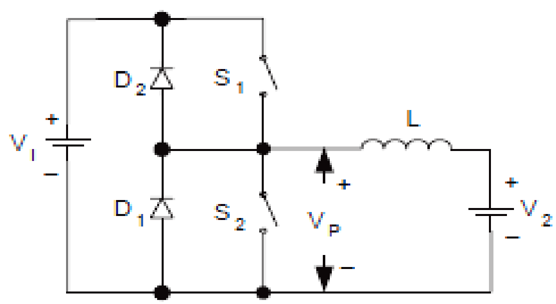


FIGURE 1.15: The One and Two Quadrant Chopper Circuit Diagram.

1.3.7 THE THREE AND FOUR QUADRANT CHOPPER

The three and four quadrant chopper is shown in Figure 1.16. Dual quadrant operation is usually requested in the system with two voltage sources V1 and V2. Both voltage polarities are defined in the figure; we just concentrate their absolute values in analysis and calculation. Assume that the condition V1 > V2, the inductor L is ideal component. During quadrant I operation, S1 and D2 work, and S2 and D1 are idle. Vice versa, during quadrant II operation, S2 and D1 work, and S1 and D2 are idle. The relation between the two voltage sources can be calculated by the formula (1.38).

$$V_2 = \begin{cases} -kV_1 & \text{QIII Operation} \\ -(1-k)V_1 & \text{QIV Operation} \end{cases} \quad (1.38)$$

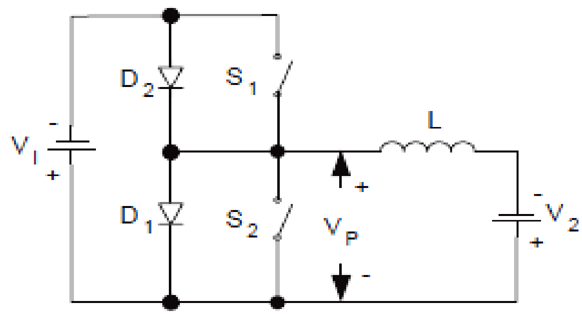


FIGURE 1.16: The Three and Four Quadrant Chopper Circuit Diagram.

1.3.8 THE FOUR-QUADRANT CHOPPER

The four-quadrant chopper is shown in Figure 1.17. The input voltage is positive; output voltage can be either positive or negative. The switches and diode status for the operation are shown in Table 1.1. The output voltage can be calculated by the formula (1.39).

$$V_2 = \begin{cases} kV_1 & \text{QI Operation} \\ (1-k)V_1 & \text{QII Operation} \\ -kV_1 & \text{QIII Operation} \\ -(1-k)V_1 & \text{QIV Operation} \end{cases} \quad (1.39)$$

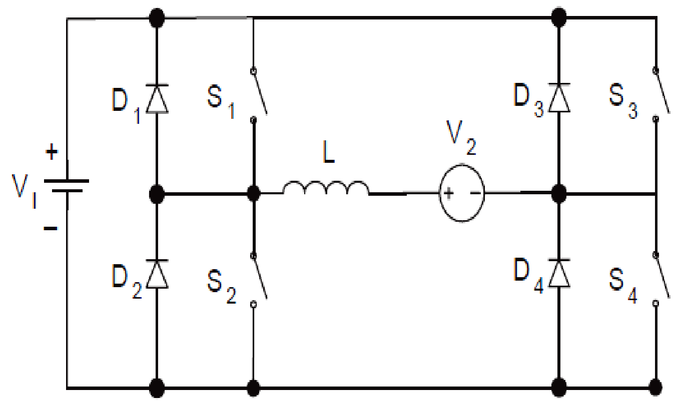


FIGURE 1.17: The Four Quadrant Chopper Circuit Diagram.

Table-1.1:

The Switches and Diode's Status for Four-Quadrant Operation

Switch or Diode	Quadrant I	Quadrant II	Quadrant III	Quadrant IV
S_1	Works	Idle	Idle	Works
D_1	Idle	Works	Works	Idle
S_2	Idle	Works	Works	Idle
D_2	Works	Idle	Idle	Works
S_3	Idle	Idle	On	Idle
D_3	Idle	Idle	Idle	On
S_4	On	Idle	Idle	Idle
D_4	Idle	On	Idle	Idle
Output	$V_2 +, I_2 +$	$V_2 +, I_2 -$	$V_2 -, I_2 -$	$V_2 -, I_2 +$

Four quadrant chopper is a chopper composed of two ½ H bridge and the other choppers are the subclass of Four quadrant choppers. DC-DC choppers according to their V-I quadrants of operation are also shown in Figure 1.18 as follows:

In the parts a to e of Figure: 1.18, the subscript of the active switches or switches and diodes specify in which quadrants operation is possible. For example, the chopper in Figure 1.18d, uses switches T1 and T3, so can only operate in the one (+Io,+Vo) and three (-Io,-Vo) quadrants.

The quadrant-one chopper in Figure: 1. 18a, (and Figure: 1. 18c) produces a positive voltage across the load since the freewheel diode D1 prevents a negative output voltage. Also delivers current from the dc source to the load through the unidirectional switch T1. So It is a single quadrant chopper and only operates in the quadrant-one (+Io,+Vo).

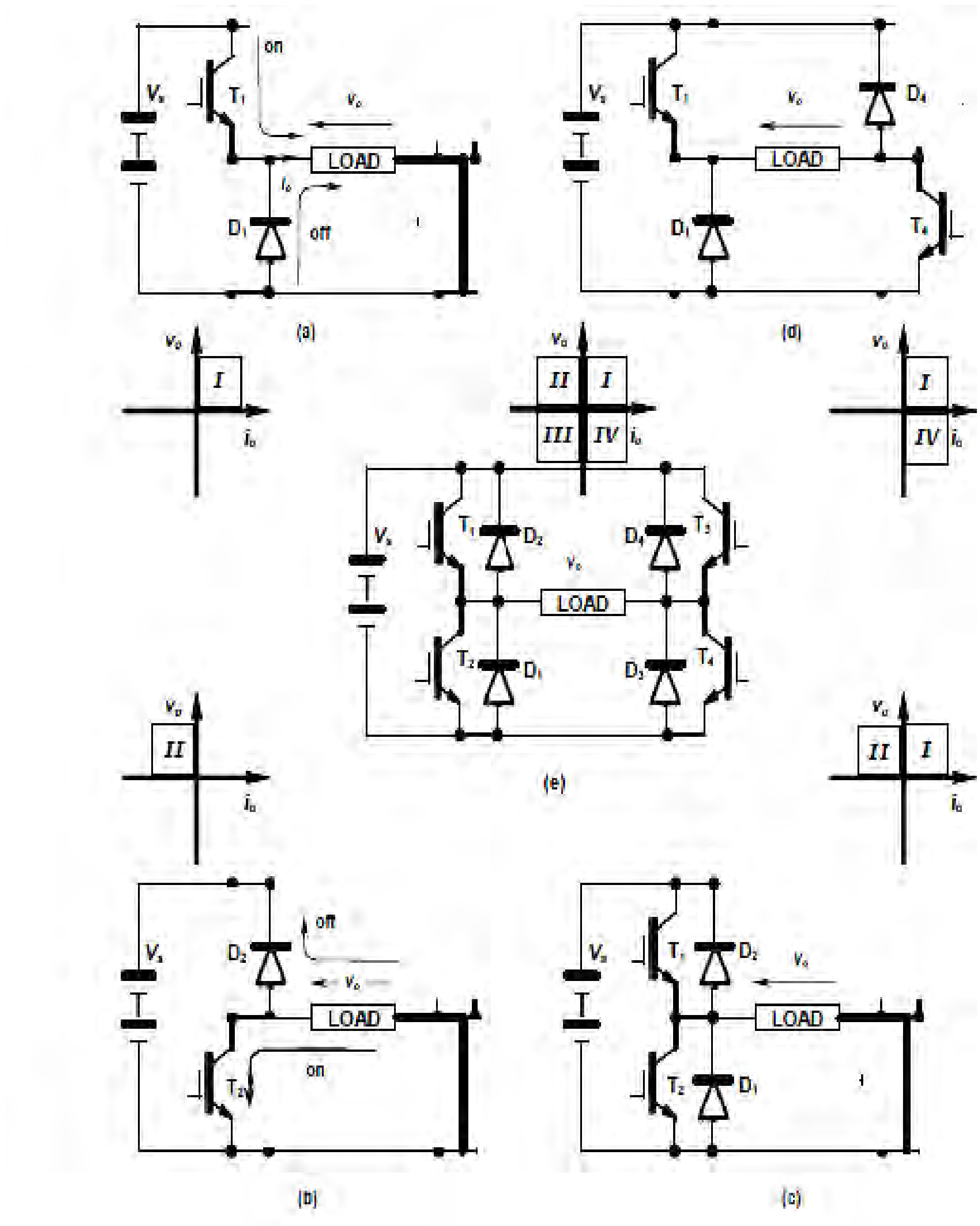


Figure:1. 18. Fundamental four quadrant chopper (centre) showing deviations of four subclass DC choppers, (a). First quadrant choppers-I, (b). Second quadrant choppers-II, (c). First and second quadrant choppers-I & II, (d). First and Fourth quadrant choppers – I & IV, and (e). Four quadrant choppers.

The quadrant-two chopper, (-Io,+Vo), in Figure: 1. 18 b, is a voltage boost circuit and current flows from the load to the supply, Vs. The switch T2 is turned on to build-up the inductive load current. When the switch is turned off current is forced to flow through diode D2 into the dc supply. The two current paths (when the switches on and when it is off) are shown in Figure: 1. 18b.

In the two-quadrant chopper, quadrants I and II chopper, (±Io,+Vo), Figure: 1. 18c, the load voltage is clamped between 0V and Vs, because of the freewheel diodes D1 and D2. Because this chopper is a combination of the quadrant-one chopper in Figure; 1.18a and the quadrant-two chopper in Figure: 1.18b, it combines the characteristics of both. Bidirectional load current is possible but the average output voltage is always positive. Energy can be regenerated into the supply Vs due to the load inductive stored energy which maintains current flow from the back emf source in the load.

The two-quadrant chopper, quadrants I and IV chopper, (+Io,±Vo), Figure; 1.18d, produces a positive voltage, negative voltage or zero volts across the load, depending on the duty cycle of the switches and the switching sequence. When both switches are switched simultaneously, an on-state duty cycle of less than 50% ($\delta < ½$) results in a negative average load voltage, while $\delta > ½$ produces a positive average load voltage. Since V_o is reversible, the power flow direction is reversible, for the shown current i_o. Zero voltage loops are created when one of the two switches is turned off.

The four-quadrant chopper in the centre of Figure: 1.18e and Figure 1.17, combines all the properties of the four subclass choppers. It uses four switched and is capable of producing positive or negative voltages across the load, and deliver current to the load in either direction, (±Io,±Vo).

A single topology is not available for these power converters to operate in all four quadrants except in H-bridge or Half H-bridge configuration. Four-quadrant switch mode dc-dc converters are usually used in dc drives (for motoring, braking and regenerative modes), large chemical processes and magnet power supplies etc [3]. In conventional dc-dc converters parasitic losses restricts the voltage gain achievable and the efficiency of conversion. Luo has proposed incorporation of voltage lift techniques in conventional switch mode circuits to obtain better voltage gain control and higher efficiencies in a wide range of duty cycle control [4-7]. Luo proposed forward and reverse dc-dc converters, which operate in two quadrants. Luo also suggested four-quadrant operation using two separate circuits and with complicated logic implementation for gate signal generation of the switching devices of two forward and reverse converter separately. Reports on other zero voltage and zero current switched four quadrant switch mode dc-dc converters are available in literature [7-14]. As mentioned, Luo converters have the advantage of voltage lift technique incorporated in conventional circuits to have stable voltage gain over wide range of duty cycle control and at the same time maintains high conversion efficiency. But none of the Luo converters operate in a single source circuit configuration in all four quadrants.

1.4 SPECIFIC AIMS AND POSSIBLE OUTCOMES:

The objective of the thesis is to propose and investigate a high frequency switching four quadrant dc-dc converter with improved performance.

In reference [6] two separate switch mode converters with voltage lift circuits with two sources and complex gate pulse control has been reported. To reduce the number of supplies to one and ease the control signals, differential connection of Luo forward and Luo reverse two quadrant choppers are investigated in this research. A new topology emerged out of the research to provide four quadrant operation of a high frequency dc-dc converter having one supply source with simple gate pulse control. The new topology is developed out of switching dc-dc converters with voltage lift circuit; its operational range will be wide at high conversion efficiency, whereas, the present four quadrant switching dc-dc converters' conversion efficiency decreases around the operation of a particular duty cycle.

It is expected that this study will yield an effective design strategy of a four quadrant switching dc-dc converter and higher efficiency which can be economically fabricated making it commercially viable.

1.5. THESIS OUTLINE:

This thesis consists of four chapters. Chapter-1 deals with introduction to SMPS, review of DC Choppers. It incorporates various advantages and requirements the SMPS. Objective of the research and discussion on expected results are also included in chapter-1.

Chapter-2 includes the study of Four Quadrant DC-DC converters with voltage lifting Circuit. In reference [6] two separate switch mode dc-dc converters with voltage lift circuits, one working in two quadrant forward mode and the other working in two quadrant reverse mode have been switched by complex gate pulses to obtain the four quadrant dc-dc operation. Two sources are necessary for such circuit. Combining the two circuits to have single source topology would result in mal-operation due to overlapping switches. In this research differential connection of the load at the output of the two converters fed by same source will be investigated as per claimed of Lou for a new FOUR QUADRANT SWITCH MODE DC-DC CONVERTER. This will result in a single source topology and can be switched by conventional ON/OFF duty cycle control as used in other high power chopper circuits. The combined topology will be analyzed and studied by spice simulation.

Chapter-3 concludes the thesis with summary, achievements and suggestion on future works.

Chapter-2

PROPOSED FOUR QUADRANT DC-DC CONVERTER AND RESULTS

2.1 BASICS OF MULTIQUADRANT LUO CONVERTERS [1-2, 14-16, 21-25, 38, 41]:

The objective of this will be approached through investigating circuit characteristics and adopting suitable control strategy and methods to improve performance of the FOUR QUADRANT SWITCH MODE DC-DC CONVERTER.

In this chapter the principle of four Quadrant DC-DC converter using two separate circuits and complicated logic implementation with other signal and two quadrant choppers introduced by Lou, is described and based on his finding a new single circuit chopper is proposed.

Conventional dc/dc converters are widely used in industrial applications and computer hardware circuits, and there are five generations of dc/dc converters, as described by LUO [1-7]. These are as,

- First Generation (Classical) Converters.
- Second Generation (Multiquadrant) converter.
- Third Generation (Switched-component) converters.
- Forth Generation (Soft- switching) converters.
- Fifth Generation (Synchronous rectifier) converters.

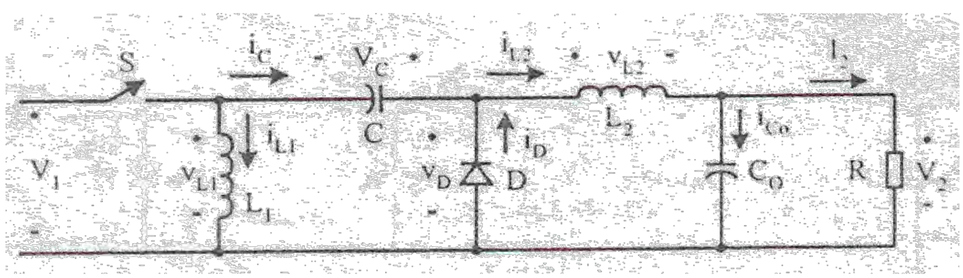
First generation converters perform in a single quadrant mode and low power range (up to 500W), which includes the BUCK, BOOST, BUCK-BOOST converters and output voltage and power transfer efficiency of this first generation converters are restricted voltage lifting technique is a popular method because it effectively overcomes the effect of parasitic elements, therefore these converters can converts the source voltage to higher output voltage with high power efficiency, high power density.

Following discussion concentrate with Second Generation (multiquadrant) Lou converters which performs in two or four quadrant operation with medium voltage range like 100W or higher. Because of high power conversion necessary in industrial application with high power transmission as DC motor (generating and bracking).

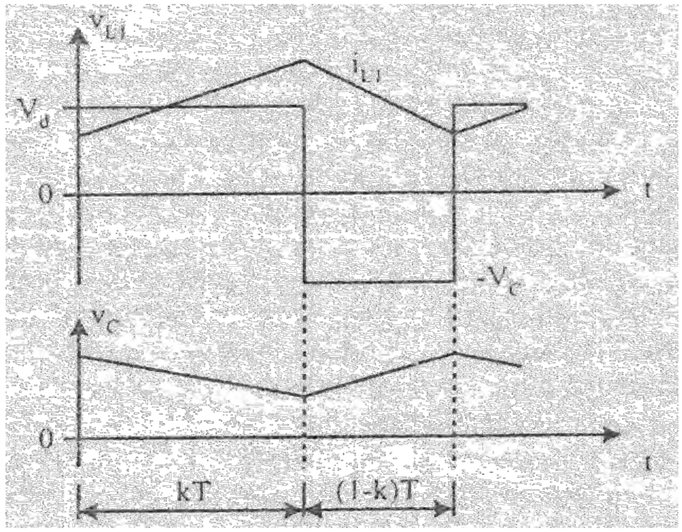
2.1.2 POSITIVE OUTPUT LUO-CONVERTERS [1-7]:

About each type of fundamental topologies of first generation converters are described in Chapter-1. All of these Luo converters work in the discontinuous mode when frequency f is small, k is small, inductance L is small and load current is high because of the effect of parasitic elements, but the voltage lifting technique can overcome the effect of parasitic elements. In the developed topologies of this converters are as follows:

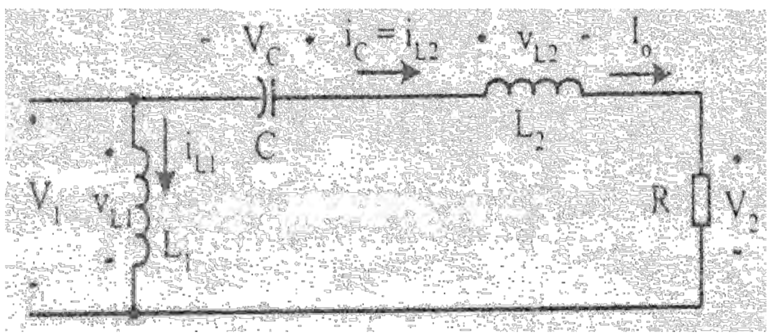
The developed topology of BUCK-BOOST converter is the positive output Luo converter, which has one more inductor and capacitor. In Figures 2.1 (a,b,c,d) are shown the circuit diagram, output voltage and current, and equivalent circuit of switch on and switch off periods. This type converter operates as step up/ step down.



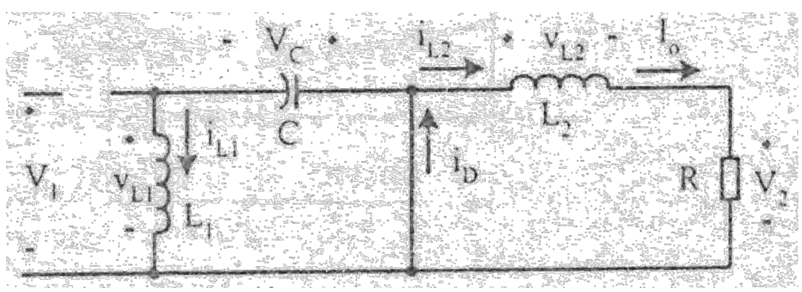
(a) Circuit Diagram



(b) Waveforms of Inductor voltage and current



(c) Switch on equivalent circuit



(d) Switch off equivalent circuit.

Figure 2.1(a,b,c,d): Positive output Luo -converter.

So the output voltage and current are:

$$Vo = \frac{k}{1-k} V1 \tag{2.1}$$

$$Io = \frac{1-k}{k} I1 \tag{2.2}$$

When k is greater than 0.5, the output voltage will be higher than the input voltage. This type of luo converter perform the voltage conversion from one positive source to another positive load voltage using the voltage lifting technique, works in first quadrant with high voltage transfer gain.

The voltage transfer gain (M) in the continuous mode:

For elementary circuit,

$$M_E = \frac{Vo}{V_1} = \frac{I_1}{Io} = \frac{1-k}{k} I_1 \tag{2.3}$$

For self lift circuit,

$$M_S = \frac{Vo}{V_1} = \frac{I_1}{Io} = \frac{1}{1-k} \tag{2.4}$$

For re lift circuit,

$$M_R = \frac{Vo}{V_1} = \frac{I_1}{Io} = \frac{2}{1-k} \tag{2.4}$$

For triple lift circuit

$$M_T = \frac{Vo}{V_1} = \frac{I_1}{Io} = \frac{3}{1-k} \tag{2.5}$$

For quadruple lift circuit

$$M_Q = \frac{Vo}{V_1} = \frac{I_1}{Io} = \frac{4}{1-k} \quad (2.6)$$

And for all positive output luo converters the general voltage transfer gain is

$$M_J = \frac{kh(j)\left[j + h(j)\right]}{1-k}, \quad (2.7)$$

Where j=0, for elementary circuit

J=1, for self-lift circuit,

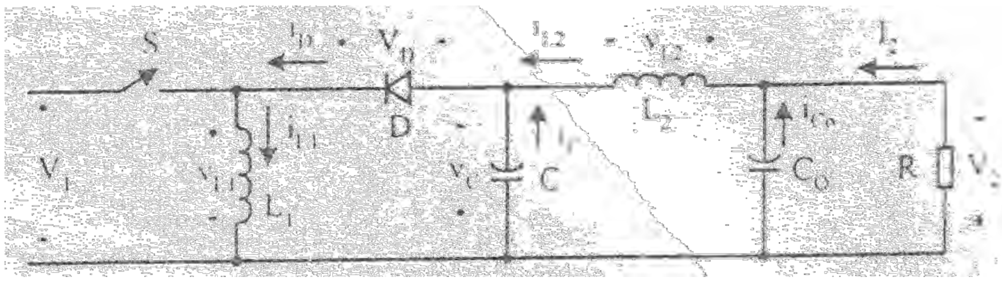
J=2, for re-lift circuit

J=3, for triple lift circuit,

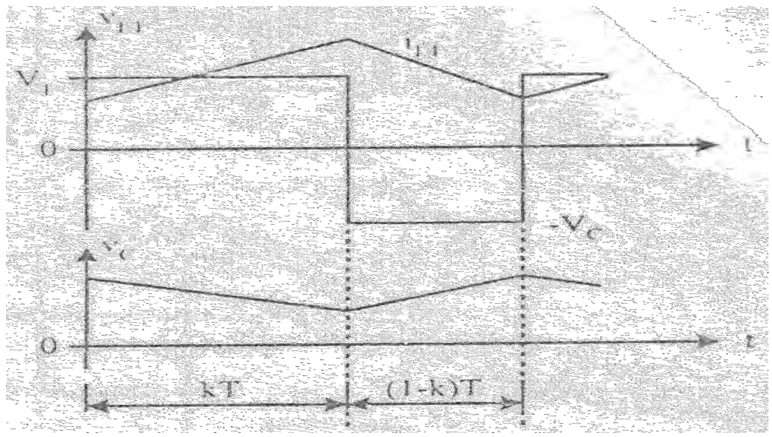
J=4, for quadruple lift circuit and so on.

2.1.3 NEGATIVE OUTPUT LUO-CONVERTERS [1-7]:

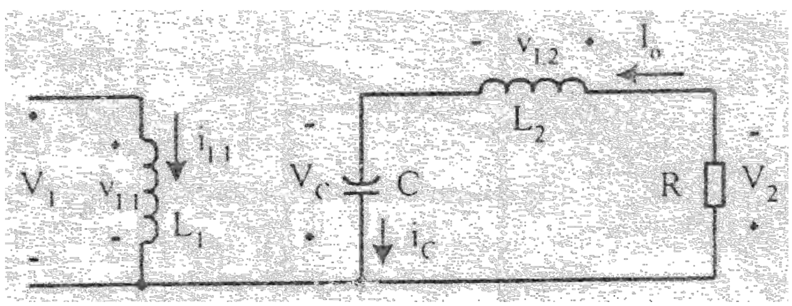
The developed topology of BUCK-BOOST converter is the negative output Luo converter, which has one more inductor and capacitor. In Figures: 2.2(a,b,c,d) are shown the circuit diagram, output voltage and current, and equivalent circuit of switch on and switch off periods. This type converter operates as step down / step up.



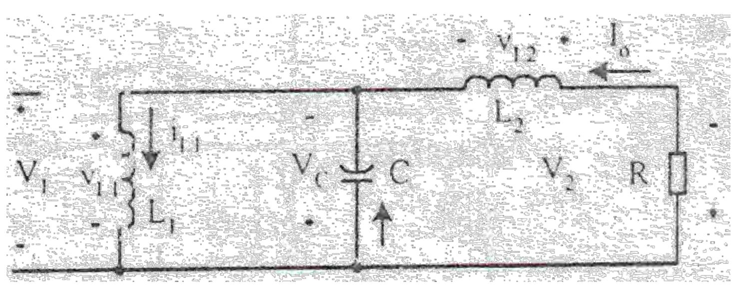
(a) Circuit Diagram



(b) Waveforms of Inductor voltage and current.



(c) Switch on equivalent circuit.



(d) Switch off equivalent circuit.

Figure 2.2 (a,b,c,d): Negative output Luo -converter.

The output voltage and current are:

$$Vo = \frac{k}{1-k} V1 \tag{2.8}$$

and

$$Io = \frac{1-k}{k} I1 \tag{2.8}$$

When k is greater than 0.5, the output voltage will be higher than the input voltage.

The negative output Luo converter converts voltage from positive to negative voltages using the voltage-lift technique. Operates in third quadrant and voltage transfer gain is high.

The voltage transfer gain (M) and variation ratio in the continuous mode

For elementary circuit,

$$M_E = \frac{Vo}{V_1} = \frac{I_1}{Io} = \frac{k}{1-k} \tag{2.9}$$

For self lift circuit,

$$M_S = \frac{Vo}{V_1} = \frac{I_1}{Io} = \frac{1}{1-k} \tag{2.10}$$

For re lift circuit,

$$M_R = \frac{Vo}{V_1} = \frac{I_1}{Io} = \frac{2}{1-k} \tag{2.10}$$

For triple lift circuit

$$M_T = \frac{Vo}{V_1} = \frac{I_1}{Io} = \frac{3}{1-k} \quad (2.11)$$

For quadruple lift circuit

$$M_Q = \frac{Vo}{V_1} = \frac{I_1}{Io} = \frac{4}{1-k} \quad (2.12)$$

The general voltage transfer gain is

$$M_J = \frac{kh(j)\left[j + h(j)\right]}{1-k}, \quad (2.13)$$

Where j=0, for elementary circuit

J=1, for self-lift circuit,

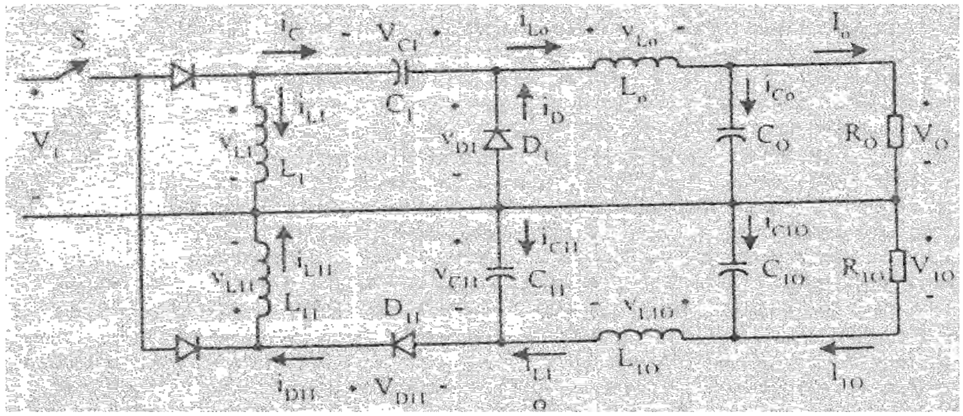
J=2, for re-lift circuit

J=3, for triple lift circuit,

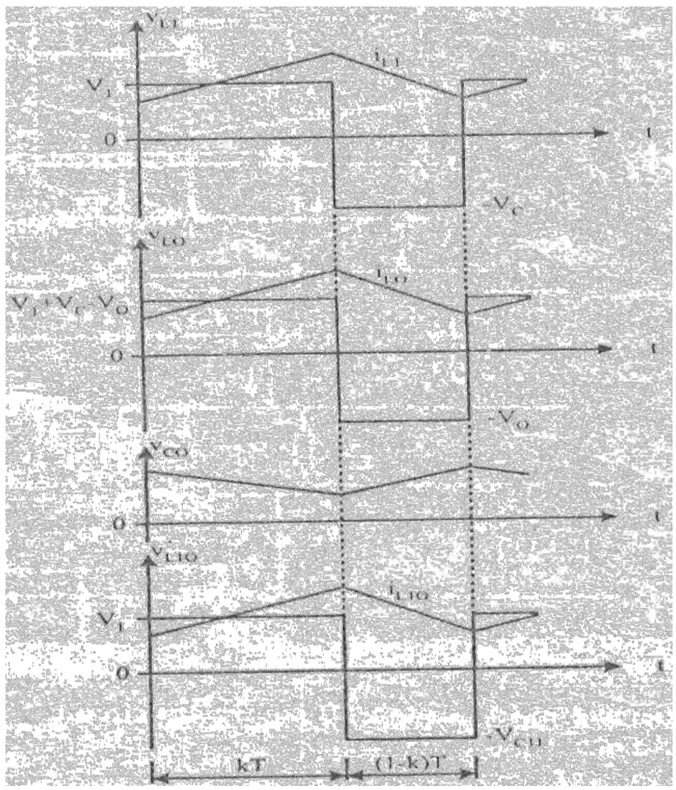
J=4, for quadruple lift circuit and so on.

2.1.4 DOUBLE OUTPUT LUO-CONVERTERS [1-7]:

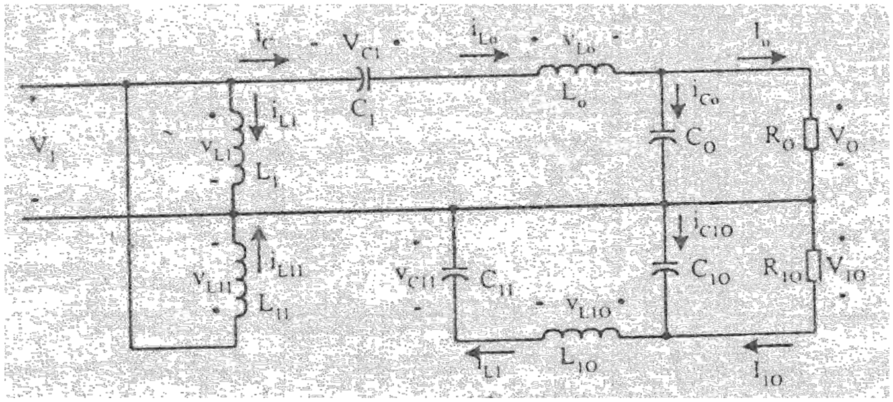
The double output luo converter which has been developed form of positive output and negative output Luo converters have two conversion paths and two output voltages V0+ and V0 -. In Figures 2.3 (a,b,c,d) are the circuit diagram, output voltage and current, and equivalent circuit of switch on and switch off periods are shown.



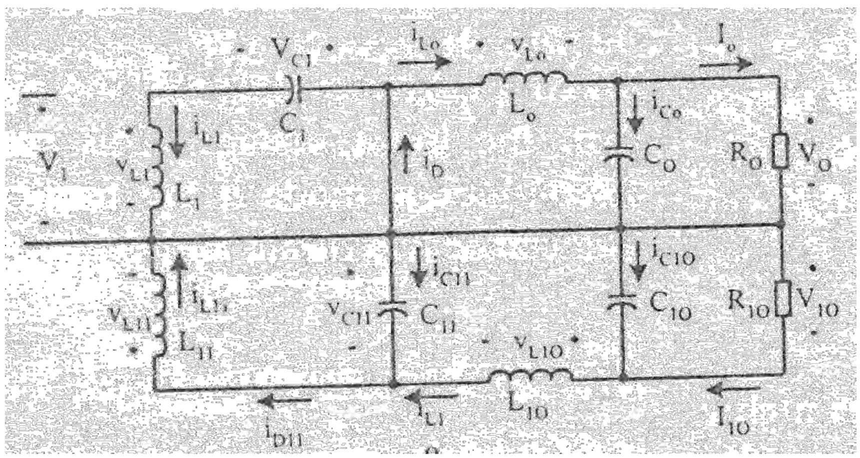
(a) Circuit diagram.



(b) Waveforms of Inductor voltage and current.



(c) Switch on equivalent circuit.



(d) Switch off equivalent circuit.

Figure 2.3(a,b,c,d): Double output Luo -converter.

So the output voltage and current are:

$$Vo+ = |V_{o-}| = \frac{k}{1-k}V_1 \tag{2.14}$$

$$Io+ = \frac{1-k}{k}I_{1+} \tag{2.15}$$

$$Io- = \frac{1-k}{k}I_{1-} \tag{2.16}$$

When k is greater than 0.5, the output voltage will be higher than the input voltage.

These type converters perform the voltage conversion from positive to positive and negative to negative voltage simultaneously using voltage lifting technique. Operates in the first and third quadrant with large voltage amplification and large transfer gain.

All double output Luo converters has two conversion paths- a positive conversion path and a negative conversion path, where considered normalized inductance $L=L_1L_2/L_1+L_2$, and Impedances are, ZN+=R/fL for the positive path and ZN-=R1/fL_{11} for the negative path.

The voltage transfer gain is

$$M_E = \frac{Vo+}{V_1} = \frac{|Vo-|}{V_1} = \frac{k}{1-k} \tag{2.17}$$

These types of luo converters are simplified by reducing one switch, According to output voltages and currents the simplified converters;

The voltage transfer gain is

$$Ms = \frac{Vo+}{V_1} = \frac{|Vo-|}{V_1} = \frac{1}{1-k} \tag{2.18}$$

For the re-lift circuit

The voltage transfer gain is

$$M_R = \frac{Vo+}{V_1} = \frac{|Vo-|}{V_1} = \frac{2}{1-k} \tag{2.19}$$

For the triple-lift circuit

The voltage transfer gain is

$$M_T = \frac{Vo+}{V_1} = \frac{|Vo-|}{V_1} = \frac{3}{1-k} \tag{2.20}$$

For the qudraple-lift circuit

The voltage transfer gain is,

$$M_Q = \frac{Vo+}{V_1} = \frac{|Vo-|}{V_1} = \frac{4}{1-k} \tag{2.21}$$

For all simplified double output luo converters the general voltage gain gain expression is,

$M = \frac{Vo+}{V_1} = \frac{|Vo-|}{V_1}$, $L_1=L_{11}$, $R=R_1$, $ZN+=R/fL_1$, $ZN-=R_1/fL_{11}$, so that ZN= ZN+= ZN-

And commonly formulated as

$$M_j = \frac{j}{1-k} \tag{2.22}$$

Where j=0, for elementary circuit

J=1, for self-lift circuit,

J=2, for re-lift circuit

J=3, for triple lift circuit,

J=4, for quadruple lift circuit and so on.

2.2. MULTIPLE QUADRANT LUO CONVERTERS [1-7]:

Second-generation converters operate in multiple-quadrant .These converters usually perform between two voltage sources V1 and V2. Voltage sources V1 is the positive voltage and voltage V2 is the load voltage. Where, voltages are constant voltage, as V1 and V2 are constant values, the voltage-transfer gain is constant. Multiple-quadrant Luo-converters are of three types,

a) two-quadrant dc/dc Luo -converter in forward operation;

b) two-quadrant dc/dc Luo -converter in reverse operation;

c) four-quadrant dc/dc Luo -converter

There is no single developed four-quadrant dc/dc Luo-converter circuit which can perform both in forward operation and reverse operation. The most challenging task in this research is to develop efficient and economic combined circuit of four-quadrant dc/dc Luo-converter for speedy calculation of the working current, minimum conduction duty k min , and the power transfer efficiency n.

2.2.1 MULTIPLE QUADRANT LUO CONVERTER IN FORWARD OPERATION [1-7]:

Two-quadrant dc/dc Luo-converter in forward operation has been derived from the positive output Lou-converter. It performs in the first quadrant QI (electrical energy is transferred from source side V1 to load side V2) and the second quadrant QII (electrical energy is transferred from load side V2 to source side V1) corresponding to the dc motor forward operation in motoring and regenerative braking states.

Where in Figure 2.4 and 2.5 shown, switches S1 and S2 are power MOSFET devices, and driven by Pulse With Modulation (PWM) signal with repeating frequency f and duty cycle k.

And switch on the voltage drop across the switch and diode is Vs and Vd. And equivalent here are two modes of operation as

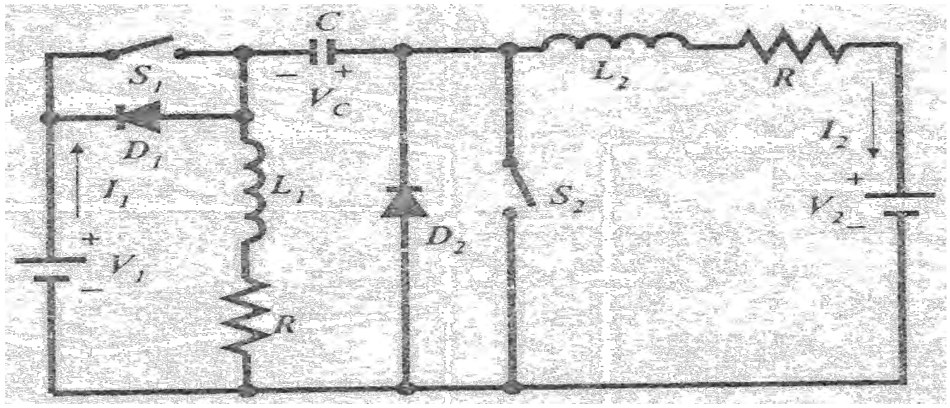


Figure 2.4: Forward two quadrant operating Luo -converter.

Mode-A: First Quadrant Q I : The equivalent circuits of this converter during switch on and off the output voltage and current are shown in Figure 2.4(a,b,c)

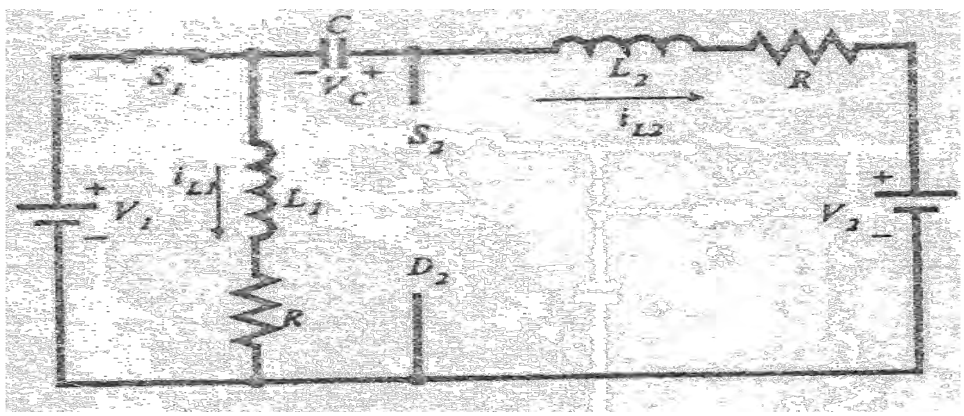


Figure 2.4(a): Switch (S_1) on-Forward two quadrant operating Luo -converter.

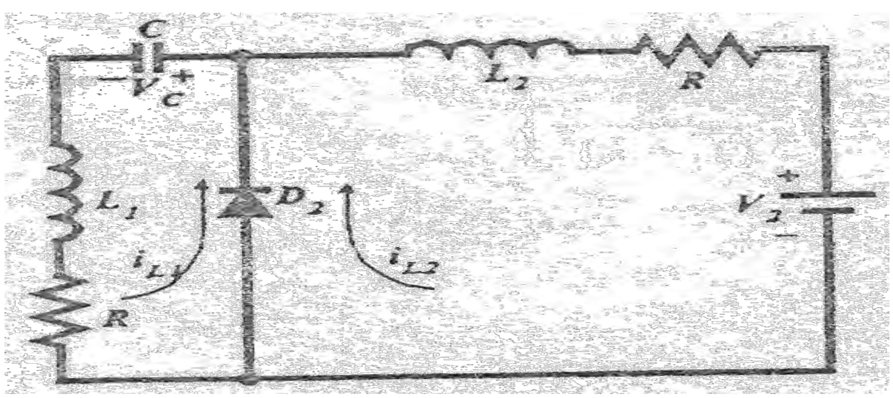


Figure 2.4(b): Switch (S_1) off-Forward two quadrant operating Luo -converter.

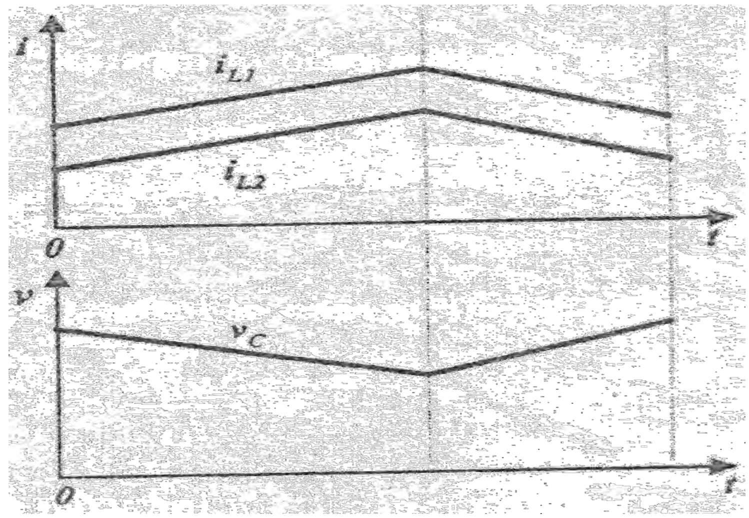


Figure 2.4(c): Waveforms-Forward two quadrant operating Luo -converter.

Output current ,

$$I_2 = \frac{1-k}{k} I_1 \tag{2.23}$$

And

$$I_2 = \frac{V_1 - V_S - V_D - V_2 \frac{1-k}{k}}{R\left(\frac{k}{1-k} + \frac{1-k}{k}\right)} \tag{2.24}$$

When minimum conduction duty k corresponding I_2=0 then

$$K_{min} = \frac{V_2}{V_1 + V_2 - V_S - V_D} \tag{2.25}$$

Mode-B: Second Quadrant Q II : The equivalent circuits of this converter during switch on and off the output voltage and current are shown in Figure 2.4 d,e,f.

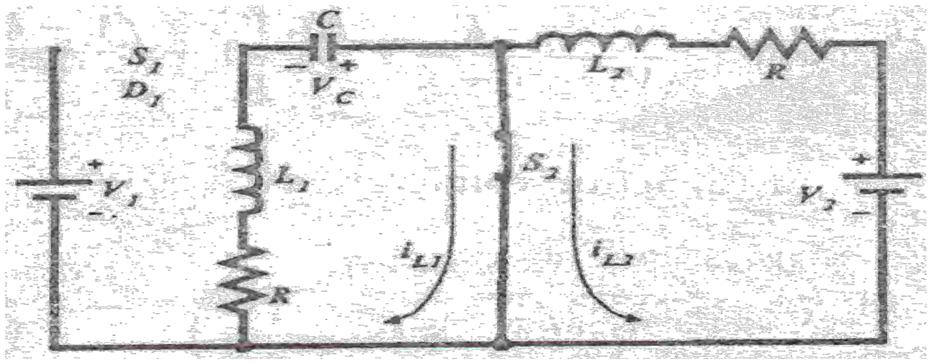


Figure 2.4(d): Switch (S_2) on-Forward two quadrant operating Luo -converter.

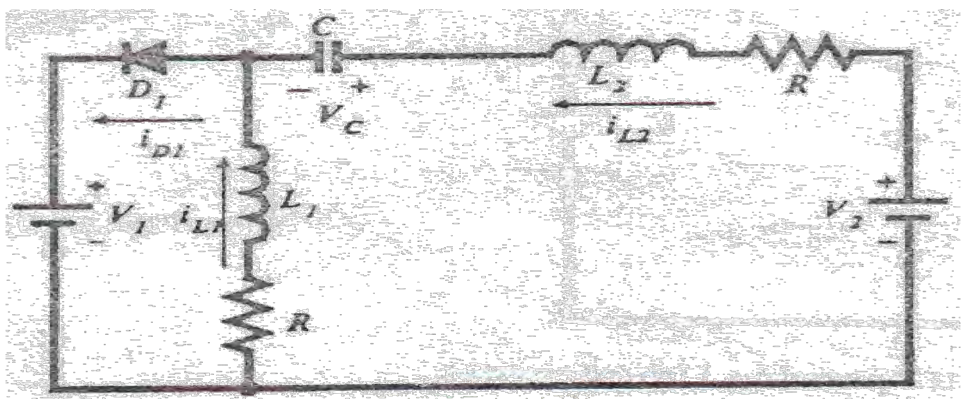


Figure 2.4(e): Switch (S_2) off-Forward two quadrant operating Luo -converter.

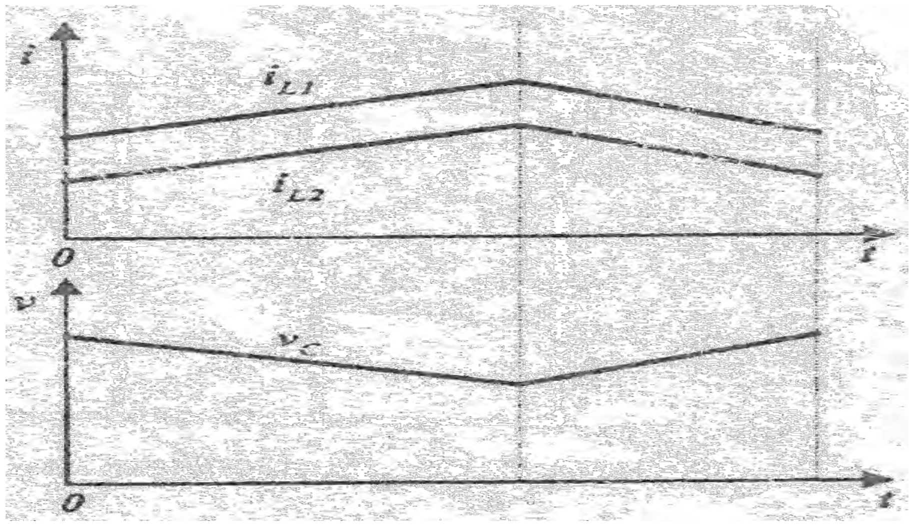


Figure 2.4(f): Waveforms-Forward two quadrant operating Luo -converter.

Output current,

$$I_1 = \frac{1-k}{k} I_2 \tag{2.26}$$

And

$$I_1 = \frac{V_2 - (V_1 + V_S + V_D)\frac{1-k}{k}}{R\left(\frac{k}{1-k} + \frac{1-k}{k}\right)} \tag{2.27}$$

When minimum conduction duty k corresponding $I_1=0$ then

$$K_{\min} = \frac{V_1 + V_S + V_D}{V_1 + V_2 + V_S + V_D} \tag{2.28}$$

2.2.2. MULTIPLE QUADRANT LUO CONVERTER IN REVERSE OPERATION [1-7]:

Two-quadrant dc/dc Luo-converter in reverse operation has been derived from the negative output Lou-converter. It performs in the Third Quadrant Q111 (electrical energy is transferred from source side V2 to load side -V2), Forth Quadrant Q1V (electrical energy is transferred from load side -V2 to source side V1) corresponding to the dc motor forward operation in motoring and regenerative braking states.

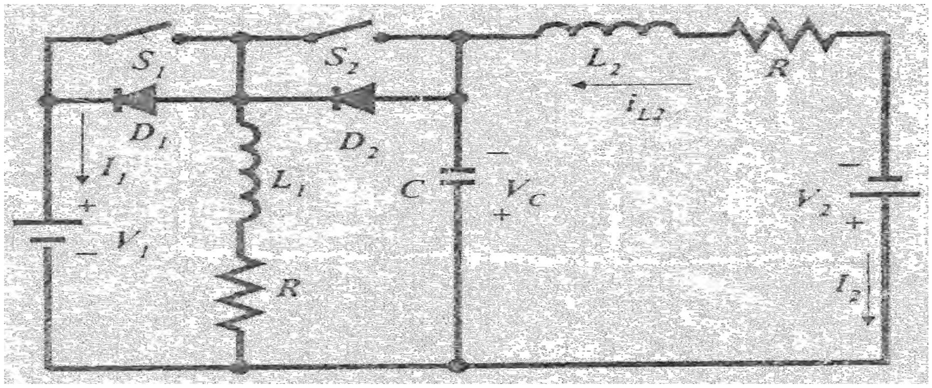


Figure 2.5: Reverse two quadrant operating Luo -converter.

Mode-C: Third Quadrant Q III : The equivalent circuits of this converter during switch on and off the output voltage and current are shown in Figure 2.5(a,b,c)

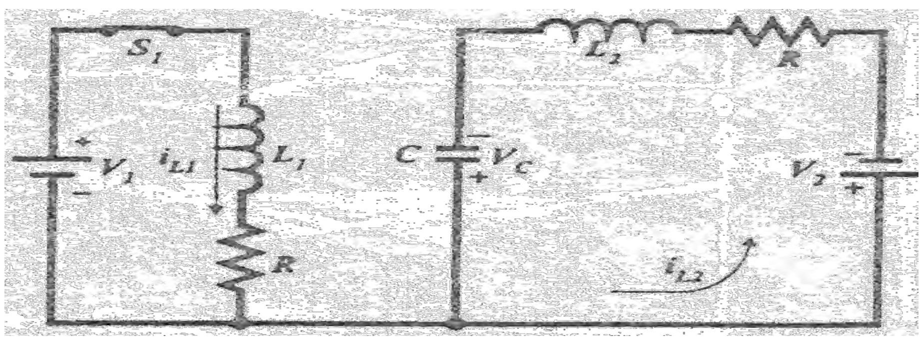


Figure 2.5(a): Switch (S_1) on-Reverse two quadrant operating Luo -converter.

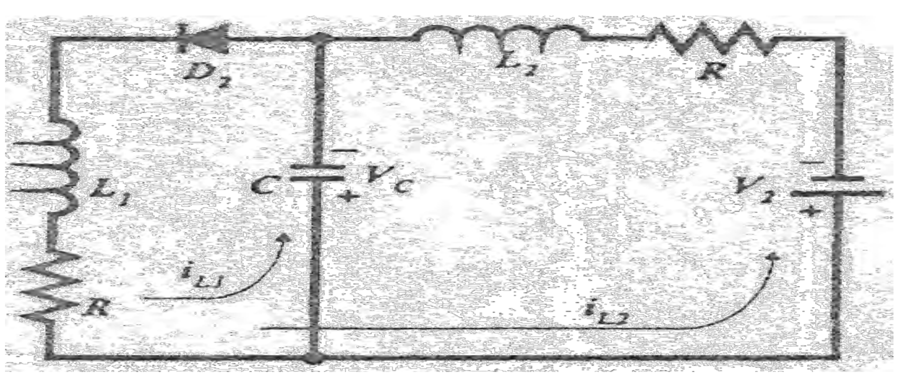


Figure 2.5(b): Switch (S_1) off-Reverse two quadrant operating Luo -converter.

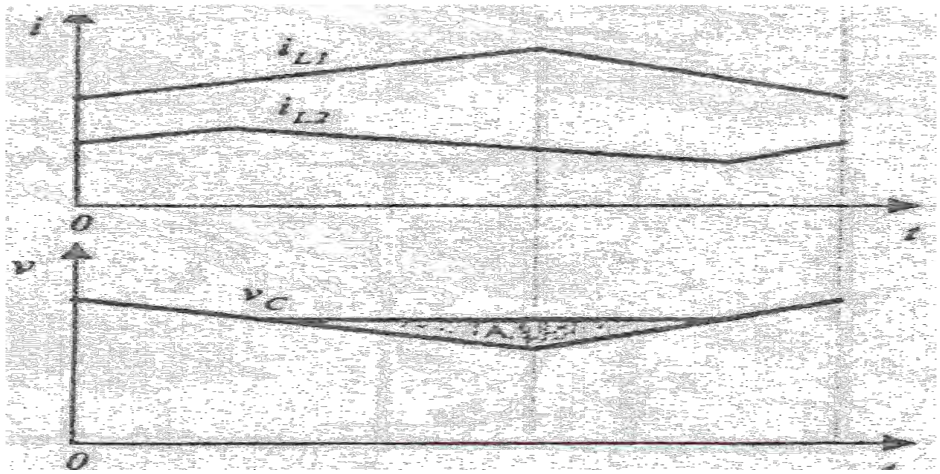


Figure 2.5(c): Waveforms-Reverse two quadrant operating Luo -converter.

Output current,

$$I_2 = \frac{1-k}{k} I_1 \tag{2.29}$$

And

$$I_2 = \frac{V_1 - V_S - V_D - V_2 \frac{1-k}{k}}{R\left(\frac{k}{k(1-k)} + \frac{1-k}{k}\right)} \tag{2.30}$$

When minimum conduction duty k corresponding $I_2=0$ then

$$K_{\min} = \frac{V_2}{V_1 + V_2 - V_S - V_D} \tag{2.31}$$

Mode-D: Fourth Quadrant Q IV : The equivalent circuits of this converter during switch on and off the output voltage and current are shown in Figure 2.5 (d,e,f).

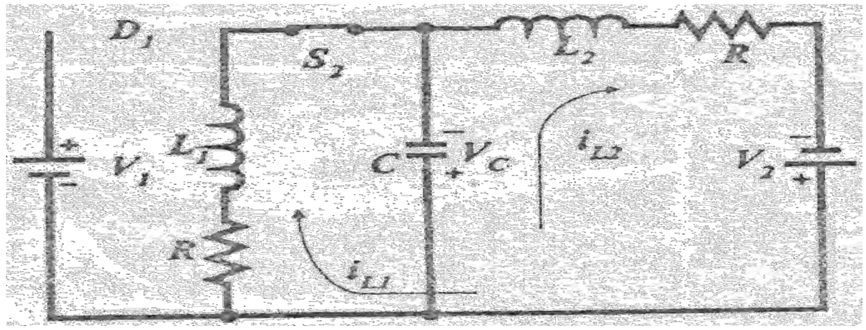


Figure 2.5(d): Switch (S_2) on-Reverse two quadrant operating Luo -converter.

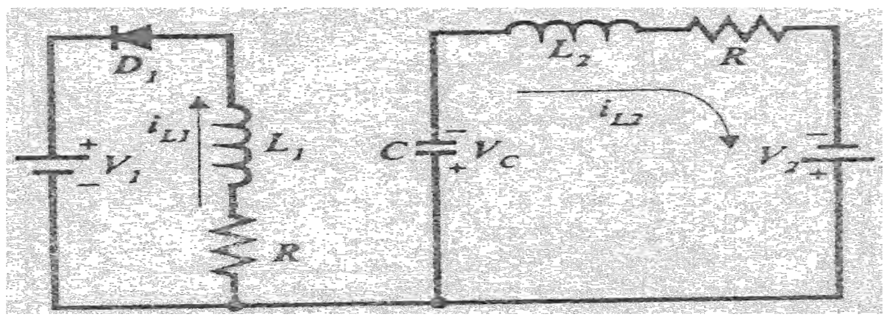


Figure 2.5(e): Switch (S_2) off-Reverse two quadrant operating Luo -converter.

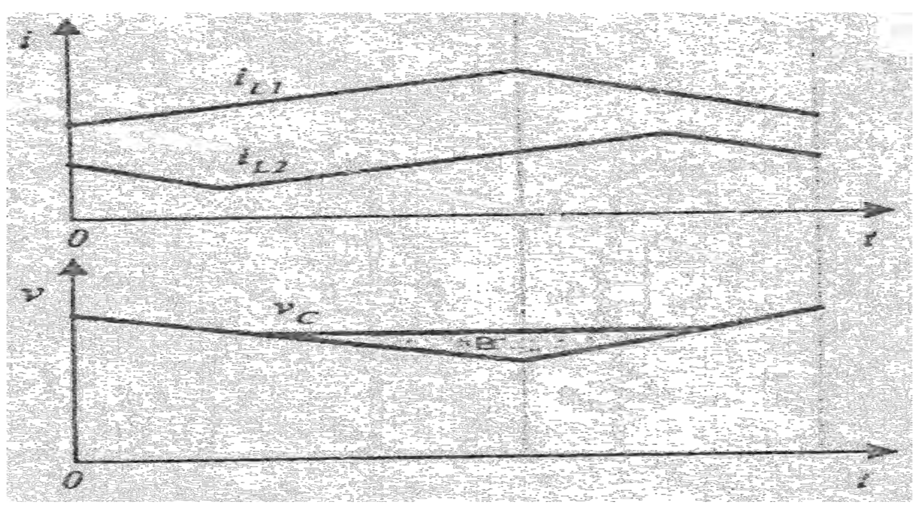


Figure 2.5(f): Waveforms-Reverse two quadrant operating Luo converter.

Output current,

$$I_1 = \frac{1-k}{k} I_2 \tag{2.32}$$

And

$$I_1 = \frac{V_2 - (V_1 + V_S + V_D)\frac{1-k}{k}}{R\left(\frac{k}{k(1-k)} + \frac{1-k}{k}\right)} \tag{2.33}$$

When minimum conduction duty k corresponding I_1=0 then

$$K_{\min} = \frac{V_1 + V_S + V_D}{V_1 + V_2 + V_S + B_D} \tag{2.34}$$

2.2.3. MULTIPLE QUADRANT (FOUR) LUO CONVERTER OPERATION [1-7]:

Four-quadrant dc/dc Luo-converter has been derived from the double output Lou-converter. It performs in the four quadrant operation corresponding to the dc motor forward and reverse operation in motoring and regenerative braking states as per claim of Mr. Lou.

This has two passive diodes, two inductors, one capacitor, by this research, There each mode has two states: “On” and “Off” and input source and output load are usually constant voltages as shown by V1 and V2. Switches are power MOSFET/IGBT devices, and they are driven by a pulse width-modulated (PWM) switching signal with repeating frequency f and operating in a different conduction duty k. In this research the switch-repeating period is T= 1/f, so that the switch-on period is kT and switch off period is (1-k) T.

By the operation of switches (as per following table) of the combined circuit, will get operational modes of four-quadrant dc/dc Luo-converter as per recommendation of Luo (four-quadrant operation using two separate circuits and complicated logic implementation for gate signal generation of the switching devices of two forward and reverse converter separately).

Table 2.1: Switching Status (as per claim of Mr. Lou)

Switch	QI		QII		QIII		QIV	
	State ON	State OFF	State ON	State OFF	State ON	State OFF	State ON	State OFF
S1	ON							
S2			ON					
S3					ON			
S4							ON	

But none of the Luo converters operate in a single source circuit configuration in all four quadrants.

In this research differential connection of the load at the output of the two converters fed by same source is investigated according to the suggestion of Mr. Lou. This resulted in a single source topology and can be switched by conventional ON/OFF duty cycle control as used in other high power chopper circuits.

2.2.3.1 THE SWITCHING SCHEME USING PWM [3,7,18-19, 32, 41-43]:

GATE SIGNAL GENERATING CIRCUIT:

The objective of the switching scheme is to enhance the continuity of the input current. MOSFETs /IGBTs are used as switch in the four quardrant converter. Where the gate pulse to the MOSFETs /IGBTs has been generated by a PWM module. PWM or Pulse Width Modulation, is a method of controlling the amount of power to a load without having to dissipate any power in the load driver

The PWM command signal can be generated in a number of ways either with the IBM-PC computer, in this case being necessary a specialized interface and the required software tools, or with a special electronic device. In this research, Switches are power MOSFET/IGBT devices, and they are driven by a pulse width-modulated (PWM) switching signal, taking into consideration in this paper an electronic device for PWM commanding the four quadrant chopper.

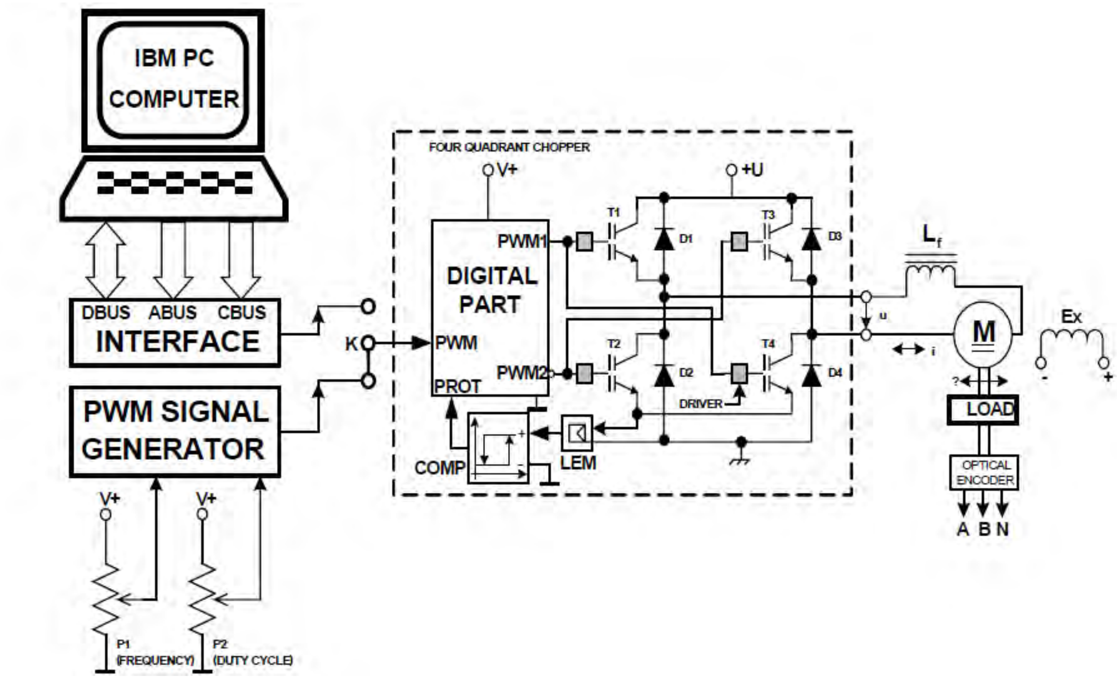


Figure 2.6: Block diagram of D.C. electrical drive system.

In voltage controller devices, the average output voltage is controlled by controlling the switch off and on duration. The output voltage is controlled by switching at a constant frequency and by adjusting the on duration of the switch. This method is called PWM switching.

A block diagram of a PWM generator is shown below:

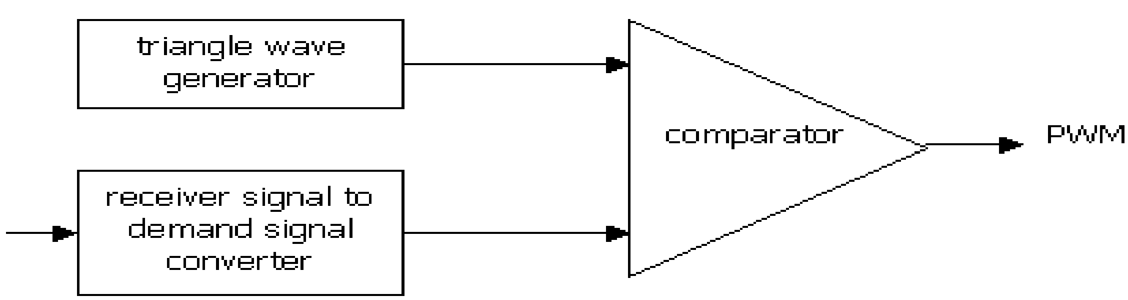


Figure 2.7: Block diagram of PWM generator system.

In PWM switching at constant frequency, the switch control signal is generated by comparing a signal level control voltage with a triangular waveform. The frequency of the repetitive waveform with a constant peak, which is shown to be saw tooth, establishes the switching frequency. This frequency is kept constant in a PWM control and is chosen to be in a few KHz to a few hundred KHz range. When the control voltage is greater than the saw tooth waveform, the switch control signal becomes high causing the switch to turn on. Otherwise the switch is off. In terms of control $V_{control}$ and peak of the saw tooth waveform V_{st} in Figure 2.8, the switch duty ratio can be expressed as $D = t_{on}/t_s = V_{control}/V_{st}$.

We are starting at the output because this is the easy bit. The diagram below shows how comparing a ramping waveform with a DC level produces the PWM waveform that we require. The higher the DC level is, the wider the PWM pulses are. The DC level is the 'demand signal'.

The DC signal can range between the minimum and maximum voltages of the triangle wave.

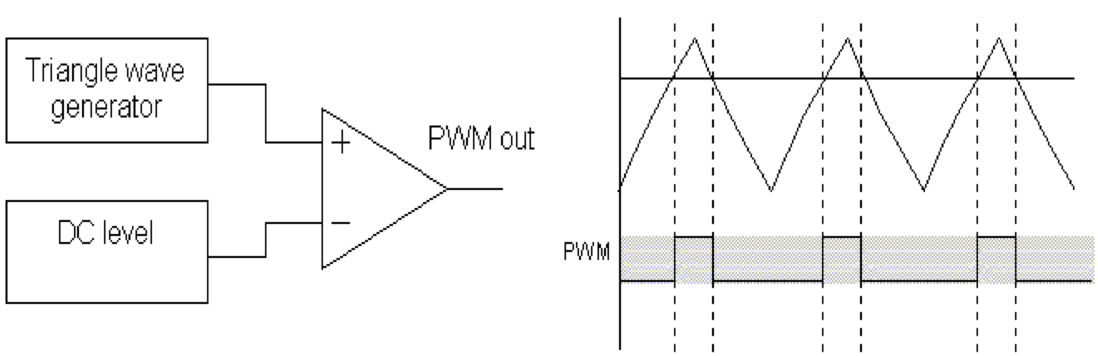


Figure 2.8: Output wave of PWM

When the triangle waveform voltage is greater than the DC level, the output of the op-amp swings high, and when it is lower, the output swings low.

The gate signal generating circuit for the regulator is shown in Figure 2.9,. The control circuit shows an OPAMP whose inputs area fixed saw tooth wave, V_{st} and a variable DC voltage $V_{control}$. OPAMP acts as a comparator, output of the OPAMP depends on the difference of two inputs, viz. (V+, V-). In this circuit positive input (DC voltage) is varied and negative input (saw tooth wave) is kept fixed. So, output pulse width depends on DC input voltage of OPAMP. The input voltage waveforms of the OPAMP and outputs and the duty cycle control signal of the voltage regulator and the corresponding gate signal of the switches.

When the reference voltage is at minimum, the PWM signal to be 100% off 0% on, and when the reference voltage is at maximum, the PWM signal to be 0% off 100% on. Output signal of OPAMP is passes through the limiters and the different Voltage controlled voltage sources for proper switching of the MOSFETs with necessary ground isolation. The function of limiters is to limits the magnitude of signal from 0-5 V without change of the shape or pulse width of signal. The output of the limiters/ Voltage controlled voltage sources is the gate signal for the switches.

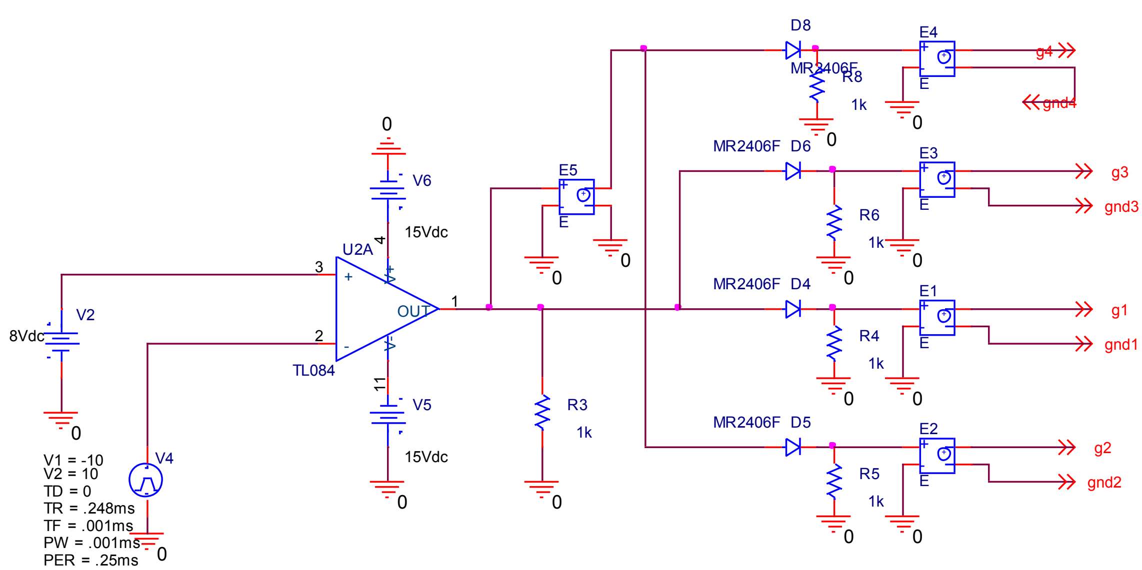


Figure 2.9: Gate signal generating circuit of Figure 2.12.

2.2.3.2 DESCRIPTION OF A NEW 4 QUADRANT SWITCH MODE DC-DC CONVERTER [1-45].

This section presents the operation of the 4-quadrant converter (switched mode DC-DC converter). Luo proposed two separate switch mode dc-dc converters with voltage lift circuits, one working in two quadrant forward mode and the other working in two quadrant reverse mode switched by complex gate pulses to obtain the four quadrant dc-dc operation. Two sources are necessary for such circuit. Two-quadrant dc/dc Luo-converter in forward operation has been derived from the positive output Lou-converter. It performs in the first quadrant Q I (electrical energy is transferred from source side V1 to load side ±V2) and the second quadrant Q II (electrical energy is transferred from load side ±V2 to source side V1) corresponding to the dc motor forward operation in motoring and regenerative braking states.

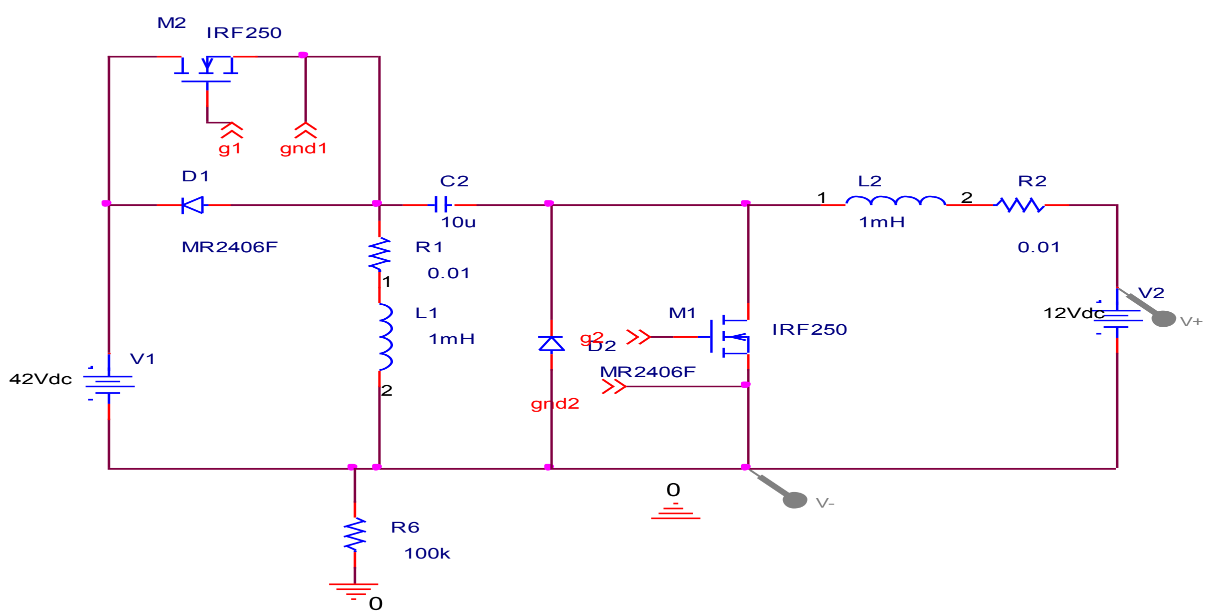


Figure 2.10: Forward operation of Luo Converter.

Two-quadrant dc/dc Luo-converter in reverse operation has been derived from the negative output Lou-converter. It performs in the third quadrant Q III (electrical energy is transferred from source side V_1 to load side ±V_2) and the forth quadrant Q IV (electrical energy is transferred from load side ±V_2 to source side V_1) corresponding to the dc motor reverse operation in motoring and regenerative braking states.

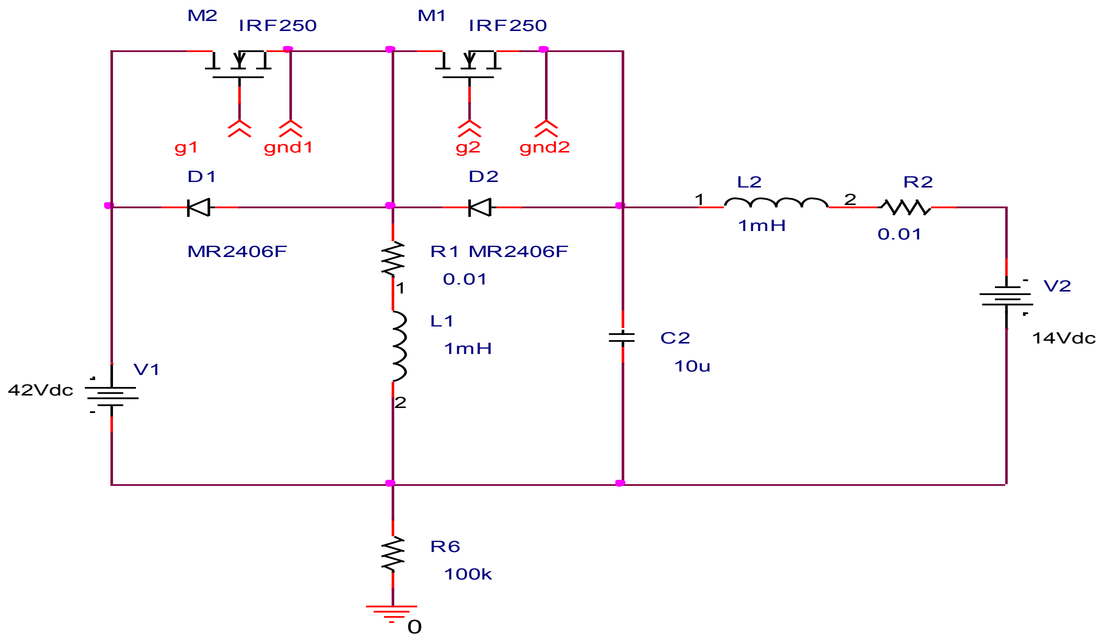


Figure 2.11: Reverse operation of Luo converter.

However, it is found in simulation that these two source converters do not operate as claimed and they cannot be combined in any way with differentially connected load to operate in four quadrants as a single power conversion circuit. Because of combined circuit arrangement should identical of Figure 1.17.

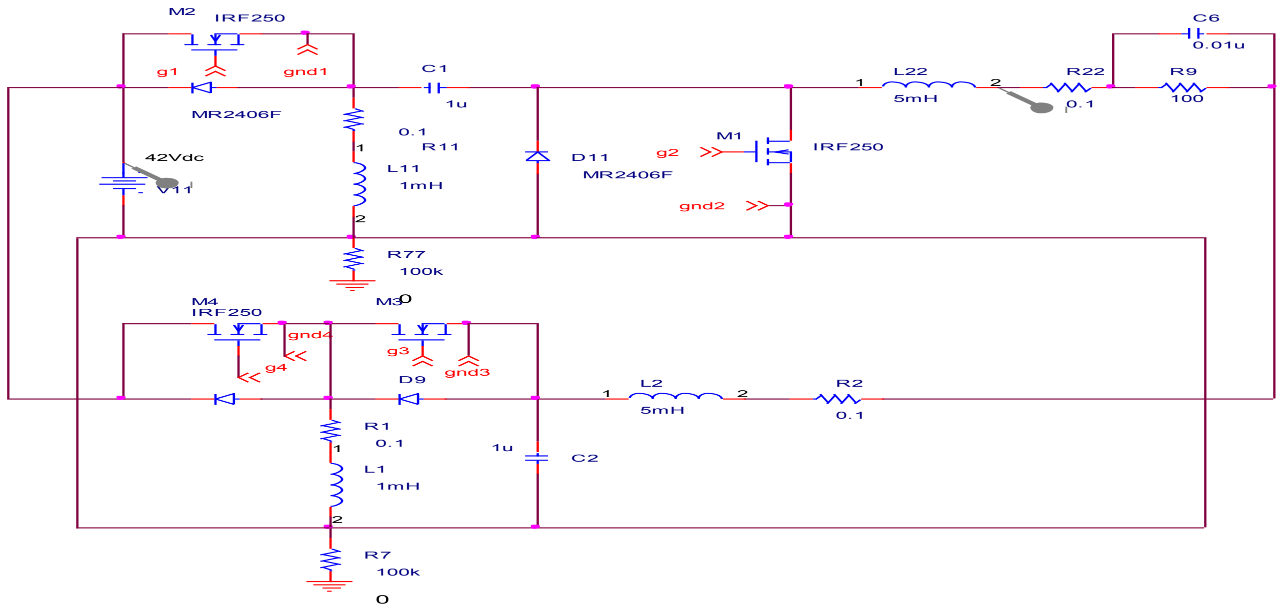
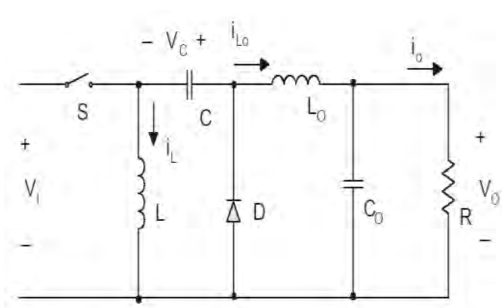


Figure 2.12 Four quadrant DC-DC converter with differential load.

In this thesis attempt was made to make the four quadrant chopper out of forward and reverse Luo converters with differential load connection as shown in Figure-2.12. But the converter did not perform as four quadrant chopper because the reverse Luo converter does not work as it has been claimed; secondly these circuits are working individually for Quadrants I & II and Quadrants III & IV.

It is therefore, necessary to investigate separate method to obtain SMPS based Buck-Boost single topology four quadrant DC-DC converter.

And



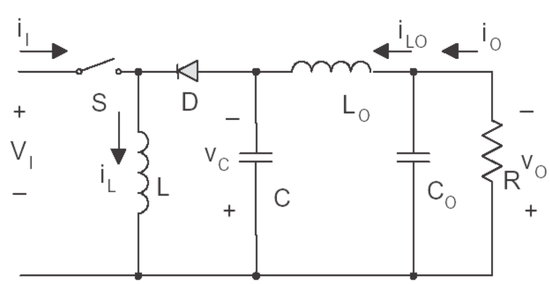


Figure 2.13(a) Positive output Luo converter. Figure 2.13(b) Negative output Luo converter.

Figure – 2.13 are positive and negative output DC-Dc Luo converter with voltage lift circuit. According to this investigation found that the converters (Fig 2.10 & 2.11) are not working as claimed, this thesis proposed another configuration Buck-Boost with lift circuit for Quadrant I & II and Quadrant III & IV as shown in Figure 2.14.

2.3.3.3 PROPOSED TOPOLOGYOF FOUR-QUADRANT CONVERTER WITH LIFT CIRCUIT.

Two Luo converters with voltage lift circuit have been taken to be combined (Figure 2.13) to obtain the four quadrant switch mode DC-DC conversion. The proposed combined circuit for quadrant I and II is shown in Figure: 2.14, in which the load is considered to be an EMF source so that it can be clearly shown that the load EMF takes or deliver current from or to the input source for both (+)ve or (-)ve polarity connections at the output indicating the circuit works in desired quadrants. Where IGBTs are switched as g1=0 or g4=0 simultaneously to get proper output waveforms for desired quadrants.

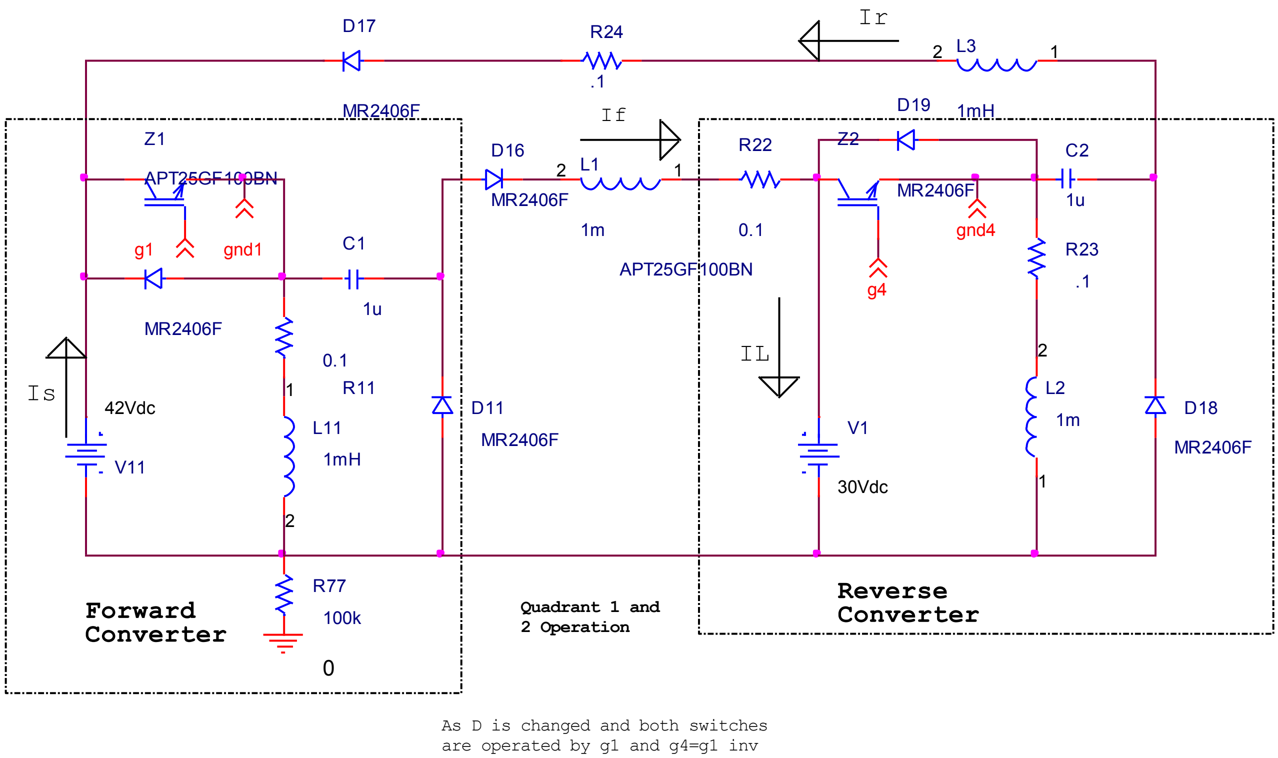


Figure 2.14: Two Quadrant Chopper mode of forward and reverse Converter.

By the Figure 2.14, found in study that, both of motoring and regenerating/brake operation is possible as;

Motoring Operation: The duty cycle is maintained such that output of the forward converter is higher than the reverse converter. As a result the load EMF gets charged and current flows in to the load source with its polarity (+)ve upwards, i e. Vo (+)ve, Io (+)ve and Vin (+)ve, Iin (-)ve. So both EMF and Io are positive, the machine in Motoring operation in the forward direction or quadrant I operation is obtained. This operation is therefore, often referred to as a step-down chopper/buck converter.

Regenerating/brake Operation: As duty cycle of switches is reversed, and at proper duty cycle resulted forward converter voltage output to stop injecting current to load source, but the reverse converter output voltage going above input source voltage starts injecting current into the source in the opposite direction. The output EMF Vo (+ve) and Io (-ve) opposite to the previous direction. Also Vin (+ve) & Iin (+ve). So EMF is positive but I_o is negative the machine in Regenerating operation/brake in the forward direction or quadrant II operation is obtained. This operation is therefore, often referred to as a step-up chopper/boost converter.

Typical waveforms with (+ve) EMF load or Quadrant I and II operation of circuit of Figure 2.14 are shown in Figures 2.15-2.18. Figures 2.19-2.20, show typical waveforms of circuit of Figure 2.14 for Quadrant I and II s duty cycle is changed.

It is possible to achieve motor and braking operation with the same circuit if all four switches are used. Only two quadrant choppers are shown in Figure 2.14, similarly for (-)ve EMF, both quantities EMF and Io are negative the machine motors in the reverse direction or Quadrant III. And EMF is negative but Io positive the machine brakes in the reverse direction or Quadrant IV will be obtained.

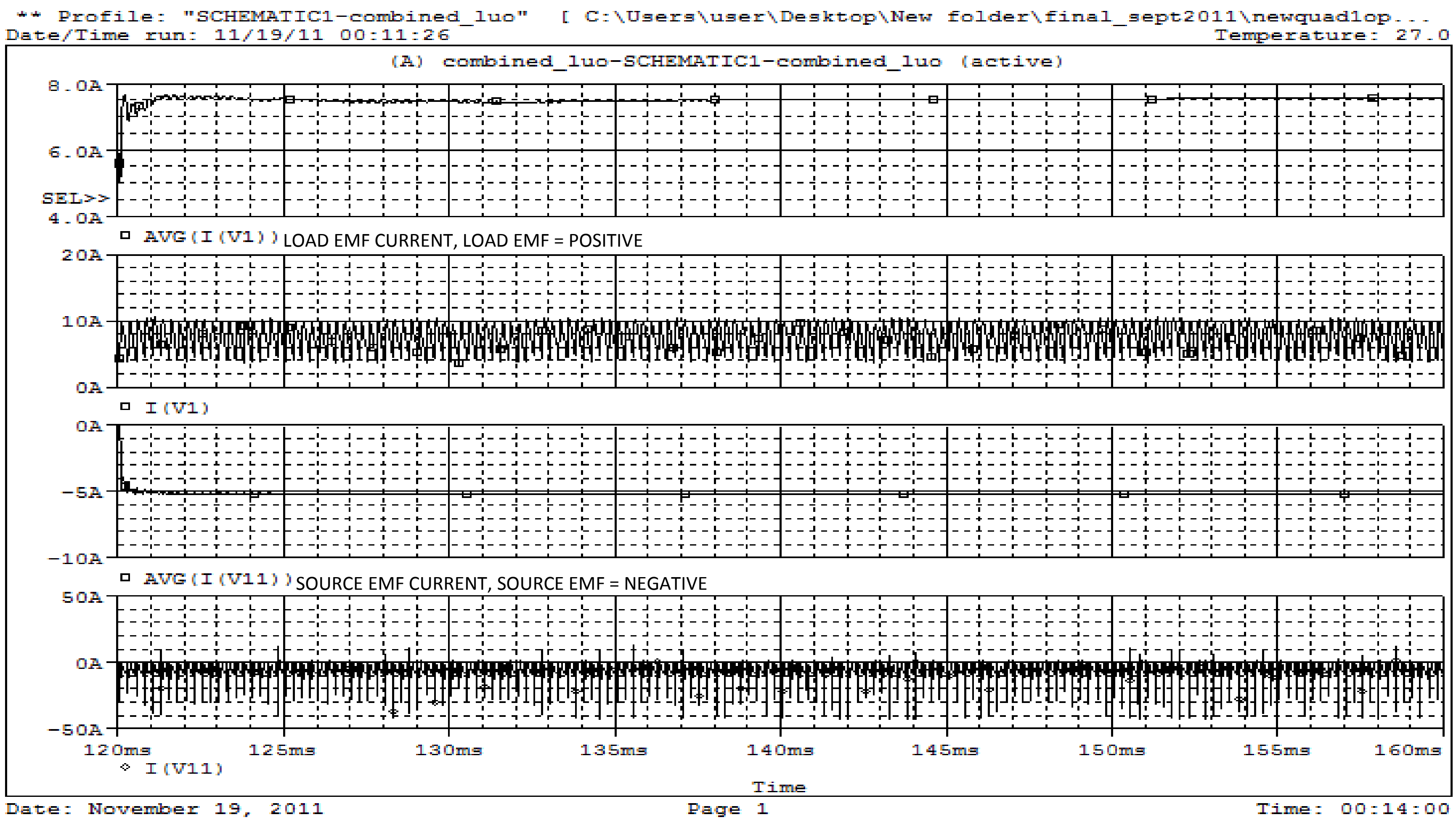


Figure 2.15: Forward motoring operation of Circuit of Figure 2.14 (where g4 = 0, gain set to 0) for Pulse Width 0.05ms (Quadrant-I).

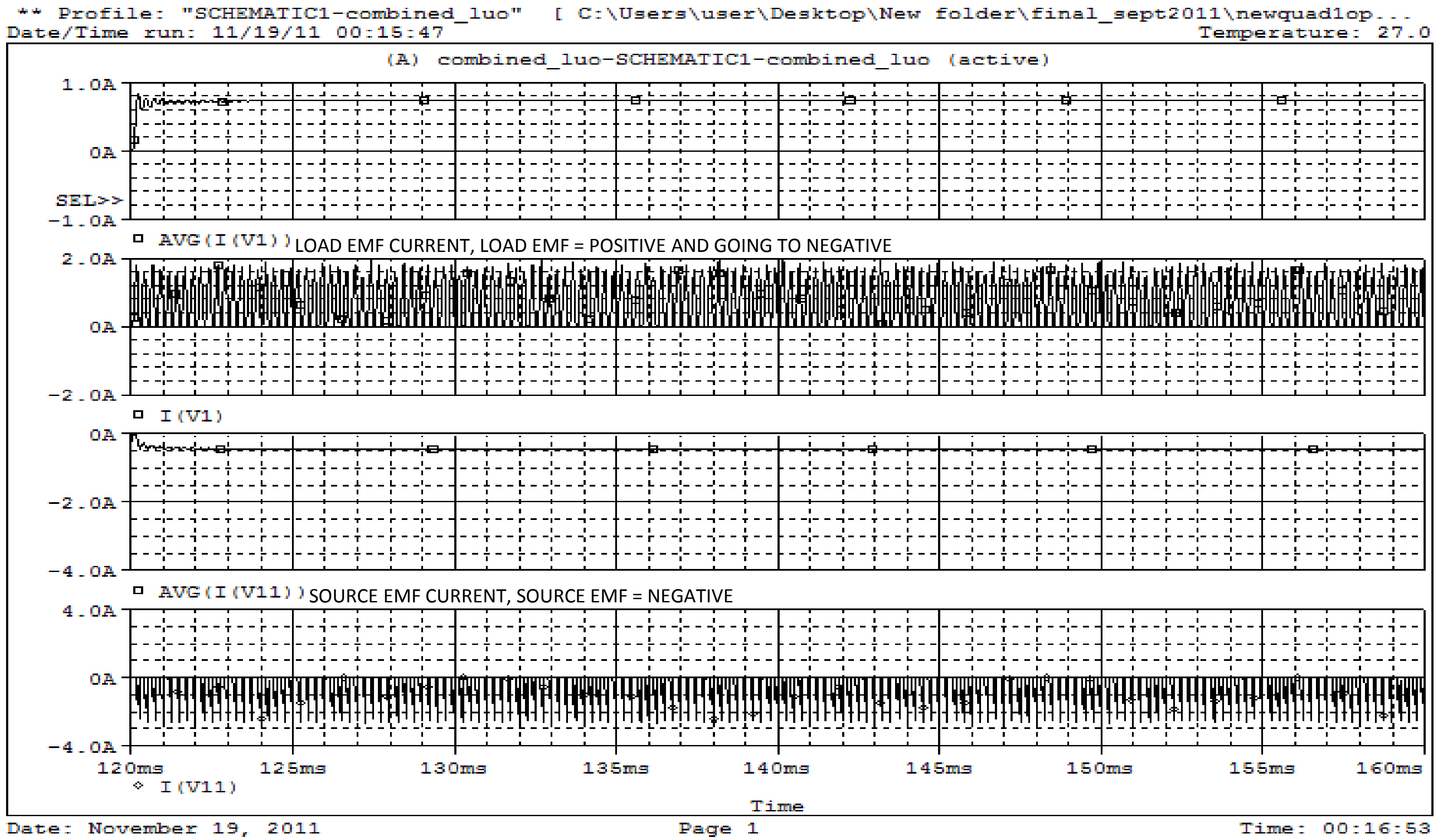


Figure 2.16: Forward motoring operation of Circuit of Figure 2.14(where g4 = 0, gain set to 0) for Pulse Width 0.15ms.

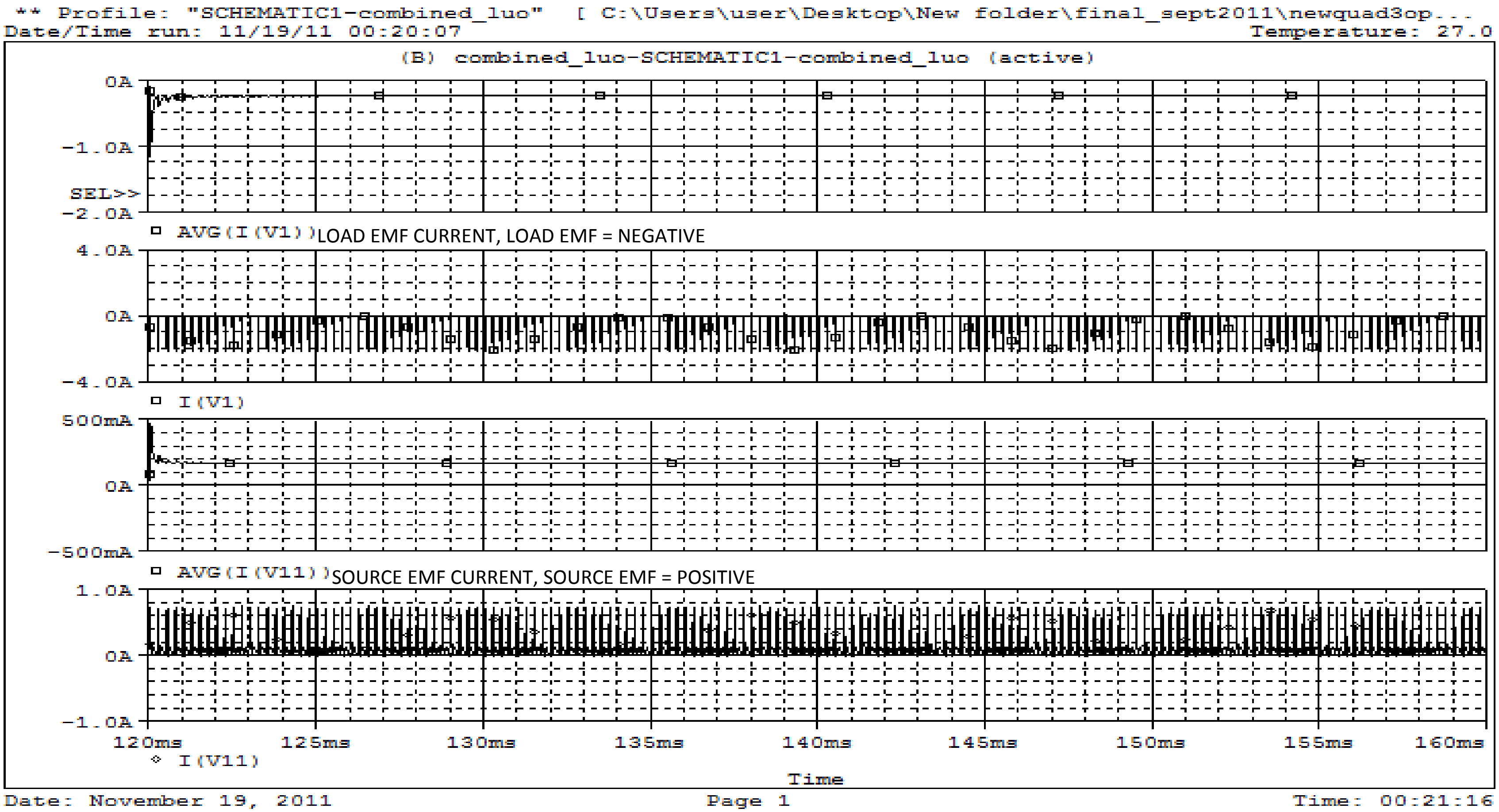


Figure 2.17: Forward Regerating/brake operation of Circuit of Figure 2.14(where g1 = 0, gain set to 0) for Pulse Width 0.05ms (Quadrant-II).

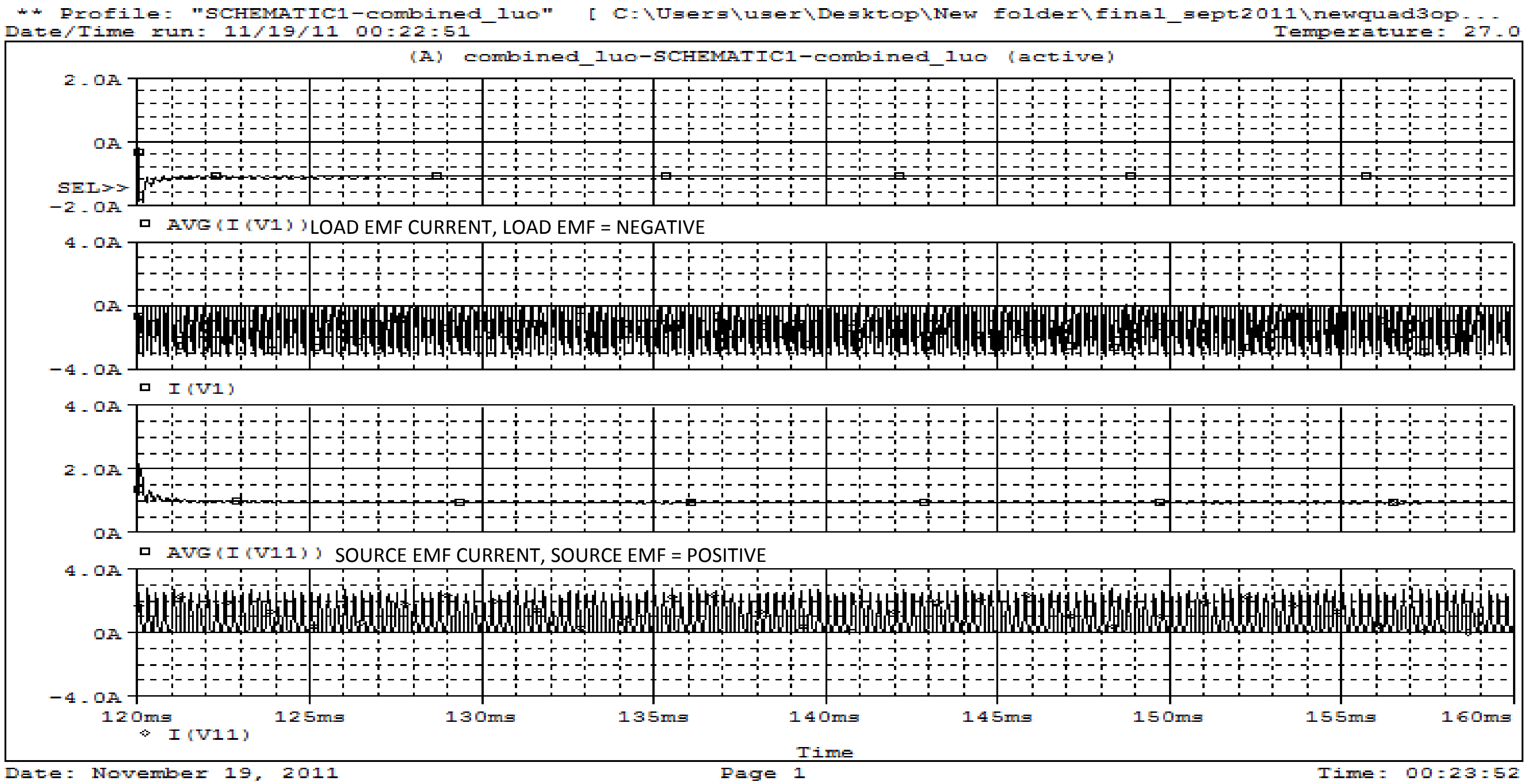


Figure 2.18: Forward Regerating/brake operation of Circuit of Figure 2.14(where g1 = 0, gain set to 0) for Pulse Width 0.15ms (Quadrant-II).

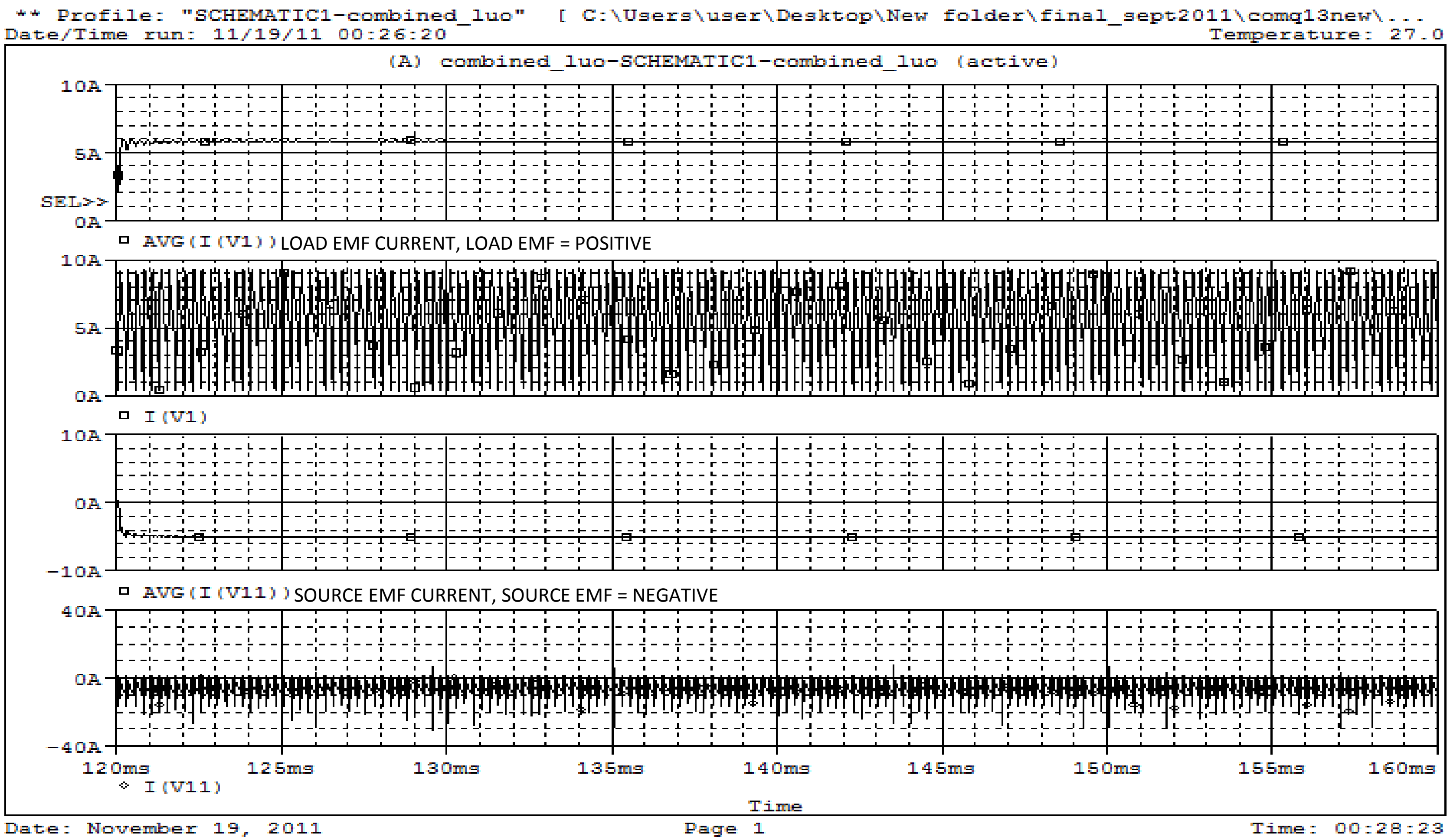


Figure 2.19: Motoring and Regenerating operation of Circuit of Figure 2.14 for Pulse Width 0.05ms (Quadrant-I).

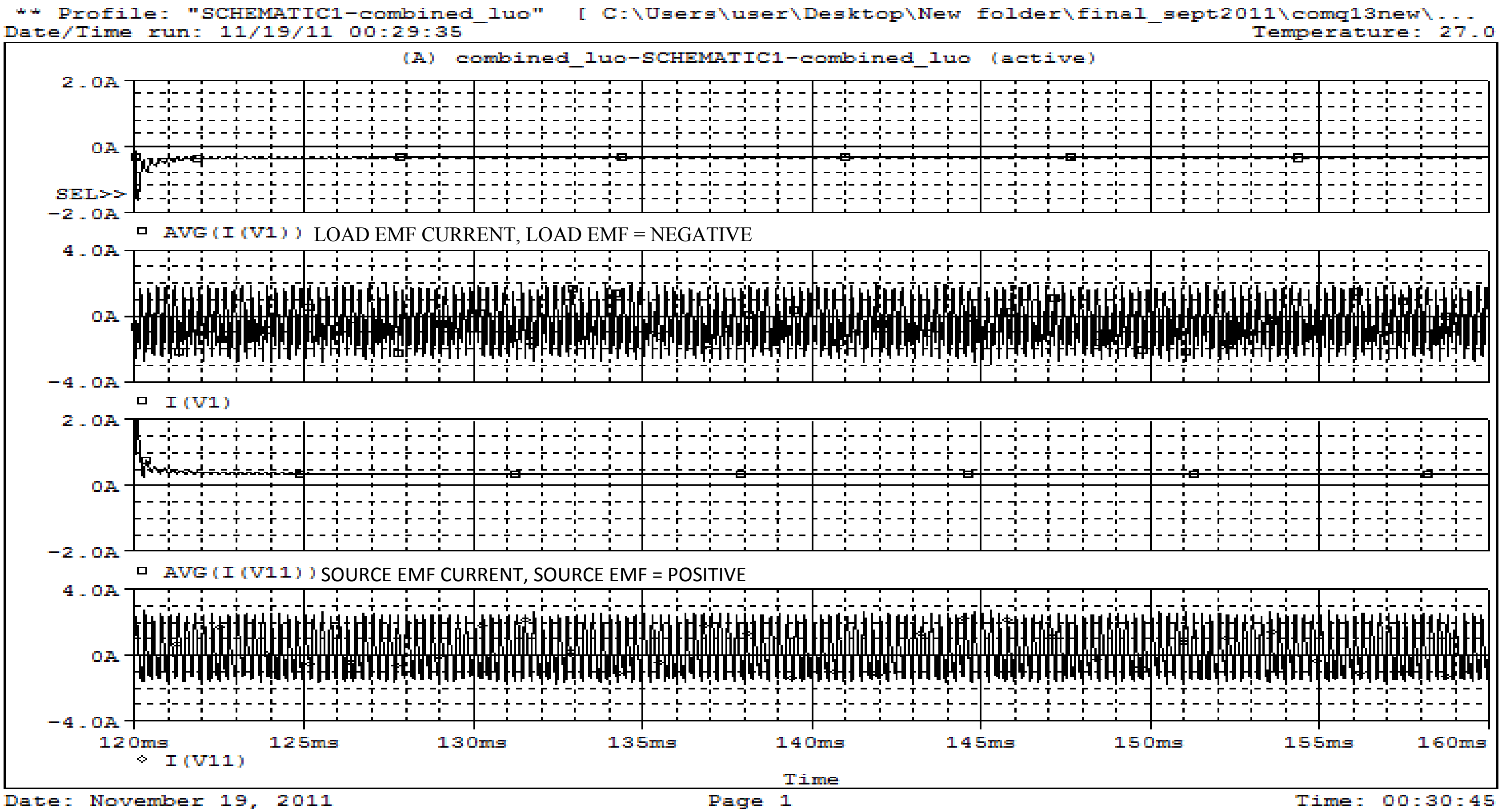
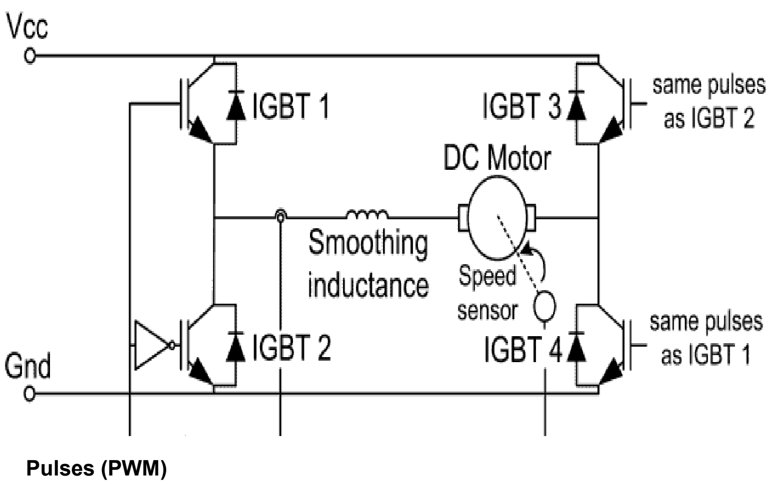
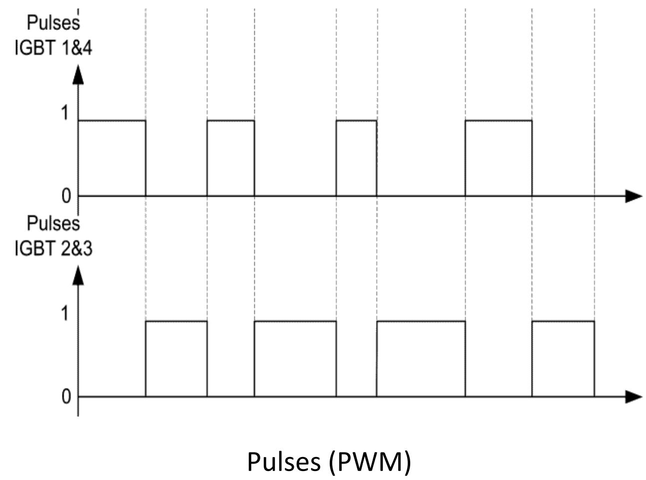


Figure 2.20: Motoring and Regenerating operation of Circuit of Figure 2.14 for Pulse Width 0.15ms (Quadrant-II).

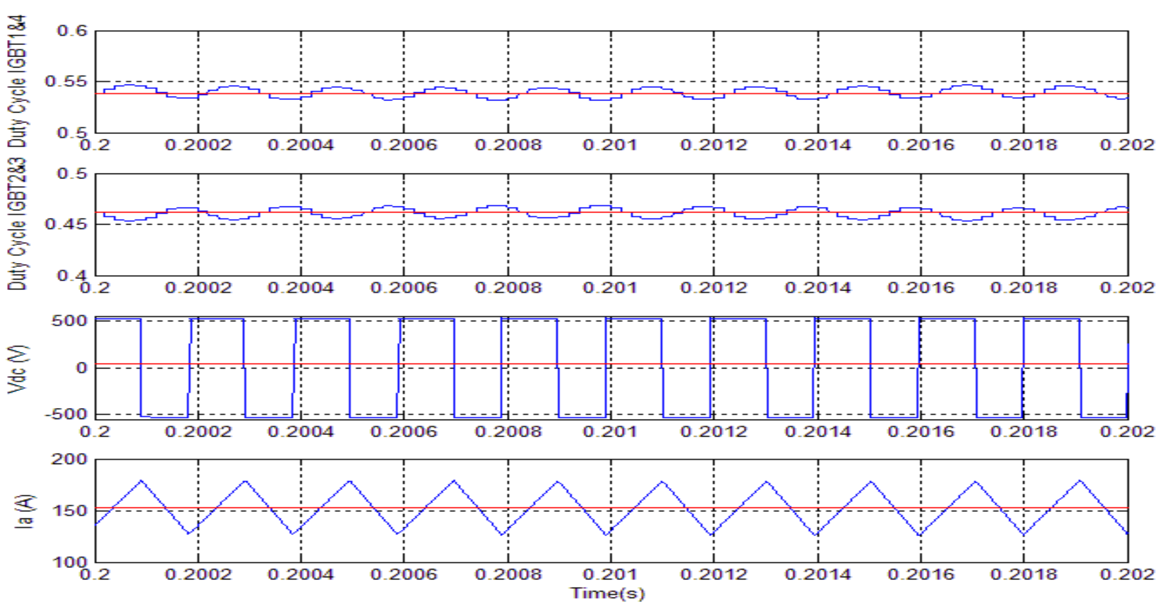
As stated earlier, it's possible to create a four-quadrant chopper which can control the motor in both the forward and reverse directions according to the circuit is shown in Figure 2.21(a.b.c), where switches need to be controlled to operate the motor in all four quadrants. For proper system behavior, the instantaneous pulse values of IGBT devices 1 and 4 are the opposite of those of IGBT devices 2 and 3. And the next figure-c, shows the duty cycles of the chopper pulses and the corresponding armature voltage and current waveforms during a time interval of 2 ms.



a.



b.



c. Duty cycles of the chopper pulses and the corresponding armature voltage and current waveforms.

Figure 2.21(a,b,c): A four Quadrant Chopper mode of forward and reverse Converter.

COMBINED FORM OF FOUR QUADRANT CHOPPER: A four quadrant power converter design is strongly depends on its use, considering several criteria reviewed in the first part of this thesis. Some well known solutions are commonly used and short explanation of the principles is given before. Second part of this thesis gives the key points of the design of a specific FOUR QUADRANT power converter by combination two nos. of Two Quadrant Chopper mode of forward and reverse Converter of Figure 2.14 with differential load connection to yield a four quadrant chopper as shown in Figure 2.22 (a, b) and Figure 2.23(a, b, c, d, e, f).

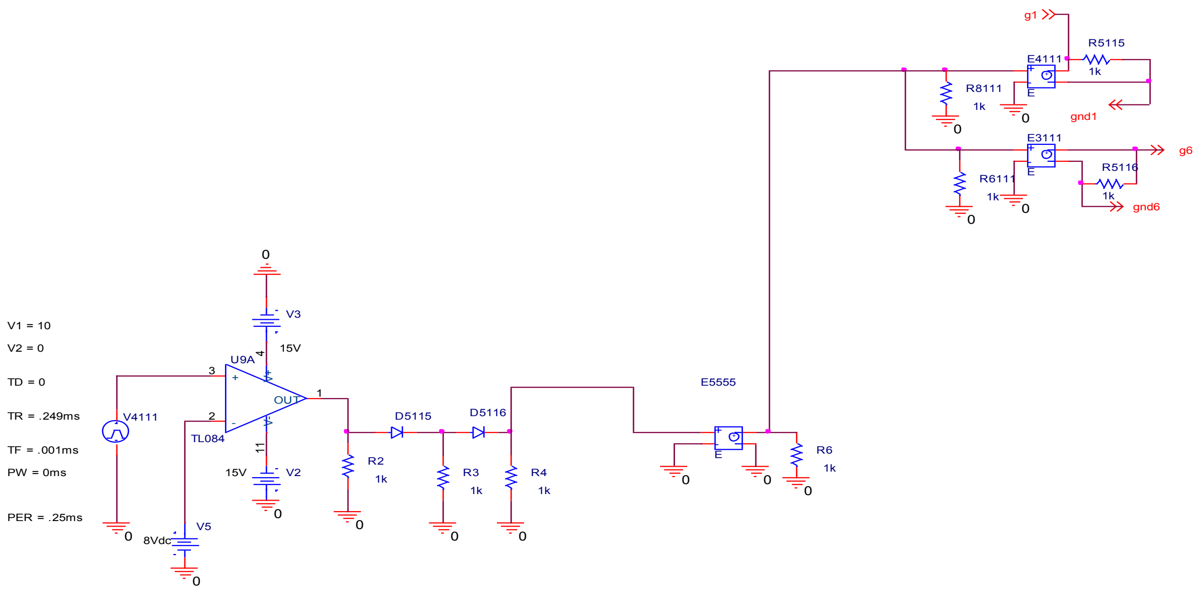


Figure 2.22(a): Gate Signal Generating Circuit for 4-Quadrant Converter of particular quadrant operation.

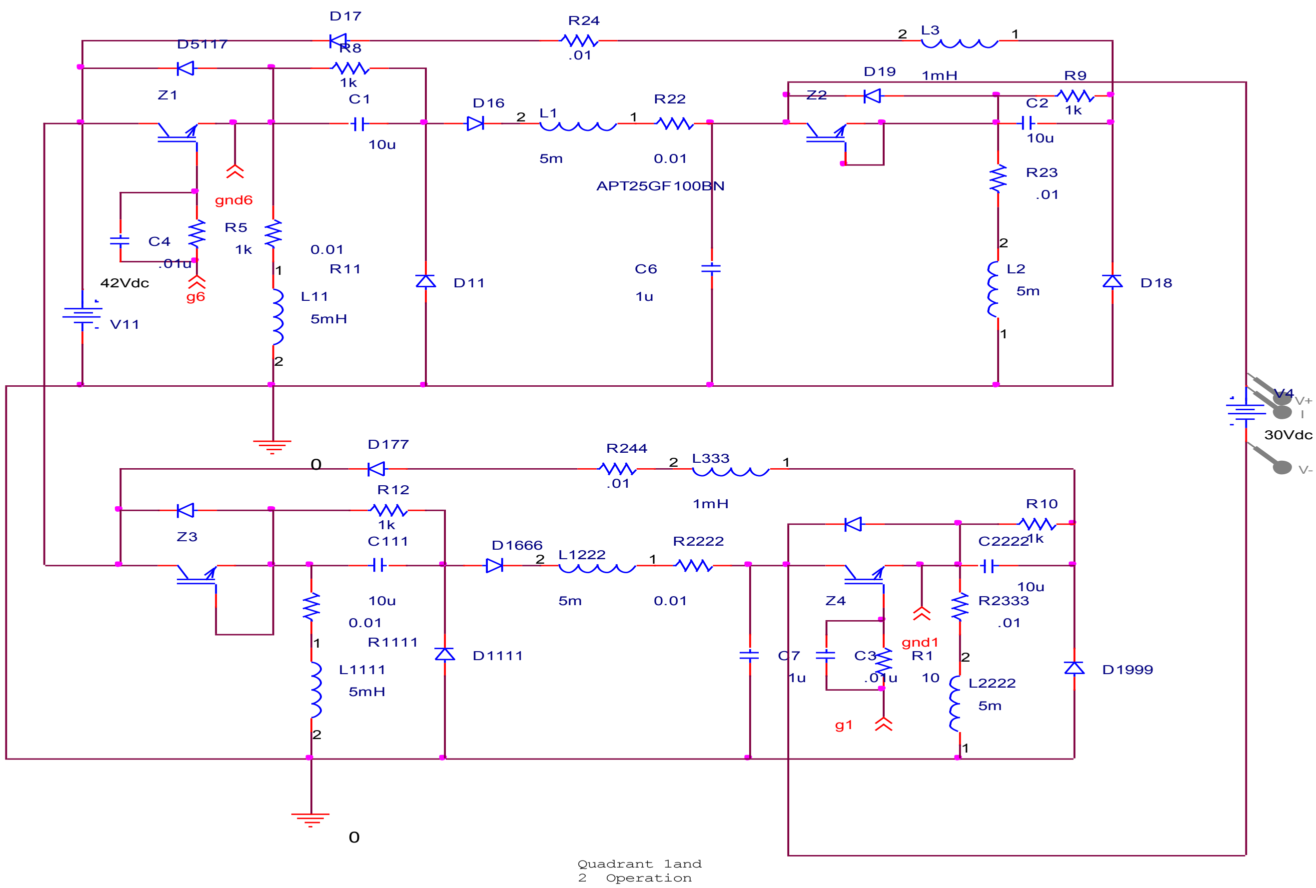


Figure 2.23(a): Combined form of proposed new Four Quadrant Converter with differentially connected (+)ve EMF and IGBTs Z_1 and Z_4 are conducting.

Typical waveforms of proposed new Four Quadrant Converter with differentially connected (+)ve EMF load of circuit of Figure 2.23(a), are shown in Figures 2.24-25. Where IGBTs Z_1 and Z_4 are conducting at a time and Z_2 and Z_3 are off state as of Figure 2.21(b). Figures 2.24-25. show typical waveforms of circuit of Figure 2.23(a) for forward motoring/Quadrant I. Where load EMF current is increased / decreased as duty cycle is changed.

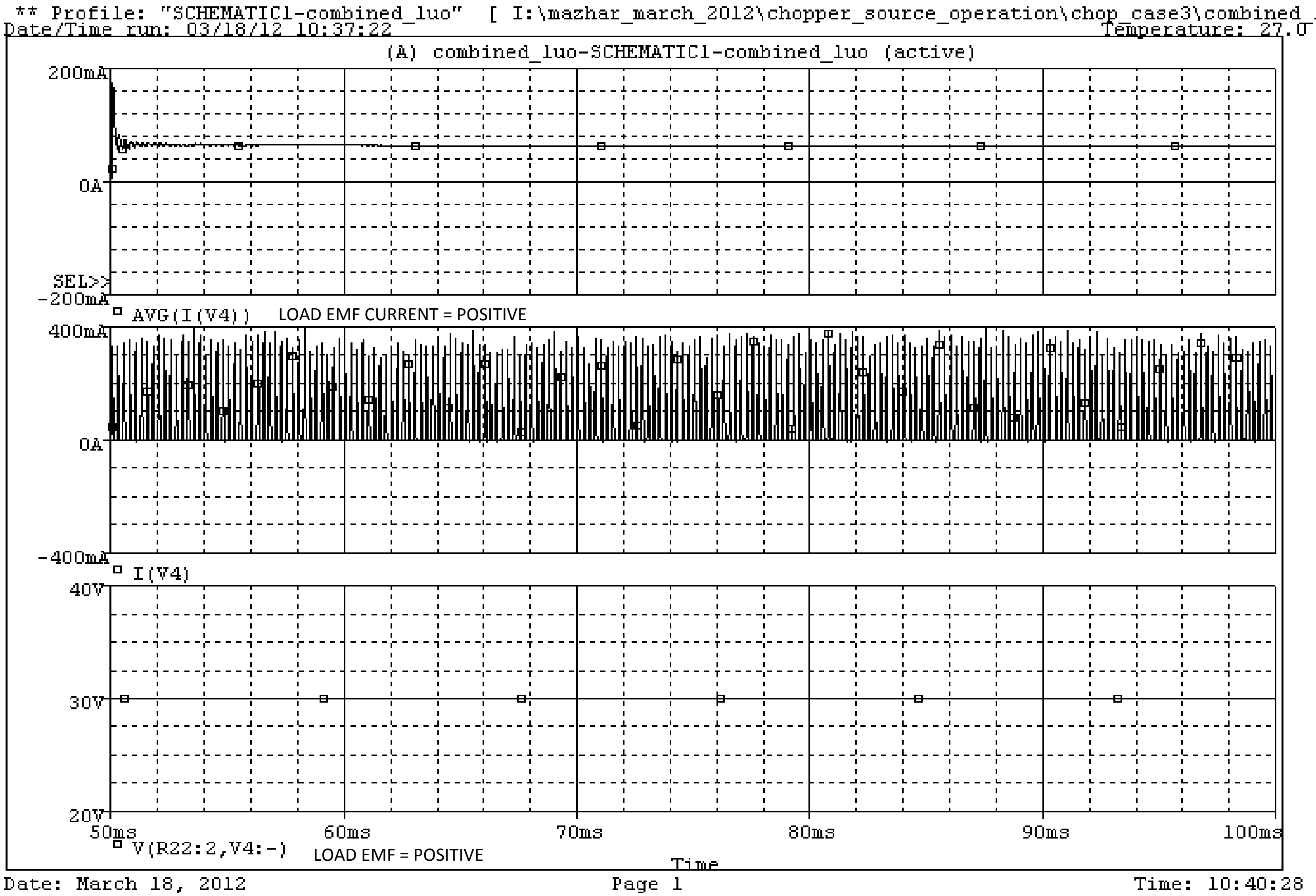


Figure 2.24: Forward Motoring operation of Circuit of Figure 2.23a for DC level 8v (Quadrant-I).

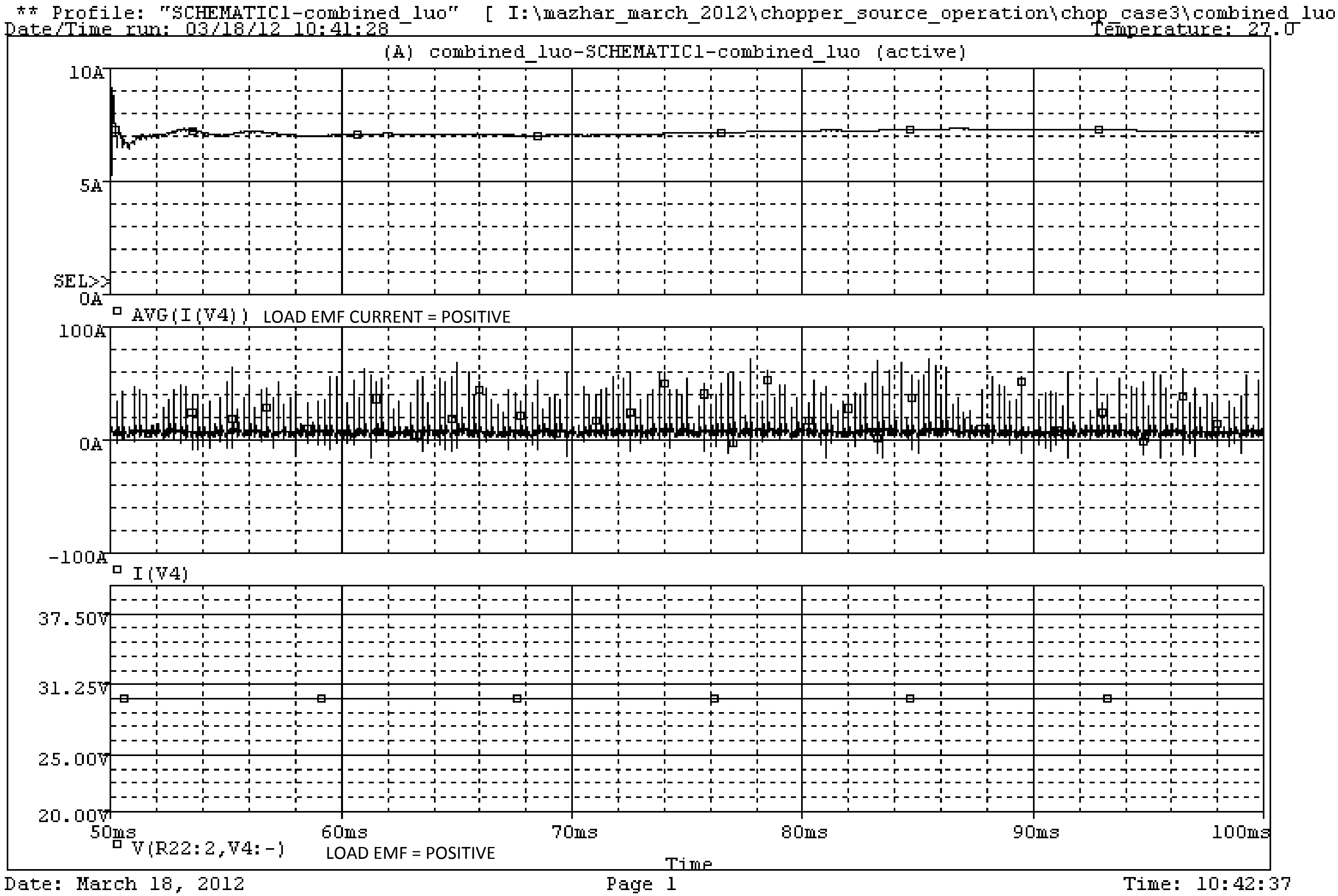


Figure 2.25: Forward Motoring operation of Circuit of Figure 2.23a for DC level 3v (Quadrant-I).

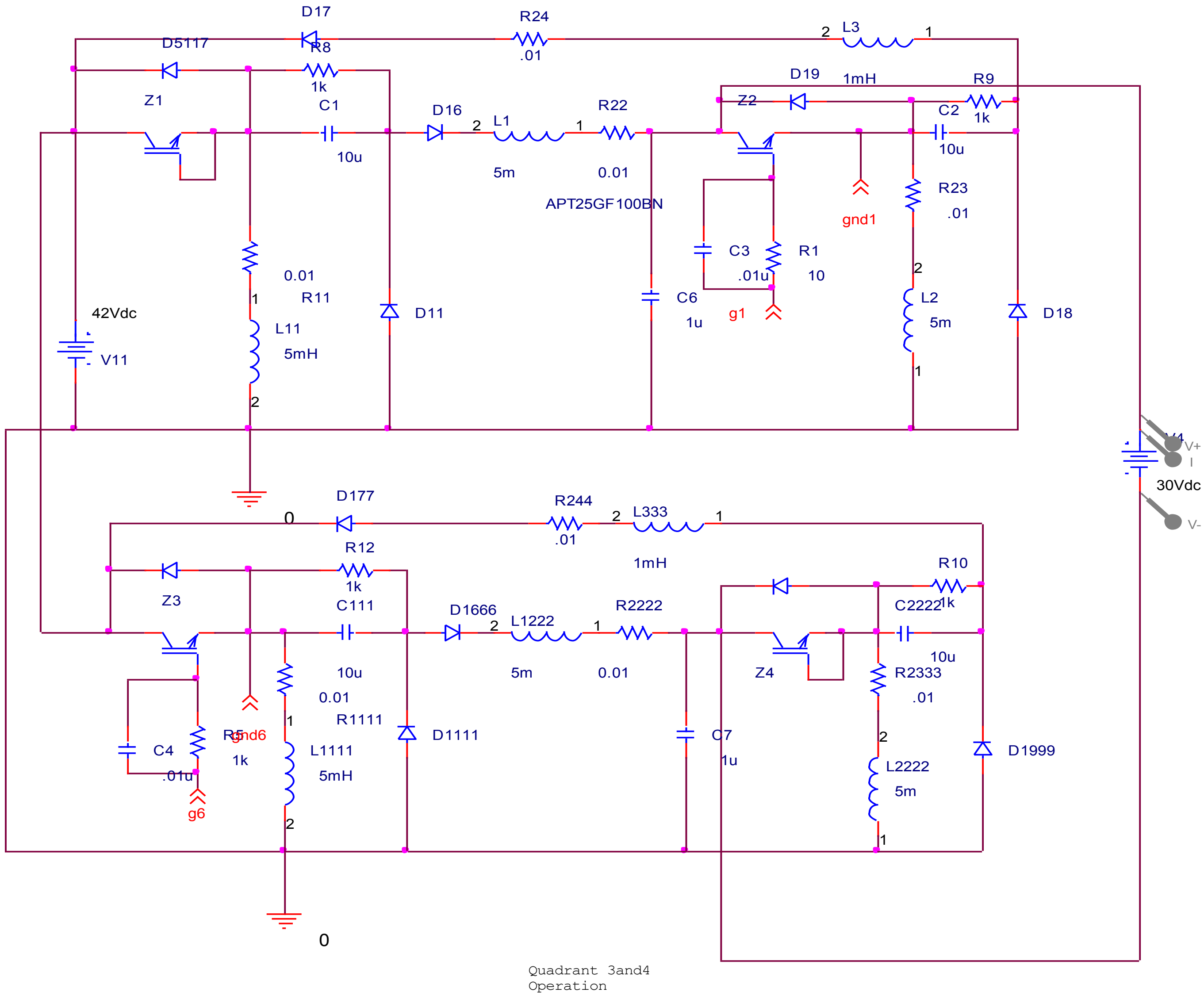


Figure 2.23(b): Combined form of proposed new Four Quadrant Converter with differentially connected (+)ve EMF and IGBTs Z_2 and Z_3 are conducting.

Typical waveforms of proposed new Four Quadrant Converter with differentially connected (+)ve EMF load of circuit of Figure 2.23(b) are shown in Figures 2.26-2.27. Where IGBTs Z_2 and Z_3 are conducting at a time and Z_1 and Z_4 are off state as of Figure 2.21(b). Figures 2.26-2.27. show typical waveforms of circuit of Figure 2.23(b) for forward regenerating/Quadrant II. Where load EMF current is increased / decreased as duty cycle is changed.

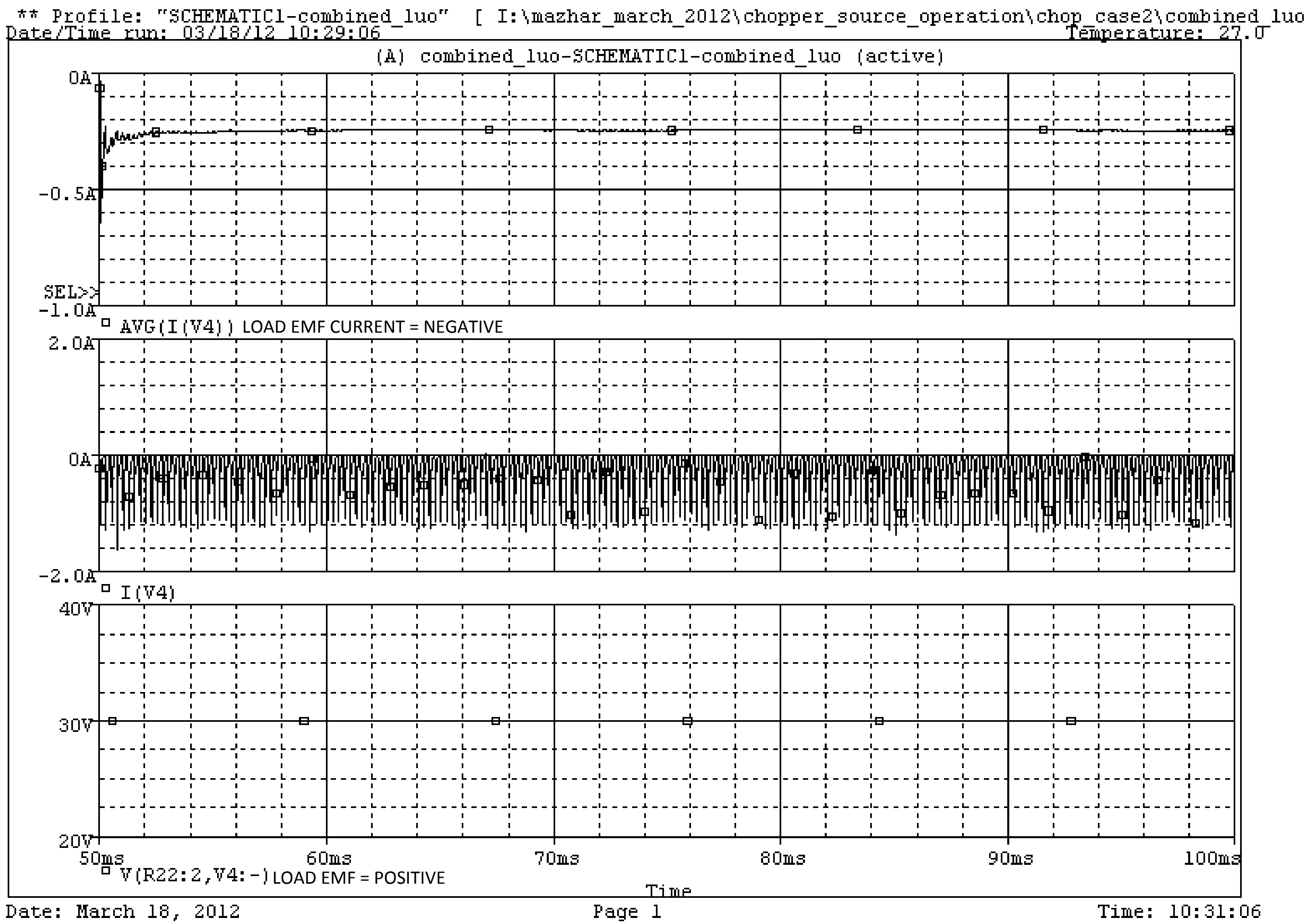


Figure 2.26: Forward Regenerating/brake operation of Circuit of Figure 2.23b for DC level 8v (Quadrant-II).

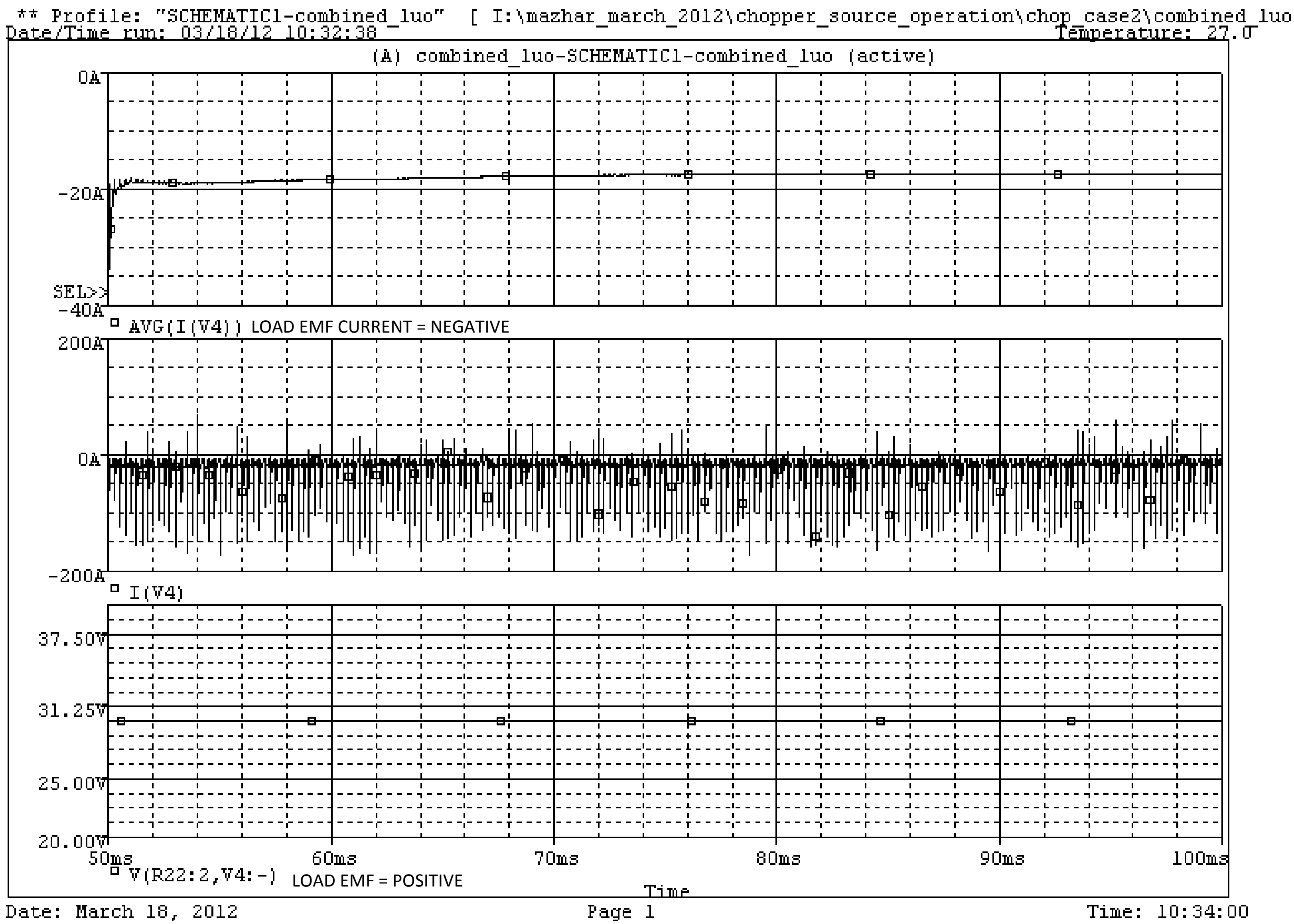


Figure 2.27: Forward Regenerating/brake operation of Circuit of Figure 2.23b for DC level 3v (Quadrant-II).

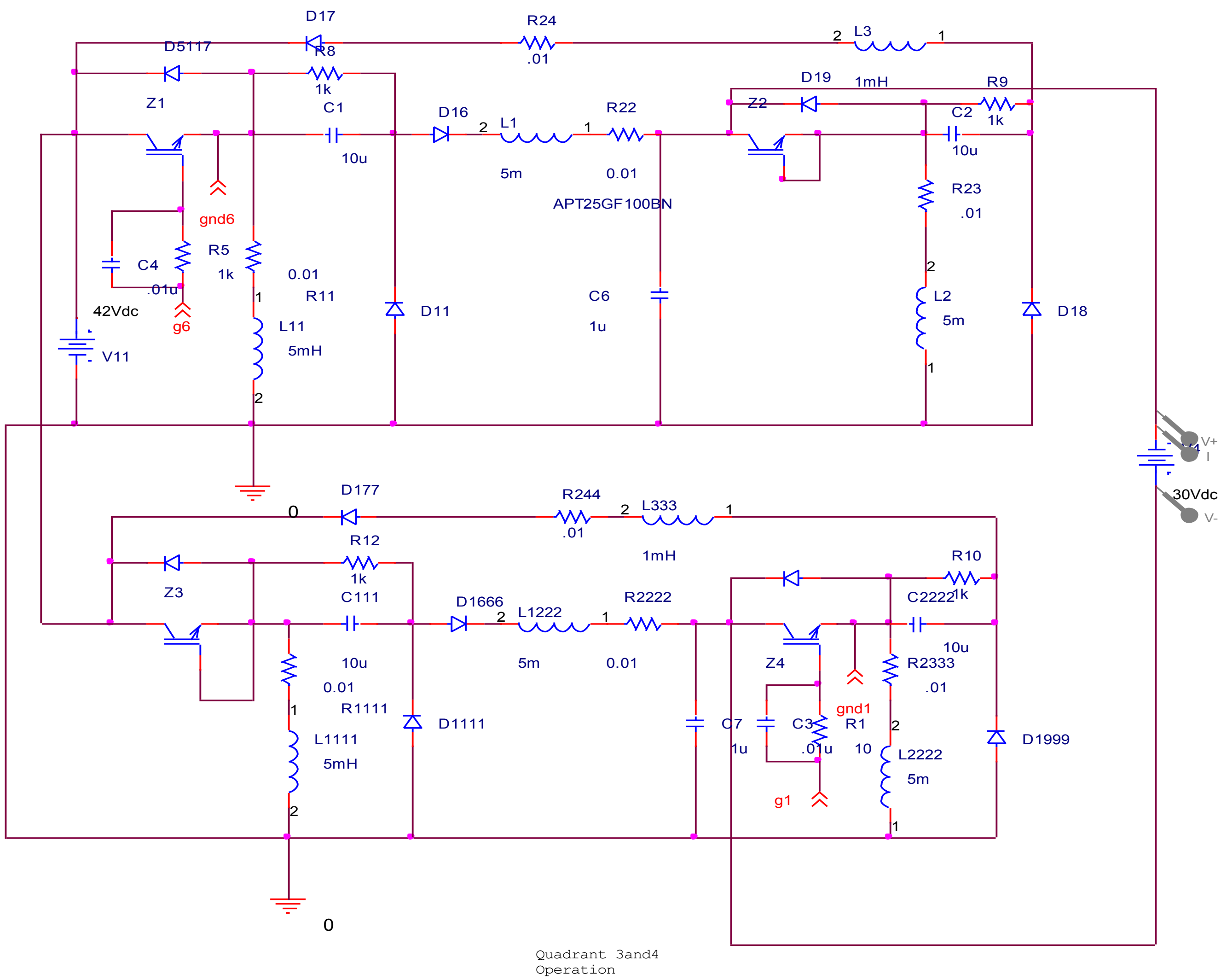


Figure 2.23(c): Combined form of proposed new Four Quadrant Converter with differentially connected (-)ve EMF and IGBTs Z_1 and Z_4 are conducting.

Typical waveforms of proposed new Four Quadrant Converter with differentially connected (+)ve EMF load of circuit of Figure 2.23(c) are shown in Figures 2.28-2.29. Where IGBTs Z_1 and Z_4 are conducting at a time and Z_2 and Z_3 are off state as of Figure 2.21(b). Figures 2.28-2.29 show typical waveforms of circuit of Figure 2.23(c), for reverse regenerating/Quadrant IV. Where load EMF current is increased / decreased as duty cycle is changed.

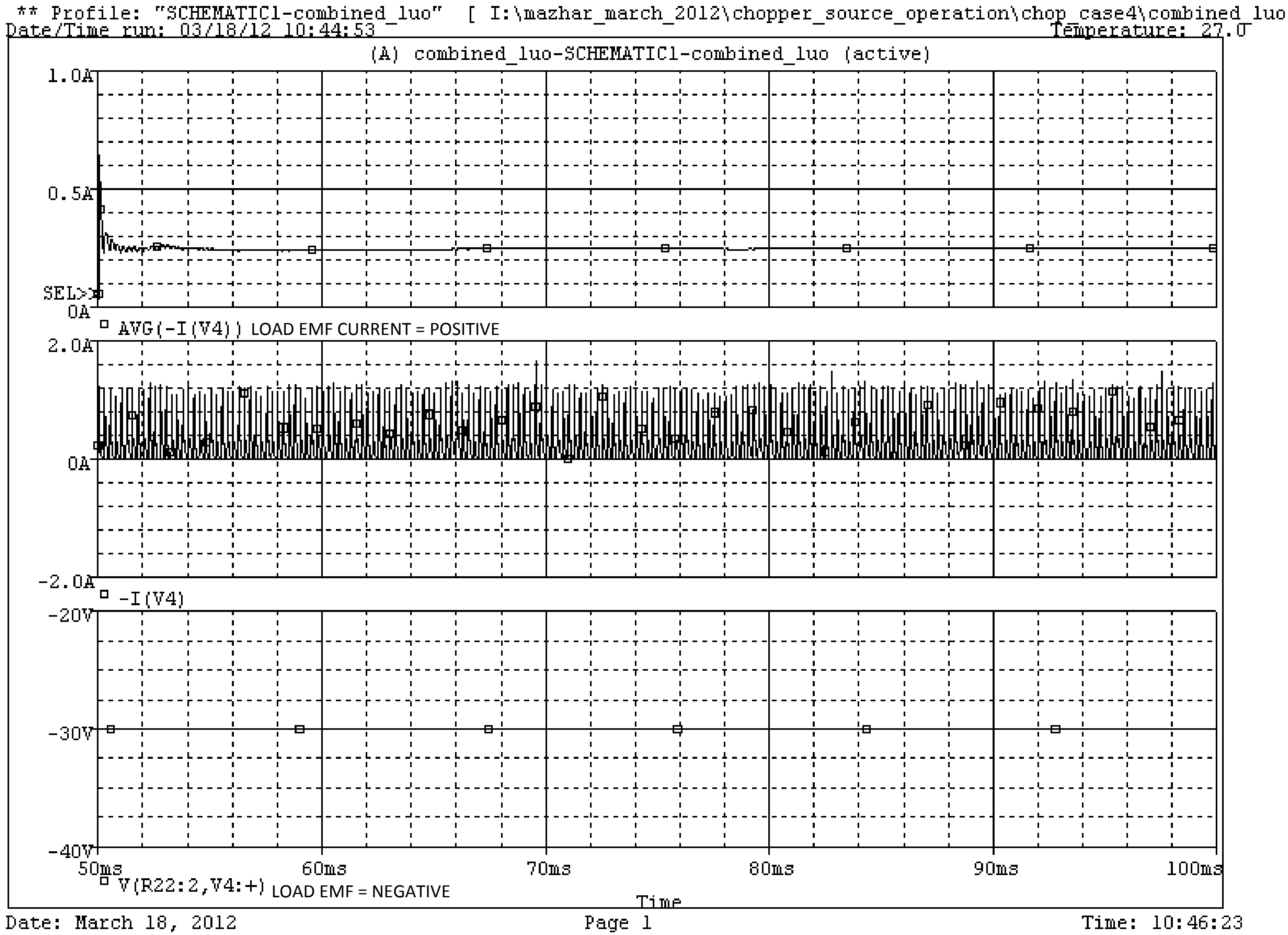


Figure 2.28: Reverse Regenerating/brake operation of Circuit of Figure 2.23c for DC level 8v (Quadrant-IV).

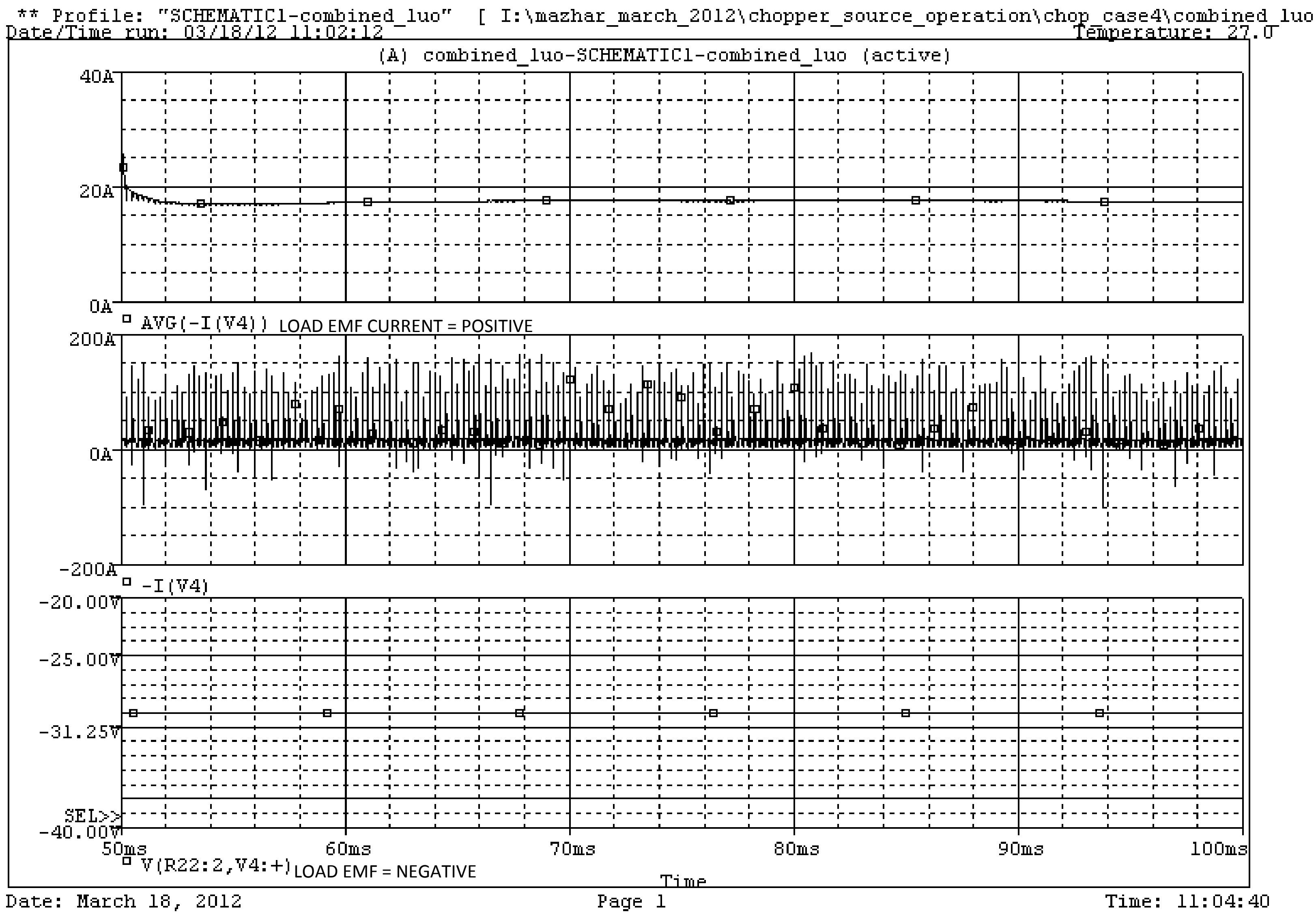


Figure 2.29: Reverse Regenerating/brake operation of Circuit of Figure 2.23c for DC level 3v (Quadrant-IV).

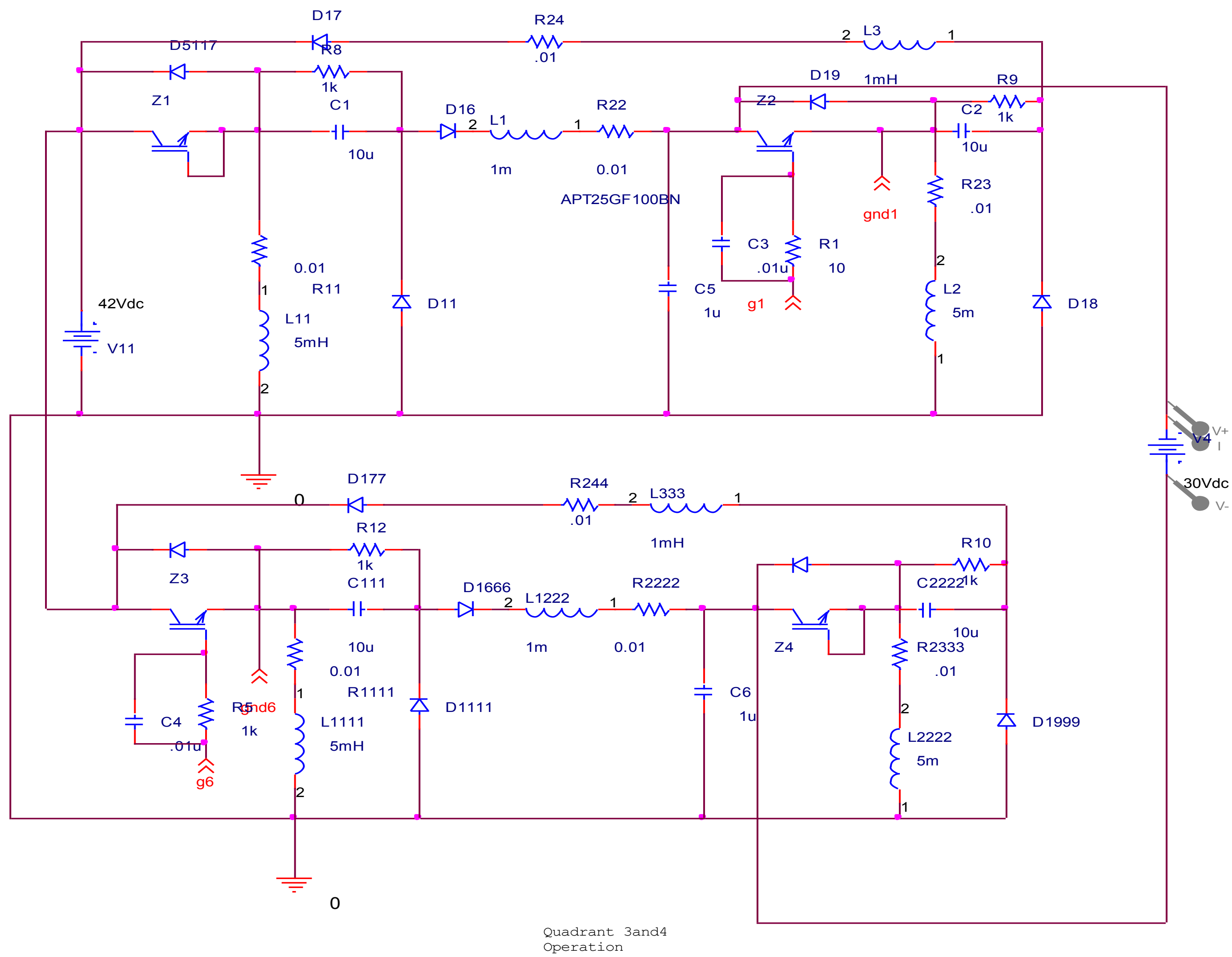


Figure 2.23(d): Combined form of proposed new Four Quadrant Converter with differentially connected (-)ve EMF and IGBTs Z_2 and Z_3 are conducting.

Typical waveforms of proposed new Four Quadrant Converter with differentially connected (-)ve EMF load of circuit of Figure 2.23(d) are shown in Figures 2.30-2.31. Where IGBTs Z_2 and Z_3 are conducting at a time and Z_1 and Z_4 are off state as of Figure 2.21(b). Figures 2.30-2.31, show typical waveforms of circuit of Figure 2.23(d) for reverse Motoring/Quadrant III. Where load EMF current is increased / decreased as duty cycle is changed.

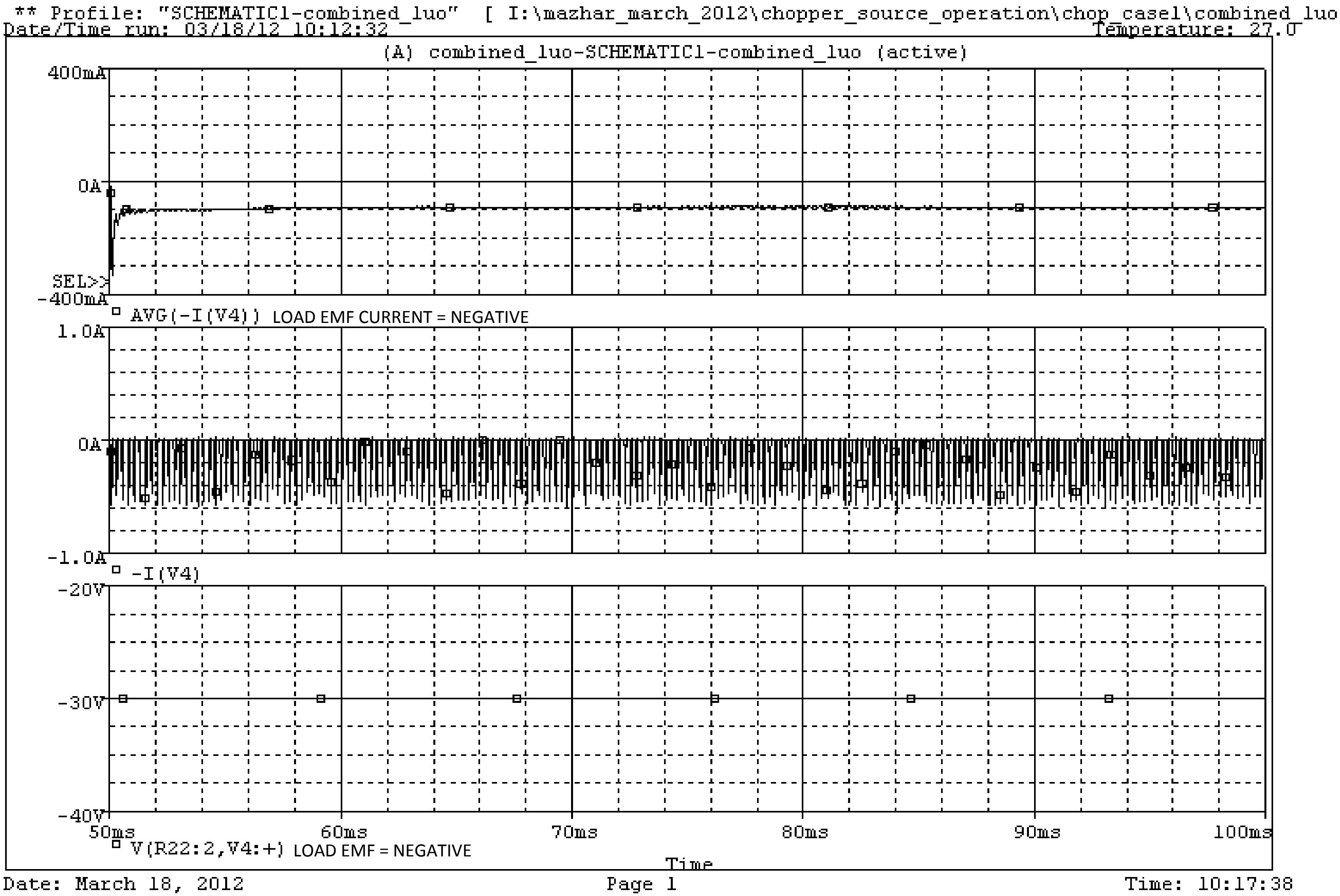


Figure 2.30: Reverse Motoring operation of Circuit of Figure 2.23d for DC level 8v (Quadrant-III).

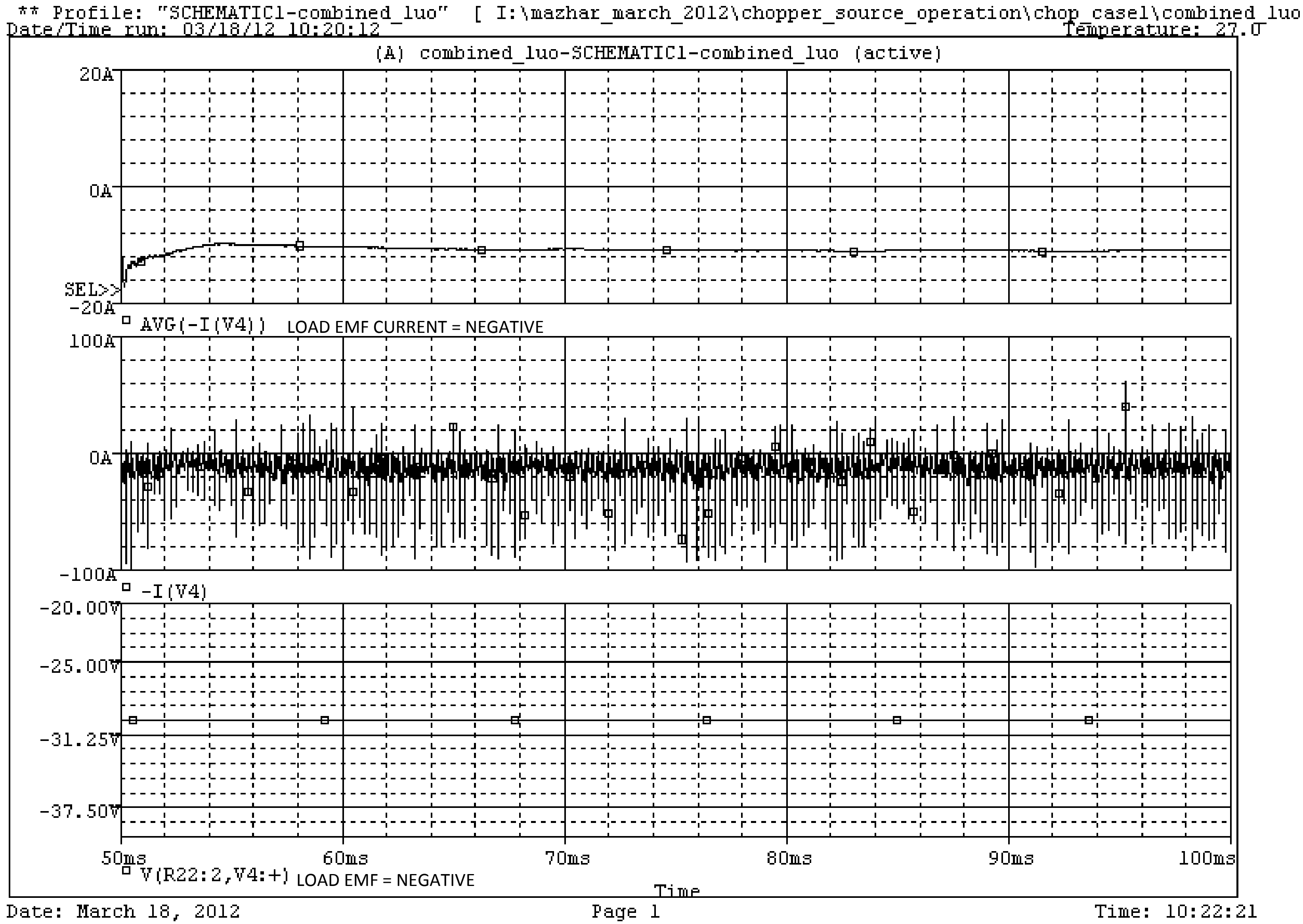


Figure 2.31: Reverse Motoring operation of Circuit of Figure 2.23d for DC level 3v (Quadrant-III).

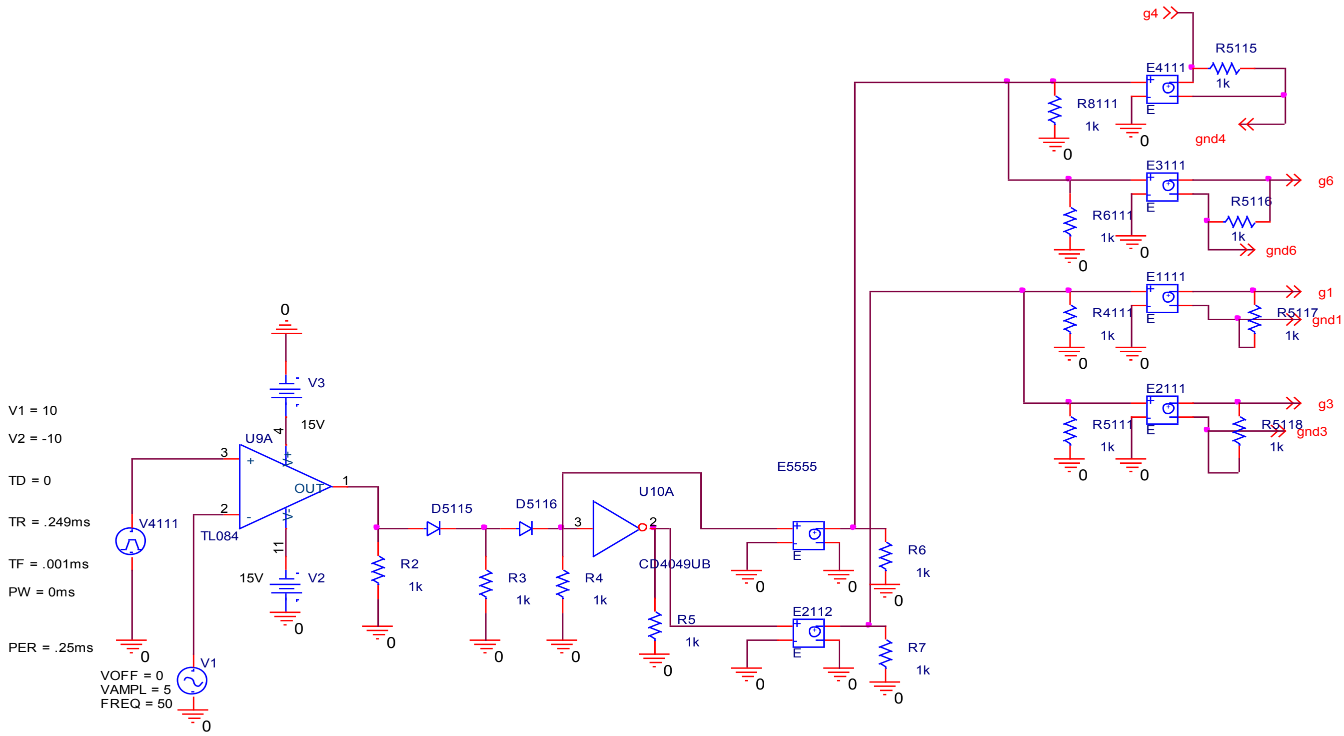


Figure 2.22(b): Gate Signal Generating Circuit for Proposed 4-Quadrant Converter, with instantaneous pulses of IGBT devices Z_1 and Z_4 are the opposite of Z_2 and Z_3.

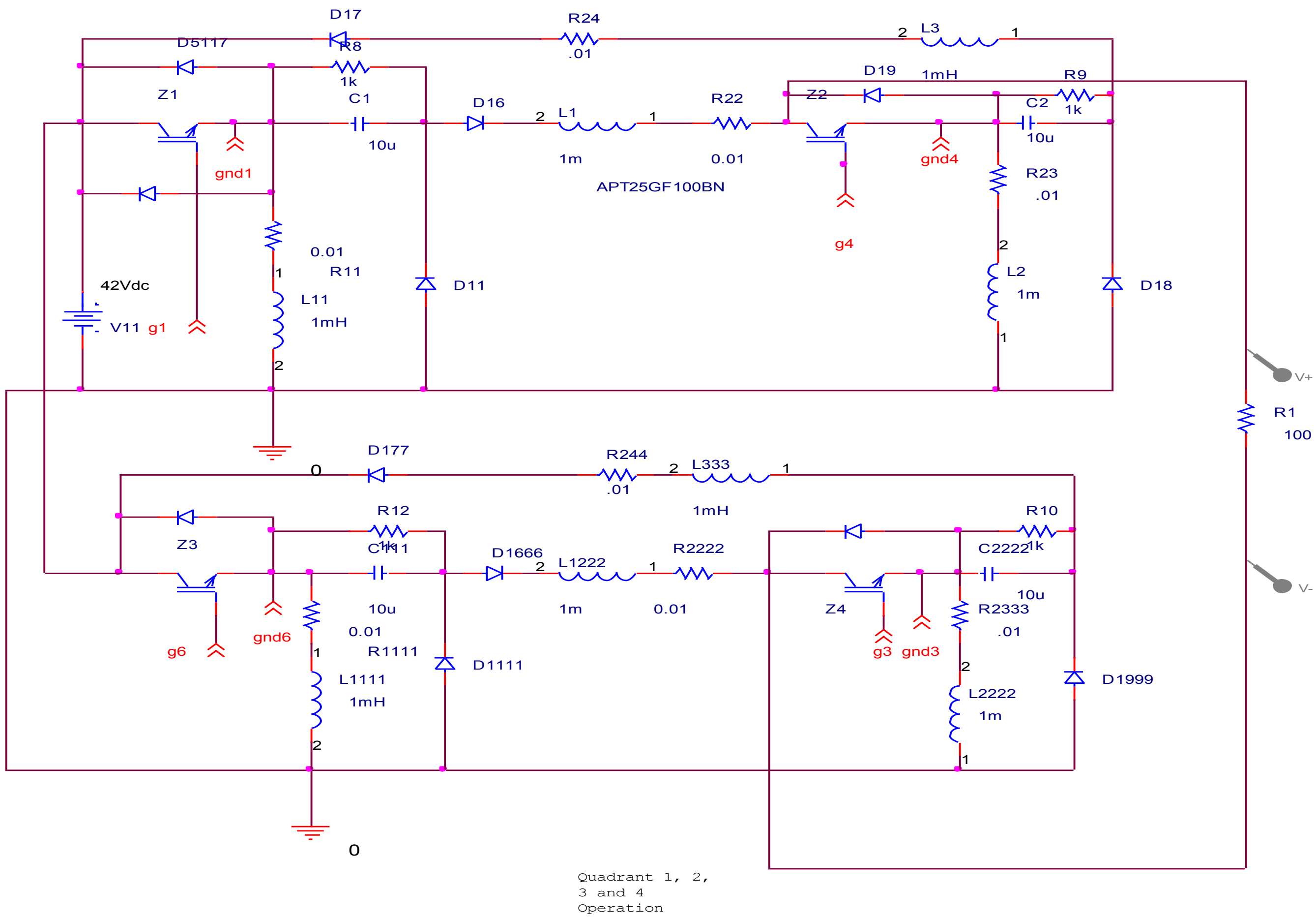


Figure 2.23(e): Combined form of proposed new Four Quadrant Converter with differentially connected resistive load (R) with instantaneous pulses of IGBT devices Z_1 and Z_4 are the opposite of Z_2 and Z_3.

Typical waveforms of proposed new Four Quadrant Converter with differentially connected Resistive load(R) of circuit of Figure 2.23(e), are shown in Figures 2.32-2.34. Where switches are controlled to operate in all four quadrants with instantaneous pulses as IGBTs Z_2 and Z_3 are conducting at a time and Z_1 and Z_4 are off state and vice verse. Figures 2.32-2.34 show typical waveforms of circuit of Figure 2.23(e), for continuous changes of current and voltage in forward and reverse direction as AC voltage across load. Where load current is increased / decreased as duty cycle is changed.

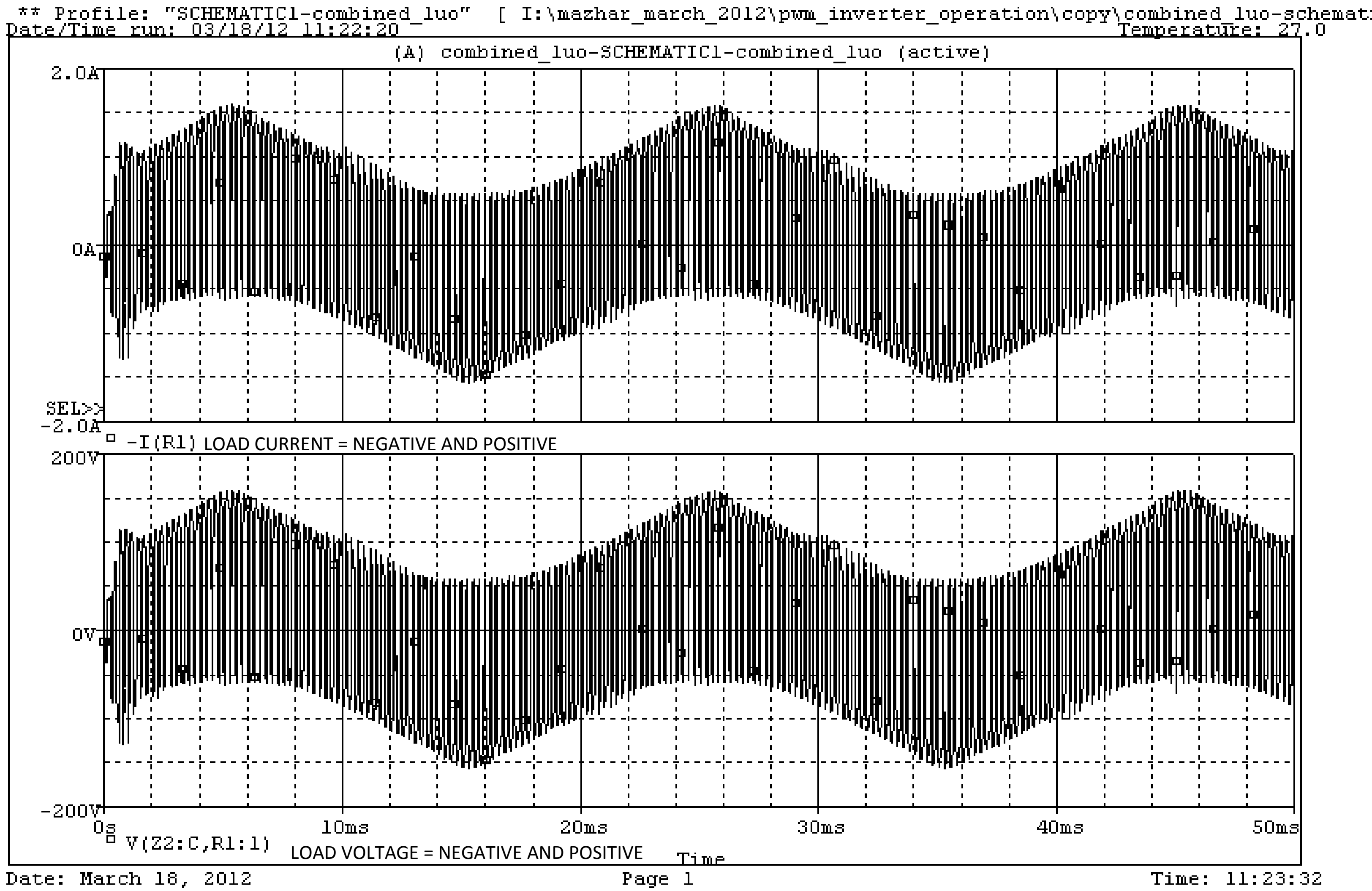


Figure 2.32: Load current and voltage in forward and reverse direction operation of Circuit of Figure 2.23e.

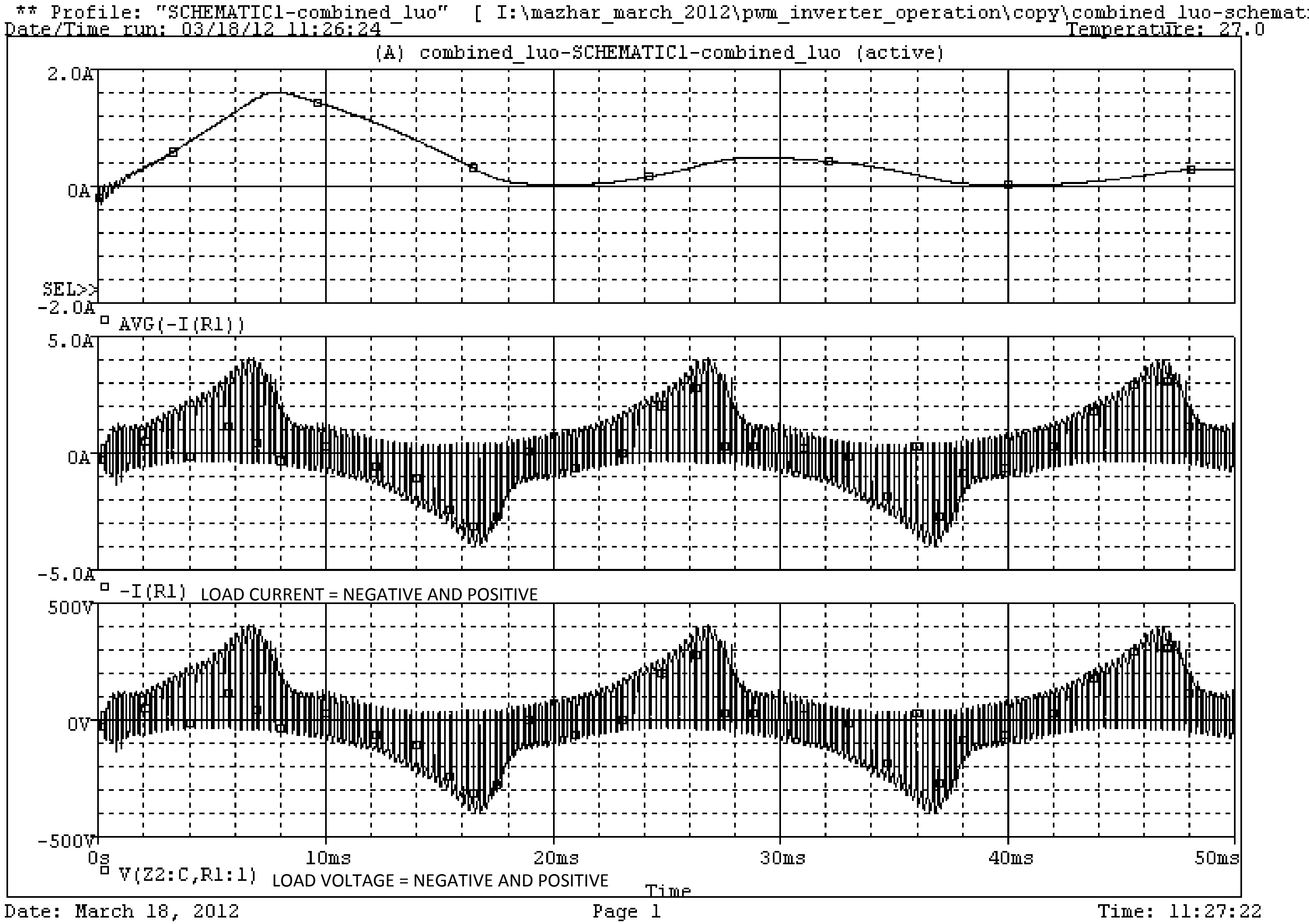


Figure 2.33: Load current and voltage in forward and reverse direction operation of Circuit of Figure 2.23e, for Vamp 8v.

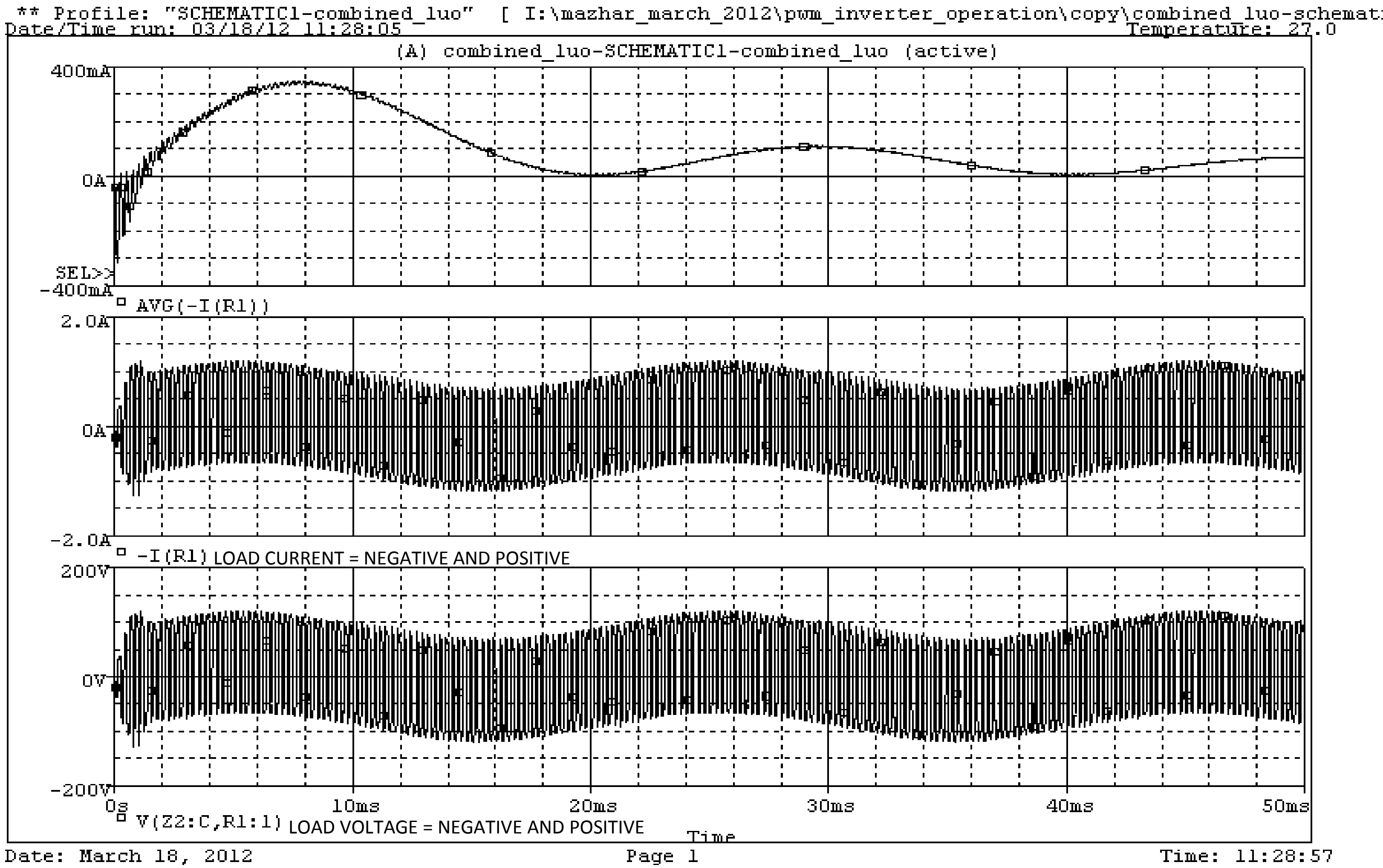


Figure 2.34: Load current and voltage in forward and reverse direction operation of Circuit of Figure 2.23e, for Vamp 3v.

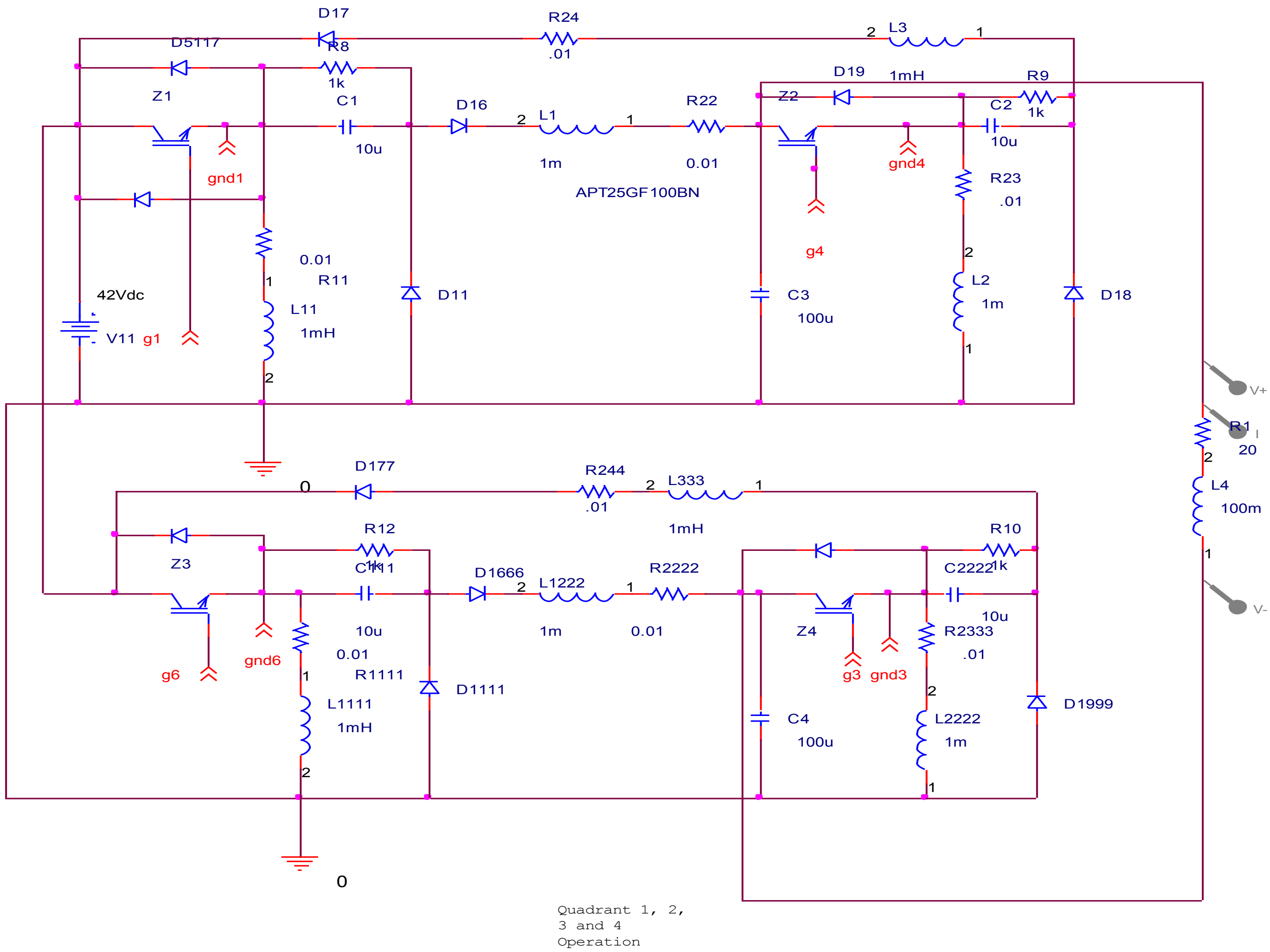


Figure 2.23(f): Combined form of proposed new Four Quadrant Converter with differentially connected R-L load with instantaneous pulses of IGBT devices Z_1 and Z_4 are the opposite of Z_2 and Z_3.

Typical waveforms of proposed new Four Quadrant Converter with differentially connected R-L load of circuit of Figure 2.23(f), are shown in Figures 2.35-2.38. Where switches are controlled to operate in all four quadrants with instantaneous pulses as IGBTs Z_2 and Z_3 are conducting at a time and Z_1 and Z_4 are off state and vice verse. Figures 2.35-2.38 show typical waveforms of circuit of Figure 2.23(f), for continuous changes of current and voltage in forward and reverse direction as a DC-AC inverter that converts direct current (DC) to alternating current (AC). Where load EMF current is increased / decreased as duty cycle is changed.

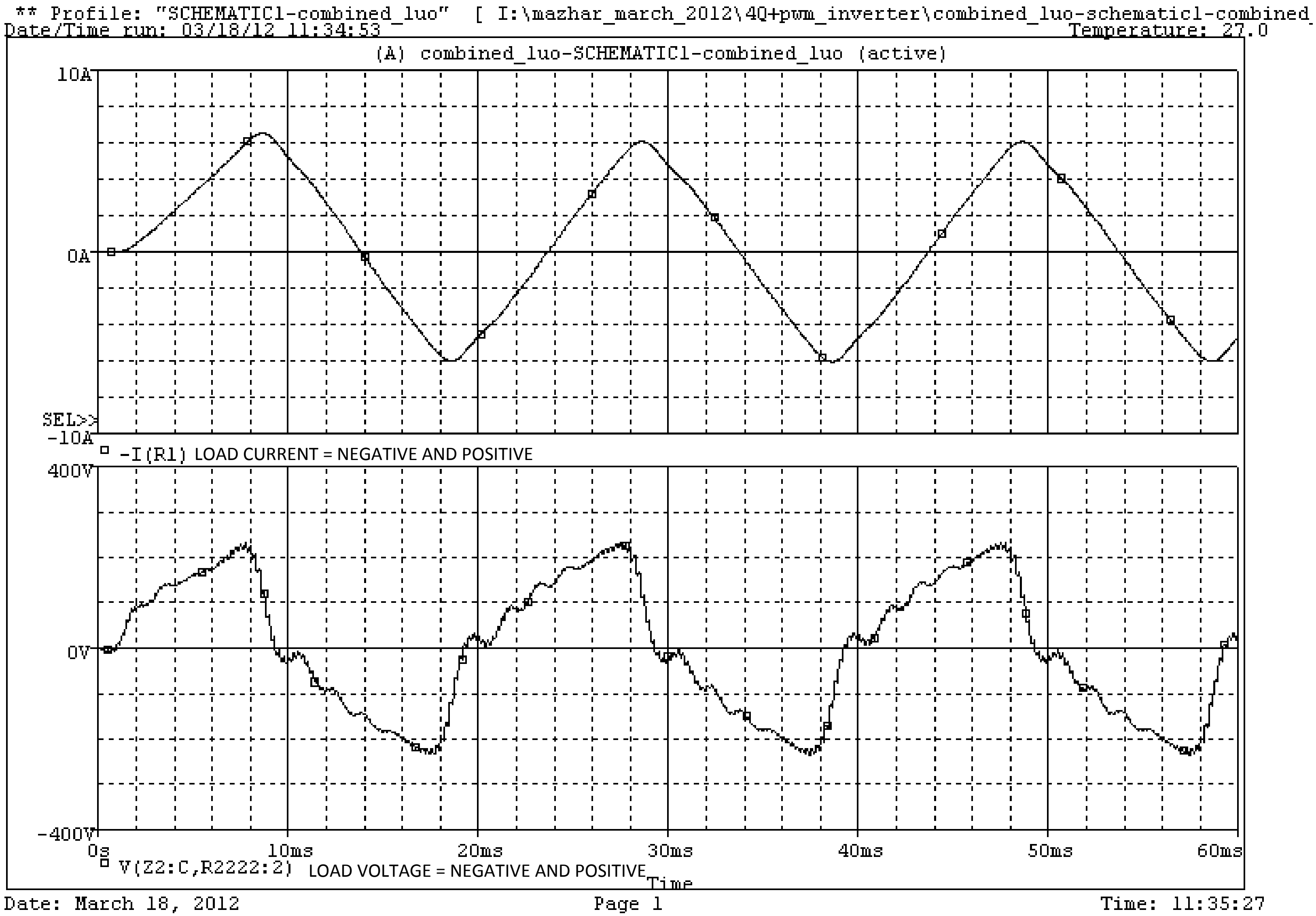


Figure 2.35: Load current and voltage in forward and reverse direction operation of Circuit of Figure 2.23f, for Vamp 8v.

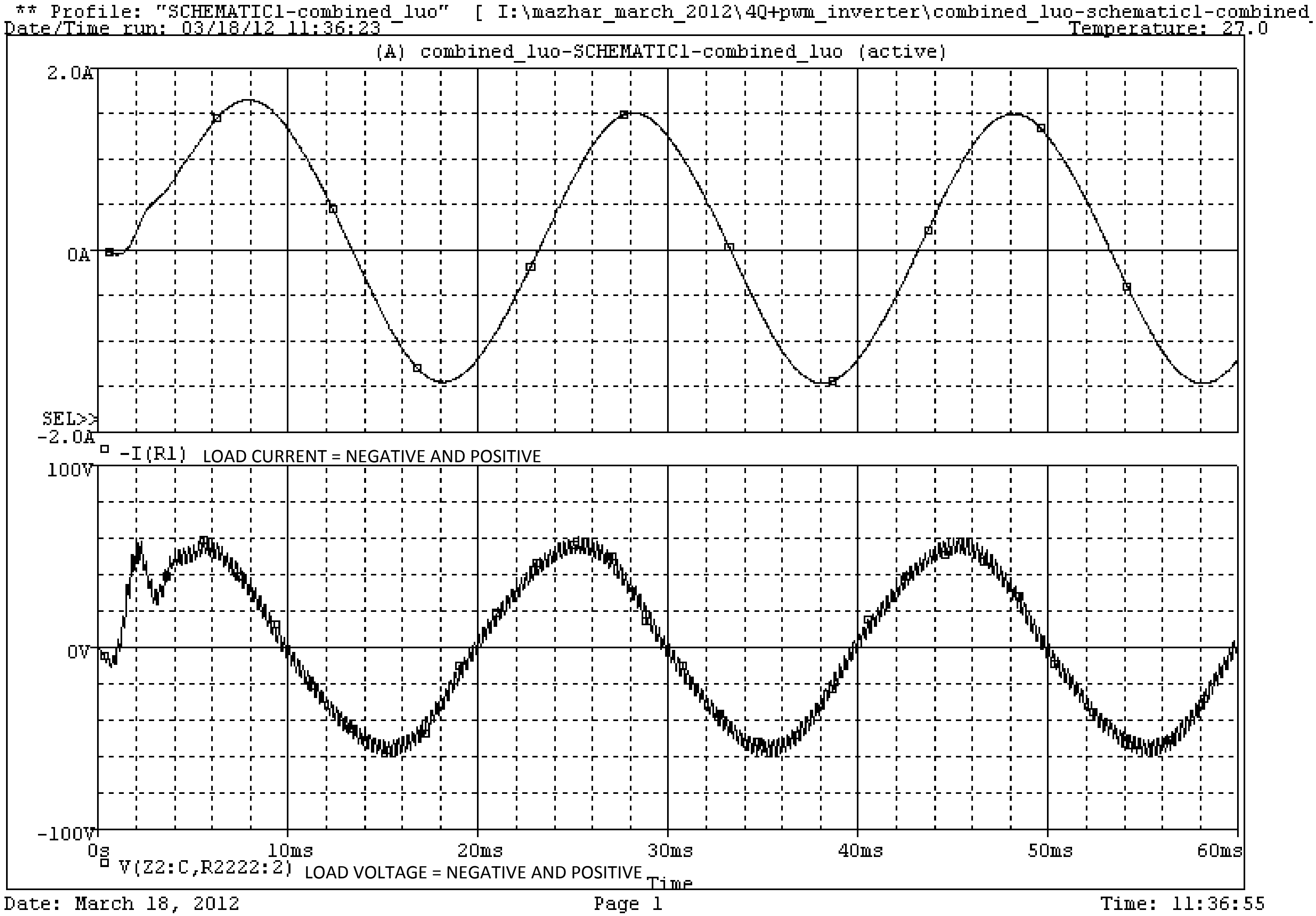


Figure 2.36: Load current and voltage in forward and reverse direction operation of Circuit of Figure 2.23f, for Vamp 3v.

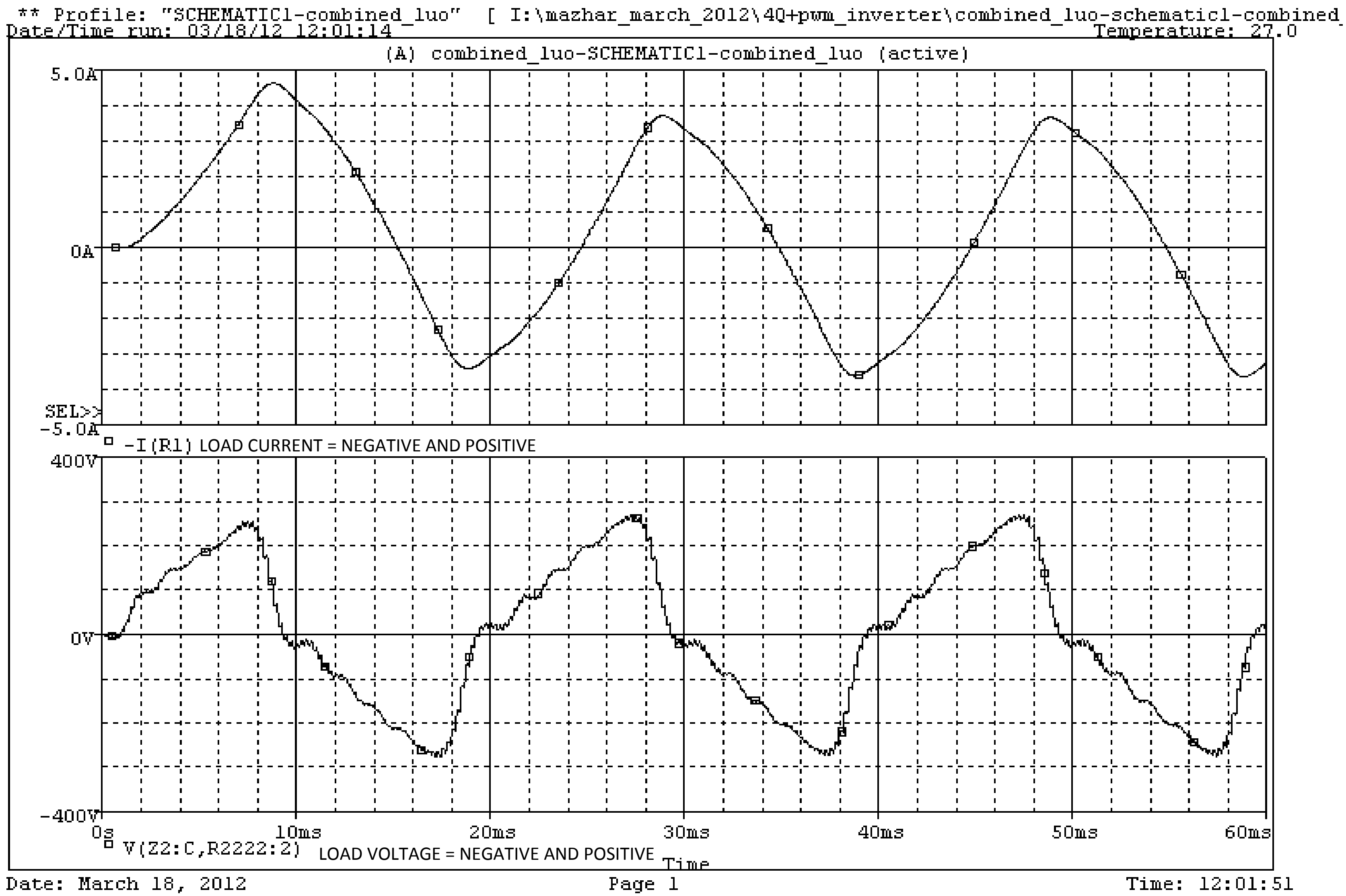


Figure 2.37: Load current and voltage in forward and reverse direction operation of Circuit of Figure 2.23f, for Inductance 200mH & Vamp 8v.

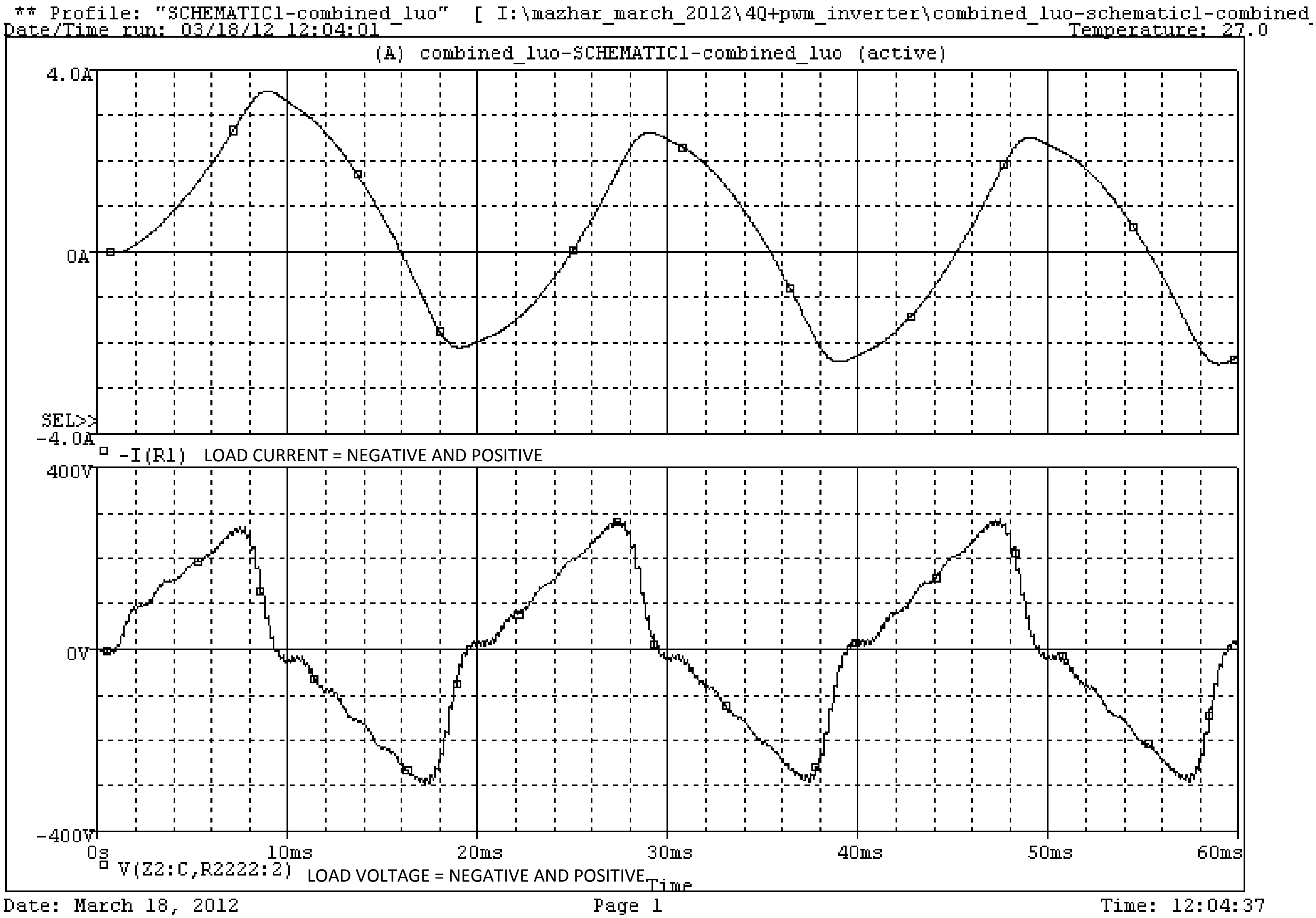
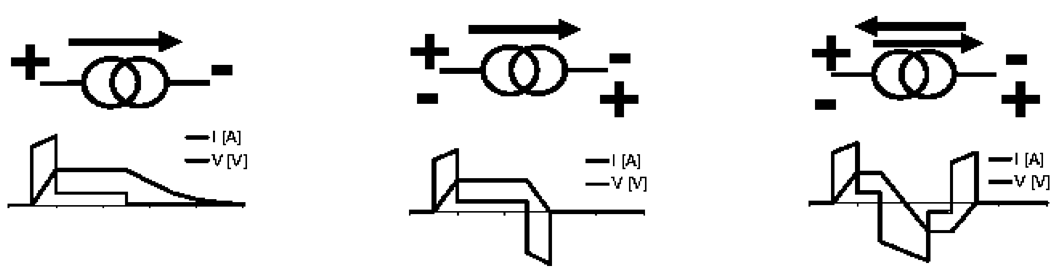


Figure 2.38: Load current and voltage in forward and reverse direction operation of Circuit of Figure 2.23f, for Inductance 300mH & Vamp 8v.

In the proposed combined form of Four-Quadrant chopper, Figure 2.22 (a,b) are the Gate signal generating circuit which are switching the power IGBTs according to duty cycle and simultaneously. And Figure 2.23(a, b, c, d, e and f), are the combined circuit of proposed Four-Quadrant Converter with lift circuit in which Load EMF/Resistive/R-L is connected differentially in this investigation. And found the characteristics of a DC-AC inverter. In practical, DC-AC inverters are the example four quadrant DC-DC converters. Inverters have (+)ve and (-)ve voltage across load (AC voltage across load). With AC voltage if the load is R-L (+)ve voltage may have (+)ve and (-)ve current and (-)ve voltage may have (+)ve and (-)ve current indicating four quadrant operation.

In the proposed circuit, typical DC-AC PWM Inverter output voltage is shown in Figures 2.32-2.34. (for resistive load). Figures 2.35-2.38, shows typical PWM AC voltage across R-L load and its corresponding current. By these figures it is clearly seen that the condition of (+)ve Voltage, (+)ve Current; (+)ve Voltage, (-)ve Current; (-)ve Voltage, (-)ve Current; (-)ve Voltage, (+)ve Current; for four quadrant operation is fulfilled according to Figure 2.21(c).

Some basic graphs are presented to summarize different types of power converters, feeding a typical four-quadrant power load: a resistance in series with an inductance (R-L).



One-quadrant mode Two-quadrant mode Four-quadrant mode

And proposed circuit is justified as a FOUR QUADRANT SWITCH MODE DC-DC CONVERTER.

Chapter-3

CONCLUSIONS

3.1 FINDINGS, ACHEIVEMENTS AND SUGGESTION ON FUTURE WORKS.

The advantages in the power semiconductor devices have led to the increase in the use of power electronic converters in various applications such as heating, lighting, ventilating and air conditioning applications, large rated dc drives and ac drives, adjustable speed drives, uninterruptible power supplies, high voltage DC systems, utility interfaces with no conventional energy sources such as solar photovoltaic systems etc., battery energy storage systems, in process technology such as electroplating, welding units etc., battery charging for electric vehicles, and power supply for telecommunications systems.

High frequency switching DC-DC converters have become part of electronic equipments to provide regulated dc of desired voltages at a low cost and high efficiency. These converters have several advantages over their counterpart the linear power supplies. Main advantages are smaller compact size due to elimination of step down transformer and small filters due to high frequency operation. These converters have high efficiency because the regulating devices in them work as switches ensuring low device loss. Their output voltage can be controlled for a wide range of input voltage fluctuation by changing the duty cycle of the switching signals.

The dc/dc converters are widely used in industrial applications and computer hardware circuits, and the dc/dc conversion technique has been developed very quickly. Four common types of switch mode converters are used in dc-to dc conversion. They are buck, boost, buck-boost and C^UK converters.

The voltage lifting technique is a popular method because it effectively overcomes the effect of parasitic elements; therefore these converters can convert the source voltage to higher output voltage with high power efficiency, high power density. Several types of converter are available which operate in single or two quadrants. One such converter is Lou converter. This thesis has proposed, investigated and suggested that combined circuit of four quadrant converter is possible. Luo proposed forward and reverse dc-dc converters, which operate in two quadrants. Luo also suggested four-quadrant operation using two separate circuits and with complicated logic implementation for gate signal generation of the switching devices of two forward and reverse converters separately. In this research differential connection of the load at the output of the two converters fed by same source has been investigated as claimed by Luo for a new FOUR QUADRANT SWITCH MODE DC-DC CONVERTER. IGBTs are used as switches in the four quadrant converter, where the gate pulse to the IGBTs has been generated by a PWM module. It is found in simulation that these two source converters do not operate as claimed and they cannot be combined in any way to operate in four quadrants as a single power conversion circuit. Because of combined circuit arrangement should identical of Figure 1.17 and 2.21(a). Therefore, separate circuit was investigated to obtain a SMPS based Buck-Boost single four quadrant DC-DC converter, out of forward and reverse Luo converters with differential load connection.

By the changing the PW value from 0.05ms to 0.15ms, we found the necessary characteristics of Operational output of Two Quadrant Chopper mode of forward and reverse Converters (Figure 2.14) as shown in Table 3.1.

Table 3.1: Operational output of Two Quadrant Chopper mode of forward and reverse Converter of circuit of Figure 2.14.

Sl no.	**Operational mode**	**Load Voltage**	**Output Current, I_L**	**Quadrant**
01	Operation -1 (Figures 2.15 - 2.16)	Positive	Positive	I
02	Operation -2 (Figure 2.17 - 2.18)	Positive	Negative	II
03	Operation -3 (Figure 2.19 - 2.20)	Positive	Positive going to Negative	I and II

And according to operational outputs of combined circuit of proposed Four-Quadrant Converter Figure 2.23 (a, b, c, d, e and f), got the characteristics of new Four Quadrant Converter are shown in Table 3.2.

Table 3.2: Operational output of new Four Quadrant Converter of circuit of Figure 2.23.

Sl no.	**Operational mode**	**Load EMF**	**Output Current, I_L**	**Quadrant**
01	Operation -1 (Figures 2.24 - 2.25)	Positive	Positive	I
02	Operation -2 (Figures 2.26 - 2.27)	Positive	Negative	II
03	Operation -3 (Figures 2.28 - 2.29)	Negative	Positive	IV
04	Operation -4 (Figures 2.30 - 2.31)	Negative	Negative	III
05	Operation -5 (Figures 2.32 - 2.38)	Positive and Negative	Positive and Negative	I, II ,III, IV

By changing the duty cycle, we found the necessary characteristics as of Four Quadrant Converter/ DC-AC inverter.

The contributions of this thesis indicate the opportunities of extending this work in future to meet other goals.

1. Only spice simulation is performed in this study. The proposed new FOUR QUADRANT SWITCH MODE DC-DC CONVERTER may be implemented practically to investigate its actual potential. Such practical implementation would give an insight regarding the cost effectiveness of the proposed scheme compared to the existing schemes for the similar purpose.

2. The PWM module has been used to generate gating signals for switching the proposed converter switches at varying duty cycles. Investigation can be made to improve the quality of the gating signals at different duty cycle.

3.2 CONCLUSION

Throughout In this research, has discussed the circuit operation of a new FOUR QUADRANT SWITCH MODE DC-DC CONVERTER (as Table 3.1 & 3.2) which operates as a Four Quadrant for I, II, III & IV (as shown in Figures 2.24 to 2.38), what actually has done as above. This results in a single source topology and has been switched by conventional ON/OFF duty cycle control (Figure 2.22 a, b) as used in other high power chopper circuits. The combined topology are analyzed and studied by spice simulation.

ANNEXURE

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