COMPARATIVE STUDY ON DC-DC CONVERTERS

BY

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THESIS FINAL SEMESTER

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DECLARATION

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

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OBJECTIVE

The objective is to perform the comparative study on the four types of DC to DC converters and doing simulations and implementing practically the target is to determine the converter circuit that suits best for necessary equipment. Here the desired equipment is a guitar processor named BOSS-MS50 for which target power is 6W and voltage is 9V.

PROJECT OVERVIEW

During pre-thesis and thesis-1 semester comparative study among the four types of converters has been done. Simulations of all circuits were performed. In final thesis more simulations have been done based on different parameters and practical implementation of desired circuit has completed where the necessary input voltage is 9v including the expected power of 6W. For this scenario a higher source voltage has been stepped down by designing, simulating and at last practically implementing a Buck converter. But for achieving a clear concept about other dc to dc converters lots of simulations result has been tried to incorporate.

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1.0 Thesis Introduction

Every Electronic circuit is assumed to operate some supply voltage which is usually assumed to be constant in nature. A voltage regulator is a power electronic circuit that maintains a constant output voltage irrespective of change in load current or line voltage. Many different types of voltage regulators with a variety of control schemes are used. With the increase in circuit complexity and improved technology a more severe requirement for accurate and fast regulation is desired. This has led to need for newer and more reliable design of dc-dc converters. The dc-dc converter inputs an unregulated dc voltage input and outputs a constant or regulated voltage. The regulators can be mainly classified into linear and switching regulators. All regulators have a power transfer stage and a control circuitry to sense the output voltage and adjust the power transfer stage to maintain the constant output voltage. Since a feedback loop is necessary to maintain regulation, some type of compensation is required to maintain loop stability. Compensation techniques vary for different control schemes and a small signal analysis of system is necessary to design a stable compensation circuit. State space analysis is typically used to develop a small signal model of a converter and then depending on the type of control scheme used, the small signal model of converter is modified to facilitate the design of the compensation network. In contrast to a state space approach, PWM switch modeling develops a small signal of switching components of converter.

Behavioral modeling of the IC system represents the functionality of an IC with macro models rather than actual implementation of the circuit using more efficient modeling techniques. ORCAD is powerful tool to develop behavioral models of electronic system. Simulation offers the advantage of its graphical user interface and block diagram implementation of any system. It also supports writing function and integration of C program code. The study undertaken in this thesis develops a system level design approach for switching voltage regulators of the three major control schemes. The basic converter topologies and their waveforms are reviewed. In Particular, a small signal model along with the various transfer functions of a buck converter are derived using state space method. A very simple and easy technique to arrive at the PWM model and compensation for two types of control schemes: namely voltage control, current control scheme is discussed. System level models are implemented using the in ORCAD. The following study provides details of methodologies for designing each component or blocks mainly the BUCK converter used in the switching regulator. Finally, practical result and simulation results are presented for voltage and current schemes and specified the proper design to get expected values to run the guitar processor.

2.0 Background Study

Behavioral modeling is a fast, efficient and easy manner to establish a given theory and more importantly the most efficient manner to develop a direct comparison between competing methods. The voltage control scheme is the basis for more advanced control schemes. An orcade implementation of voltage controlled buck converter is presented. Voltage control has a slow transient response due to the bandwidth limitation of the error amplifier in the feedback path. The DC-DC converter is inherently a high ripple system and to exploit this Feature current mode control was widely used for better transient response to line variation. However this approach depends on error amplifier speed to control load variation. In this thesis all analysis are for constant frequency control or pulse width modulation (PWM).

2.1 DC-DC converter

DC –DC converters are power electronic circuits that convert a dc voltage to a different voltage level. There are different types of conversion method such as electronic, linear, switched mode, magnetic, capacitive. The circuits described in this report are classified as switched mode DC-DC converters. These are electronic devices that are used whenever change of DC electrical power from one voltage level to another is needed. Generically speaking the use of a switch or switches for the purpose of power conversion can be regarded as an SMPS. From now onwards whenever we mention DC-DC converters we shall address them with respect to SMPS. A few applications of interest of DC-DC converters are where 5V DC on a personal computer motherboard must be stepped down to 3V, 2V or less for one of the latest CPU chips; where 1.5V from a single cell must be stepped up to 5V or more, to operate electronic circuitry. In all of these applications, we want to change the DC energy from one voltage level to another, while wasting as little as possible in the process. In other words, we want to perform the conversion with the highest possible efficiency. DC-DC Converters are needed because unlike AC, DC can’t simply be stepped up or down using a transformer. In many ways, a DC-DC converter is the DC equivalent of a transformer. They essentially just change the input energy into a different impedance level. So whatever the output voltage level, the output power all comes from the input; there is no energy manufactured inside the converter. Quite the contrary, in fact some is inevitably used up by the converter circuitry and components, in doing their job.

2.2 Applications of DC-DC Converters

1. Dc converters can be used in regenerative braking of dc motors to return energy back into the supply and this feature results in energy savings for transportation system with frequent stops. As for example :

   a) Traction motor control in electric automobiles
   b) Trolley cars
   c) Marine Hoists
   d) Forklift trucks
   e) Mine Haulers

2. Also used in DC voltage regulators and also are used in conjunction with an inductor to generate a dc current source especially for the current source inverter.

2. 3 Switching Consideration of DC-DC Converters:

The converter switch can be implemented by using

a) Power bipolar junction transistor (BJT
b) Power Metal Oxide Semiconductor Field Effect Transistor (MOSFET)
c) Gate Turn Off Thyristor (GTO)
d) Insulated gate bipolar transistor (IGBT)

Practical devices have a finite voltage drop ranging from 0.5V to 2V but during the calculations for the sake of simplicity of the understanding, these switches are considered lossless.

2.4 Types Of DC-DC Converter

There different kinds of DC-DC converters. A variety of the converter names are included here:

1. The BUCK converter
2. The BOOST converter
3. The BUCK-BOOST converter
4. The CUK converter
5. The Fly-back converter
6. The Forward Converter
7. The Push-pull Converter
8. The Full Bridge converter
9. The Half Bridge Converter
10. Current Fed converter
11. Multiple output converters

2.5 Study of DC-DC Converters

There are a variety of DC-Dc converters are possible.But from the list of the converters only the first four of the converters are to be described which are basically of non isolated input output terminals.

2.5.1 The Buck Converter:

The buck converter is a commonly used in circuits that steps down the voltage level from the input voltage according to the requirement. It has the advantages of simplicity and low cost. Figure 1 shows a buck converter the operation of the Buck converters start with a switch that is open (so no current flow through any part of circuit) When the switch is closed, the current flows through the inductor, slowly at first, but building up over time. When the switch is closed the inductor pulls current through the diode, and this means the voltage at the inductors "output" is lower than it first was. This is the very basic principle of operation of buck circuit.

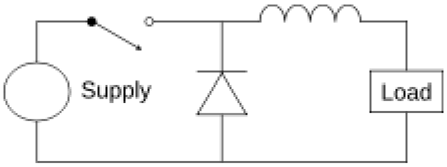


Figure 1: BUCK Converter

Analysis of the buck converter begins by making these assumptions:

1. The circuit is operating in the steady state.
2. The inductor current is continuous(always positive)
3. The capacitor is very large, and the output voltage is held constant at voltage Vo. This restriction will be relaxed later to show the effects of finite capacitance.
4. The switching period is T, the switch is closed for time DT and open for time (1-D)T
5. The components are ideal

The key to the analysis for determining the voltage Vo is to examine the inductor current and inductor voltage first for the switch closed and then for the switch open. The net change in inductor current over one period must be zero for steady state operation. The average inductor voltage is zero. There are two types of operational mode for this circuit a) Continuous Conduction Mode and b) Discontinuous Conduction Mode. They are described below.

(a) Continuous Conduction Mode

A buck converter operates in continuous mode if the current through the inductor (I_L) never falls to zero during the commutation cycle. In this mode, the operating principle is described by the chronogram in Figure 1.

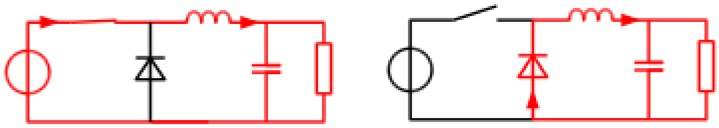


Figure 2: On and off state of Buck converter

On state (b) off State

Figure. 2: The two circuit configurations of a buck converter: (a) On-state, when the switch is closed, and(b) Off-state, when the switch is open

- When the switch pictured above is closed (On-state, top of Figure 2), the voltage across the inductor is $V_L = V_i - V_o$. The current through the inductor rises linearly. As the diode is reverse-biased by the voltage source V, no current flows through it;
- When the switch is opened (off state, bottom of figure 2), the diode is forward biased. The voltage across the inductor is $V_L = -V_o$ (neglecting diode drop). Current I_L decreases.

The energy stored in inductor L is

$$E = \frac{1}{2} L \times I_L^2$$

Therefore, it can be seen that the energy stored in L increases during On-time (as I_L increases) and then decreases during the Off-state. L is used to transfer energy from the input to the output of the converter.The rate of change of I_L can be calculated from:

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

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

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

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

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

If we assume that the converter operates in steady state, the energy stored in each component at the end of a commutation cycle T is equal to that at the beginning of the cycle. That means that the current I_L is the same at t=0 and at t=T (see Figure3).So we can write from the above equations:

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

It is worth noting that the above integrations can be done graphically: In Figure 3, $\Delta I_{L_{on}}$is proportional to the area of the yellow surface, and $\Delta I_{L_{off}}$to the area of the orange surface, as these surfaces are defined by the inductor voltage (red) curve. As these surfaces are simple rectangles, their areas can be found easily: $(V_i - V_o)\,t_{on}$for the yellow rectangle and $-V_o t_{off}$ for the orange one. For steady state operation, these areas must be equal.As can be seen on figure 4, $t_{on} = DT$and $t_{off} = (1-D)T$. D is a scalar called the *duty cycle* with a value between 0 and 1. This yield:

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

From this equation, it can be seen that the output voltage of the converter varies linearly with the duty cycle for a given input voltage. As the duty cycle D is equal to the ratio between t_{On} and the period T, it cannot be more than 1. Therefore, $V_o \leq V_i$. This is why this converter is referred to as *step-down converter*.So, for example, stepping 12 V down to 3 V (output voltage equal to a fourth of the input voltage) would require a duty cycle of 25%, in our theoretically ideal circuit.

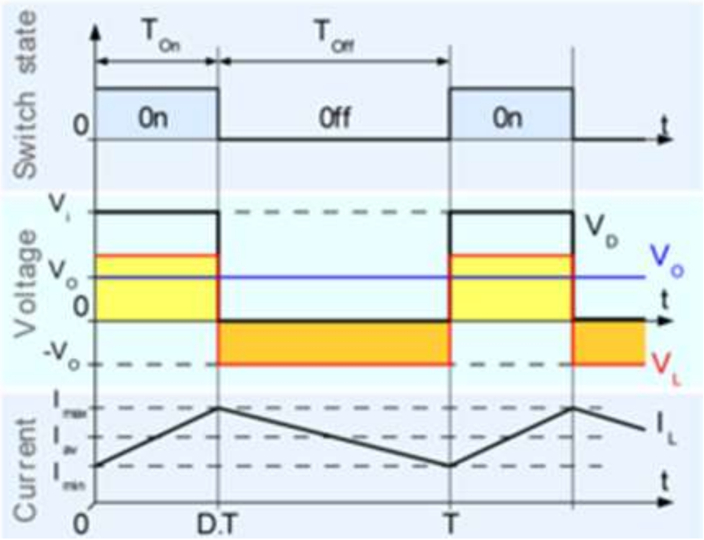


Figure 3: Evolution of the voltages and currents with time in an ideal buck converter operating in continuous mode

(b) Discontinuous Conduction Mode

In some cases, the amount of energy required by the load is small enough to be transferred in a time lower than the whole commutation period. In this case, the current through the inductor falls to zero during part of the period. The only difference in the principle described above is that the inductor is completely discharged at the end of the commutation cycle (Figure 4). This has, however, some effect on the previous equations.

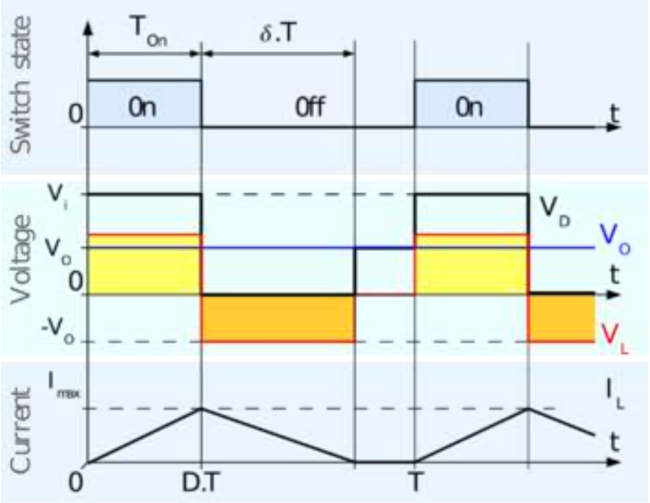


Fig. 4: Evolution of the voltages and currents with time in an ideal buck converter operating in discontinuous mode.

We still consider that the converter operates in steady state. Therefore, the energy in the inductor is the same at the beginning and at the end of the cycle (in the case of discontinuous mode, it is zero). This means that the average value of the inductor voltage (V_L) is zero; i.e., that the area of the yellow and orange rectangles in figure 5 are the same. This yields:

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

So the value of δ is:

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

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

$$\bar{I_L} = I_o$$

Where $\bar{I_L}$is the average value of the inductor current. As can be seen in figure 5, the inductor current waveform has a triangular shape. Therefore, the average value of I_L can be sorted out geometrically as follow:

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

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

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

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

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

And substituting δ by the expression given above yields:

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

This expression can be rewritten as:

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

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

2.5.2 The BOOST converter

A boost converter (step-up converter) is a power converter with an output DC voltage greater than its input DC voltage. It is a class of switching mode power supply (SMPS) containing at least two semi-conductors switches (a diode and a transistor) and at least one energy storage element. Filters made of capacitors (sometimes in combination with inductors) are normally added to the output of the converter to reduce output voltage ripple. A boost converter is sometimes called a step-up converter since it “steps up” the source voltage. Since power ($P = VI$) must be conserved, the output current is lower than the source current.

The boost converter has the same components as the buck converter, but this converter produces an output voltage greater than the source."Boost" converters start their voltage conversion with a current flowing through the inductor (switch is closed). Then they close the switch leaving the current no other path to go than through a diode (functions as one way valve) The current then wants to slow really fast and the only way it can do this is by increasing it's voltage (akin to pressure) at the end that connects to the diode, and switch. If the voltage is high enough it opens the diode, and one through the diode, the current can't flow back. This is the very basic concept of boost converter.

Circuit analysis

Analysis of the boost converter begins by making these assumptions:

- The circuit is operating in the steady state.
- The inductor current is continuous(always positive)
- The capacitor is very large, and the output voltage is held constant at voltage Vo. This restriction will be relaxed later to show the effects of finite capacitance.
- The switching period is T, the switch is closed for time DT and open for time (1-D)T
- The components are ideal

Like Buck converter boost also has two mode of operation. Details are described below

Operating principle

The key principle that drives the boost converter is the tendency of an inductor to resist changes in current. When being charged it acts as a load and absorbs energy (somewhat like a resistor); when being discharged it acts as an energy source (somewhat like a battery). The voltage it produces during the discharge phase is related to the rate of change of current, and not to the original charging voltage, thus allowing different input and output voltages.

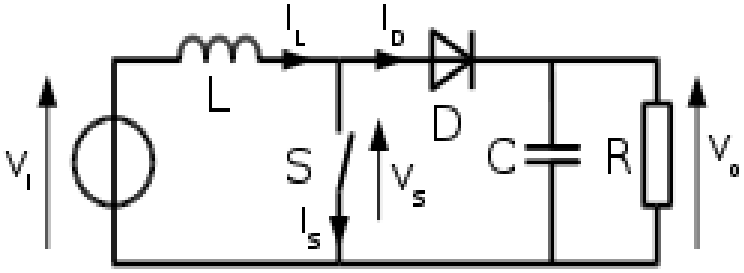
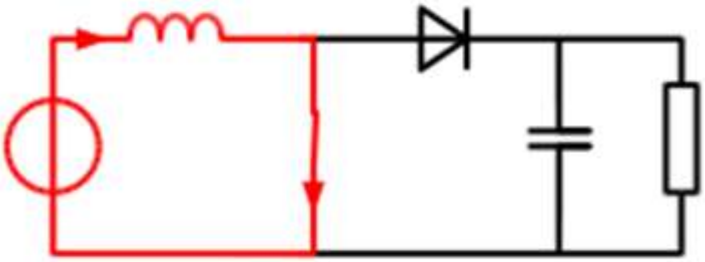
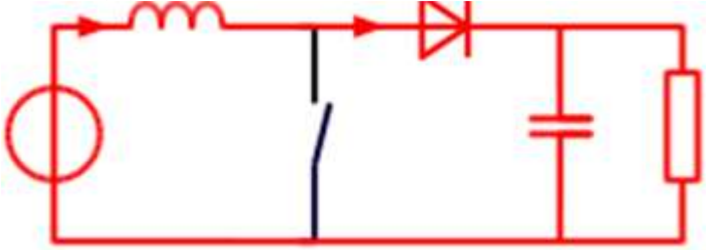


Figure. 5: Boost converter schematic



(a)Switch On



(a) Switch Off

Figure. 6: The two configurations of a boost converter, depending on the state of the switch S.

The basic principle of a Boost converter consists of 2 distinct states (Figure 6):

- in the On-state, the switch S (see figure 1) is closed, resulting in an increase in the inductor current;
- in the Off-state, the switch is open and the only path offered to inductor current is through the flyback diode D, the capacitor C and the load R. These results in transferring the energy accumulated during the On-state into the capacitor.
- The input current is the same as the inductor current as can be seen in figure 2. So it is not discontinuous as in the buck circuit and the requirements on the input filter are relaxed compared to a buck converter.

Continuous mode

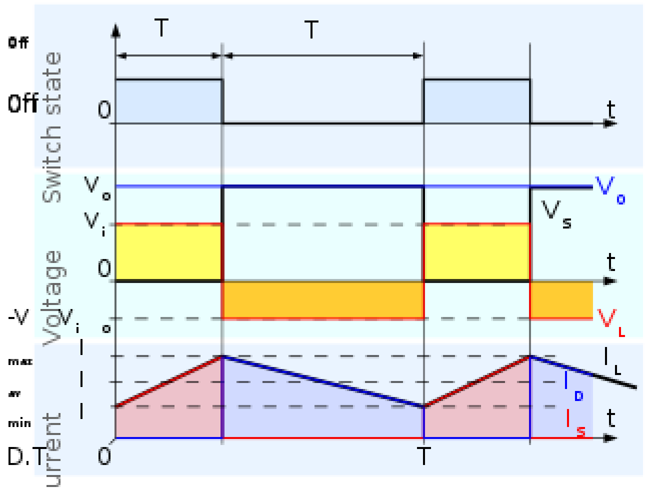


Fig. 7: Waveforms of current and voltage in a boost converter operating in continuous mode.

When a boost converter operates in continuous mode, the current through the inductor (I_L) never falls to zero. Figure 3 shows the typical waveforms of currents and voltages in a converter operating in this mode. The output voltage can be calculated as follows, in the case of an ideal converter (i.e. using components with an ideal behaviour) operating in steady conditions:

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

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

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

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

D is the duty cycle. It represents the fraction of the commutation period T during which the switch is On. Therefore D ranges between 0 (S is never on) and 1 (S is always on).

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

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

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

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

As we consider that the converter operates in steady-state conditions, the amount of energy stored in each of its components has to be the same at the beginning and at the end of a commutation cycle. In particular, the energy stored in the inductor is given by:

$$E = \frac{1}{2}LI_L^2$$

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

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

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

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

This can be written as:

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

Which in turns reveals the duty cycle to be:

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

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

Discontinuous mode

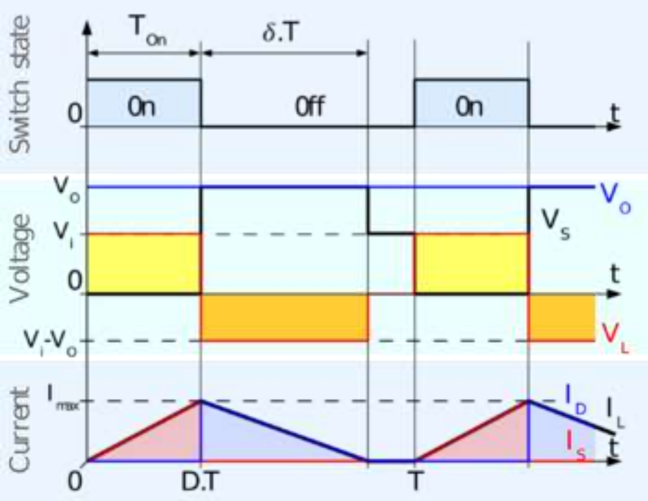


Fig. 8:Waveforms of current and voltage in a boost converter operating in discontinuous mode.

In some cases, the amount of energy required by the load is small enough to be transferred in a time smaller than the whole commutation period. In this case, the current through the inductor falls to zero during part of the period. The only difference in the principle described above is that the inductor is completely discharged at the end of the commutation cycle (see waveforms in figure 4). Although slight, the difference has a strong effect on the output voltage equation. It can be calculated as follows:

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

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

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

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

Using the two previous equations, δ is:

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

The load current I_o is equal to the average diode current (I_D). As can be seen on figure 4, the diode current is equal to the inductor current during the off-state. Therefore the output current can be written as:

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

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

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

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

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

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

2.5.3 BUCK-BOOST converter

Another basic switched mode converter is the buck-boost converter. The output of the buck-boost converter can be either higher or lower than the input voltage. Assumption made about the operation of this circuit is same as it was for the previous converter circuits.

Principle of operation

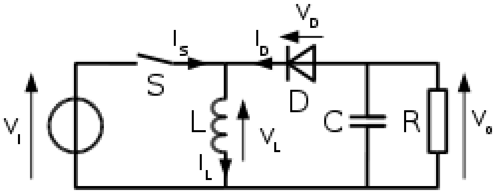


Figure. 9: Schematic of a buck–boost converter.

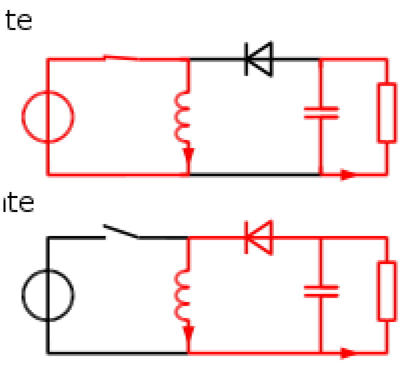


Figure 10: The two operating states of a buck–boost converter: When the switch is turned-on, the input voltage source supplies current to the inductor, and the capacitor supplies current to the resistor (output load).When the switch is opened, the inductor supplies current to the load via the diode D.

The basic principle of the buck–boost converter is fairly simple (Figure 10):

- while in the On-state, the input voltage source is directly connected to the inductor (L). This results in accumulating energy in L. In this stage, the capacitor supplies energy to the output load.
- while in the Off-state, the inductor is connected to the output load and capacitor, so energy is transferred from L to C and R.Compared to the buck and boost converters, the characteristics of the buck–boost converter are mainly:

- polarity of the output voltage is opposite to that of the input;
- the output voltage can vary continuously from 0 to $-\infty$(for an ideal converter). The output voltage ranges for a buck and a boost converter are respectively 0 to $V_i$and $V_i$to ∞.The circuit has two main mode of operations. They are described below.

Continuous mode

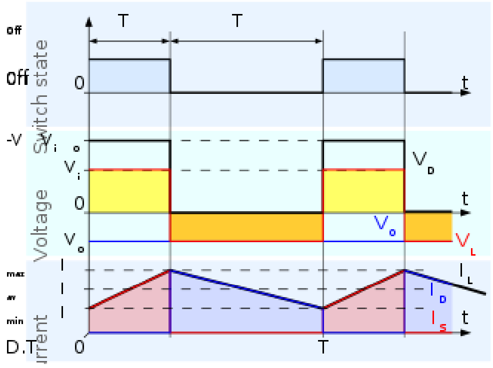


Fig 11: Waveforms of current and voltage in a buck–boost converter operating in continuous mode.

If the current through the inductor *L* never falls to zero during a commutation cycle, the converter is said to operate in continuous mode. The current and voltage waveforms in an ideal converter can be seen in Figure 3.

From $t=0$to $t=D\,T$, the converter is in On-State, so the switch *S* is closed. The rate of change in the inductor current (I_{L}) is therefore given by

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

At the end of the On-state, the increase of I_{L} is therefore:

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

D is the duty cycle. It represents the fraction of the commutation period *T* during which the switch is On. Therefore *D* ranges between 0 (*S* is never on) and 1 (*S* is always on).

During the Off-state, the switch *S* is open, so the inductor current flows through the load. If we assume zero voltage drop in the diode, and a capacitor large enough for its voltage to remain constant, the evolution of I_{L} is:

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

Therefore, the variation of I_{L} during the Off-period is:

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

As we consider that the converter operates in steady-state conditions, the amount of energy stored in each of its components has to be the same at the beginning and at the end of a commutation cycle. As the energy in an inductor is given by:

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

it is obvious that the value of I_{L} at the end of the Off state must be the same as the value of I_{L} at the beginning of the On-state, i.e. the sum of the variations of I_{L} during the on and the off states must be zero:

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

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

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

This can be written as:

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

This in return yields that:

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

From the above expression it can be seen that the polarity of the output voltage is always negative (as the duty cycle goes from 0 to 1), and that its absolute value increases with D, theoretically up to minus infinity as *D* approaches 1. Apart from the polarity, this converter is either step-up (as a boost converter) or step-down (as a buck converter). This is why it is referred to as a buck–boost converter.

Discontinuous Mode

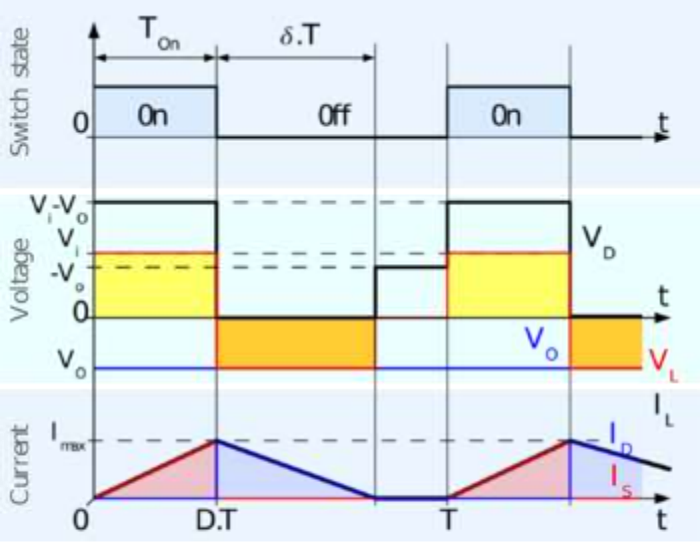


Fig 12: Waveforms of current and voltage in a buck–boost converter operating in discontinuous mode.

In some cases, the amount of energy required by the load is small enough to be transferred in a time smaller than the whole commutation period. In this case, the current through the inductor falls to zero during part of the period. The only difference in the principle described above is that the inductor is completely discharged at the end of the commutation cycle (see waveforms in figure 4). Although slight, the difference has a strong effect on the output voltage equation. It can be calculated as follows:

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

$$I_{L_{\max}} = \frac{V_i\,DT}{L}$$

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

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

Using the two previous equations, δ is:

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

The load current I_o is equal to the average diode current (I_D). As can be seen on figure 4, the diode current is equal to the inductor current during the off-state. Therefore, the output current can be written as:

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

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

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

Therefore, the output voltage gain can be written as:

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

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

Limit between continuous and discontinuous modes

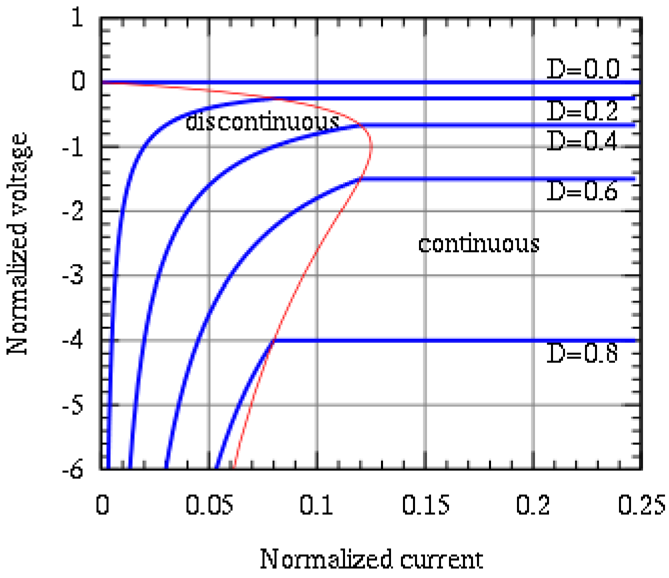


Fig 13: Evolution of the normalized output voltage with the normalized output current in a buck–boost converter.

As told at the beginning of this section, the converter operates in discontinuous mode when low current is drawn by the load, and in continuous mode at higher load current levels. The limit between discontinuous and continuous modes is reached when the inductor current falls to zero exactly at the end of the commutation cycle. with the notations of figure 4, this corresponds to :

$$DT + \delta T = T$$

$$D + \delta = 1$$

In this case, the output current $I_{o_{\text{lim}}}$(output current at the limit between continuous and discontinuous modes) is given by:

$$I_{o_{\text{lim}}} = \bar{I_D} = \frac{I_{L_{\text{max}}}}{2}(1-D)$$

Replacing $I_{L_{\text{max}}}$by the expression given in the *discontinuous mode* section yields:

$$I_{o_{\text{lim}}} = \frac{V_i DT}{2L}(1-D)$$

As $I_{o_{\text{lim}}}$is the current at the limit between continuous and discontinuous modes of operations, it satisfies the expressions of both modes. Therefore, using the expression of the output voltage in continuous mode, the previous expression can be written as:

$$I_{o_{\lim}} = \frac{V_i\,D\,T}{2L}\frac{V_i}{V_o}\,(-D)$$

Let's now introduce two more notations:

- the normalized voltage, defined by $|V_o|=\frac{V_o}{V_i}$. It corresponds to the gain in voltage of the converter;
- the normalized current, defined by $|I_o|=\frac{L}{T\,V_i}\,I_o$. The term $\frac{T\,V_i}{L}$ is equal to the maximum increase of the inductor current during a cycle; i.e., the increase of the inductor current with a duty cycle D=1. So, in steady state operation of the converter, this means that $|I_o|$ equals 0 for no output current, and 1 for the maximum current the converter can deliver.

Using these notations, we have:

- in continuous mode, $|V_o|=-\frac{D}{1-D}$;
- in discontinuous mode, $|V_o|=-\frac{D^2}{2|I_o|}$;
- the current at the limit between continuous and discontinuous mode is $I_{o_{\lim}}=\frac{V_i\,T}{2L}D(1-D)=\frac{I_{o_{\lim}}}{2|I_o|}D(1-D)$. Therefore the locus of the limit between continuous and discontinuous modes is given by $\frac{1}{2|I_o|}D(1-D)=1$.

These expressions have been plotted in figure 5. The difference in behaviour between the continuous and discontinuous modes can be seen clearly.

2.5.4The CUK Converter:

The Cuk converter is used for getting the output voltage with different polarity. That means output voltage magnitude can be either larger or smaller than the input, and there is a polarity reversal on the output.

The inductor on the input acts as a filter for the dc supply, to prevent large harmonic current. Unlike the previous converter topologies where energy transfer is associated with the inductor. Energy transfer for the cuk converter depends on the capacitor C1. The primary assumptions for this circuit analysis are as before. It also has two modes of operation which are described below.

Operating Principle

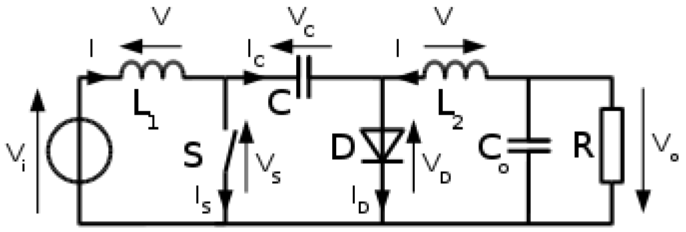


Fig 14: Schematic of a non-isolated Ćuk converter.

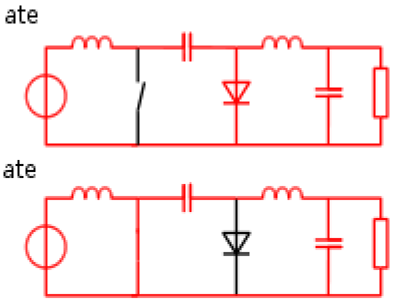


Figure 15: The two operating states of a non-isolated Ćuk converter.

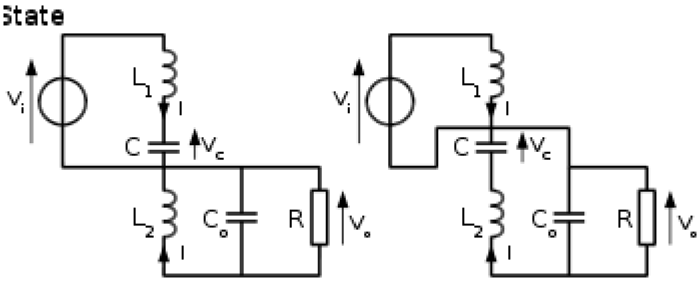


Fig 16 : The two operating states of a non-isolated Ćuk converter. In this figure, the diode and the switch are either replaced by a short circuit when they are on or by an open circuit when they are off.

It can be seen that when in the Off state, the capacitor C is being charged by the input source through the inductor L_1. When in the On state, the capacitor C transfers the energy to the output capacitor through the inductance L_2.

A non-isolated Ćuk converter comprises two inductors, two capacitors, a switch (usually a transistor), and a diode. Its schematic can be seen in figure 1. It is an inverting converter, so the output voltage is negative with respect to the input voltage.

The capacitor C is used to transfer energy and is connected alternately to the input and to the output of the converter *via* the commutation of the transistor and the diode (see figures 2 and 3).

The two inductors L_1 and L_2 are used to convert respectively the input voltage source (V_i) and the output voltage source (C_o) into current sources. Indeed, at a short time scale an inductor can be considered as a current source as it maintains a constant current. This conversion is necessary because if the capacitor were connected directly to the voltage source, the current would be limited only by (parasitic) resistance, resulting in high energy loss. Charging a capacitor with a current source (the inductor) prevents resistive current limiting and its associated energy loss.

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

Continuous mode

In steady state, the energy stored in the inductors has to remain the same at the beginning and at the end of a commutation cycle. The energy in an inductor is given by:

$$E = \frac{1}{2}LI^2$$

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

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

it can be seen that the average value of the inductor voltages over a commutation period have to be zero to satisfy the steady-state requirements.

If we consider that the capacitors C and C_o are large enough for the voltage ripple across them to be negligible, the inductor voltages become:

- in the off-state, inductor L_1 is connected in series with V_i and C (see figure 2). Therefore $V_{L1} = V_i - V_C$. As the diode D is forward biased (we consider zero voltage drop), L_2 is directly connected to the output capacitor. Therefore $V_{L2} = V_o$
- in the on-state, inductor L_1 is directly connected to the input source. Therefore $V_{L1} = V_i$. Inductor L_2 is connected in series with C and the output capacitor, so $V_{L2} = V_o + V_C$

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

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

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

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

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

So the average voltage across L_1 becomes:

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

Which can be written as:

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

It can be seen that this relation is the same as that obtained for the Buck-boost converter.

Discontinuous mode

Like all DC-DC converters Cuk converters rely on the ability of the inductors in the circuit to provide continuous current, in much the same way a capacitor in a rectifier filter provides continuous voltage. If this inductor is too small or below the "critical inductance", then the current will be discontinuous. This state of operation is usually not studied too much depth, as it is not used beyond a demonstrating of why the minimum inductance is crucial.

The minimum inductance is given by:

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

Where f_s is the switching frequency.

Chapter 3

CIRCUIT IMPLEMENTATION

Four basic converters are being implemented experimentally in the laboratory. Considering the designing parameters the circuit is implemented for the best fit values and the results obtained are almost in consistent with theoretical analysis. A general block diagram is given in Figure 3.1 to show the switch mode DC-DC Converter.

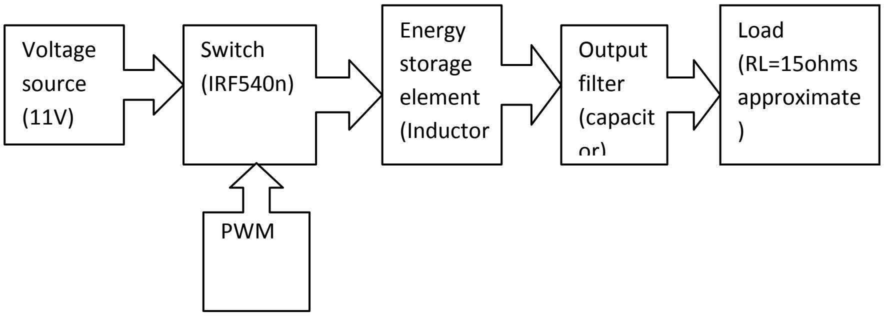


Figure 3.1.1: Block Diagram of Switch Mode DC –Dc Converter

3.1 Implementation of BUCK converter

The input voltage is set at 11V DC. The input is connected to the inductor and the load side via a switch (MOSFET IRF 540N). The MOSFET is driven by a PWM circuit constructed using the IC SG3524. When the switch is on the inductor is connected to the input and charged. When the switch is closed the input is isolated from the whole circuit and the inductor supplies current to the load. The output filter capacitor stores energy to maintain a near constant voltage to the load.For safety reasons the 15 ohms resistors provided by the lab were not appropriate for use and thus 100 ohm watt resistor was used.

The PWM circuit is constructed using the SG3524. The used circuit parameters are

Input Voltage, Vin= 12v

Input Current, Iin= 0.13A

Resistnce, Rt= 5Kohm

Capacitance Ct= .01uF

Frequency of Switching, F_{switch} = 20Khz

Theoretical calculations for the buck converter, for an input of 11 volts the output voltage should be Vo= Vs*D and the inductor value is calculated using the following equation, Lmin = (1-D)R/2f.In practical work the minimum value for the duty cycle of 0.1.

$L_{min} = (1-D)R/2f$

$= (1-.1)100/(2*20*1000)$

$=2.21mh$

The output filter capacitor is calculated using equation ΔVo/Vo= (1-D)/8LCf^2. While calculating the value of capacitor I considered the ripple voltage 2.5%

$\Delta Vo/Vo= (1-D)/8LCf^2$

Or, $.025= (1-D)/8LCf^2$

Or, C= 5uF

The max and min inductor currents are

$I(lmin) =Vo\{(1/R)-(1-D)/2Lf\}= 88$ mA

$I(lmax)= Vo\{(1/R)+(1-D)/2Lf\}= 110$ mA

These values of current were calculated using the 100 ohm resistor. However if the resistor is replaced by 15 ohm resistors, theoretically the maximum and minimum current should be

$I(lmin) =9.9\{(1/15)-(1-.9)/2*2.21*10^{-3}*20000\}=649mA$

$I(lmax) =9.9\{(1/15)+(1-.9)/2*2.21*10^{-3}*20000\}=671mA$

So, Il (average inductor current) = (649+671)/2 = 660mA

We know, ideally the average capacitor current is zero. So, Il=Ir

So, Pr = Ir^2*R= (0.66)^2*15 =6.5W

The required power was 6W for guitar processor named BOSS-MS50.

The simulation results are shown below.

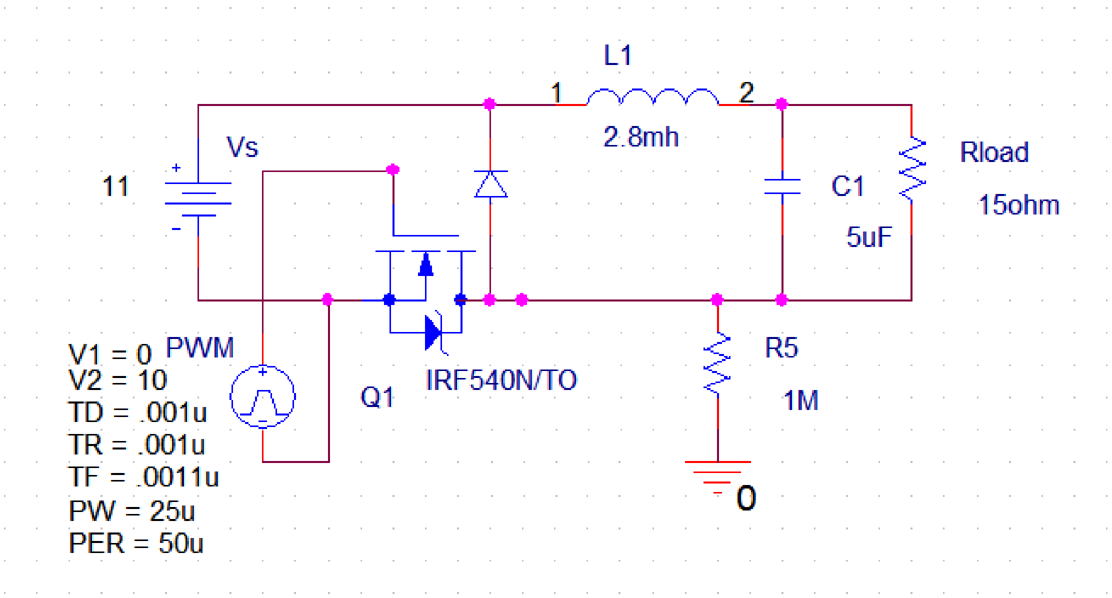


Figure 3.1.2: Practical circuit of the Buck Converter

The circuit is analyzed for different duty cycle and the performances of the circuit are summarized in table 3.1 for simulated values.

Table 3.1: The results of the simulations of Buck converter:

Duty cycle	Avg Input current (mA)	Avg Output current(mA)	Output voltage
0 .1	184.5	41	.83
0.2	304.3	104	1.76
0.3	397.2	186	2.76
0.4	560.5	248	3.74
0.5	658.9	323	4.83
0.6	730.9	381	5.82
0.7	811.3	466	6.91
0.8	950.2	549	8.04
0.9	1.2A	623	9.08

Here, (for maximum duty cycle)

The output voltage=9.08v

The output current=.623A

Output power=5.65W

Input power=11*1.2=13.2W

Efficiency =43%

The efficiency is low. But if any filter could be used at input side the efficiency would increase. Because the input current contains too much harmonics, the rms input current is very high and thus the input power increases as well which results low efficiency.

The values of the inductance and capacitance were calculated theoretically and values that were available and were closet to the calculated results were used in the circuit. The results are shown in tabulated form

Table 3.2 The results of the practical circuit of Buck converter

Duty cycle	Avg Output current(mA)	Output voltage
.1	0.02	0.4
.2	0.08	1.03
.3	0.14	2.1
.4	0.23	3.5
.5	0.30	4.6
.6	0.38	5.7
.7	0.45	6.8
.8	0.53	8
.9	0.64	8.7

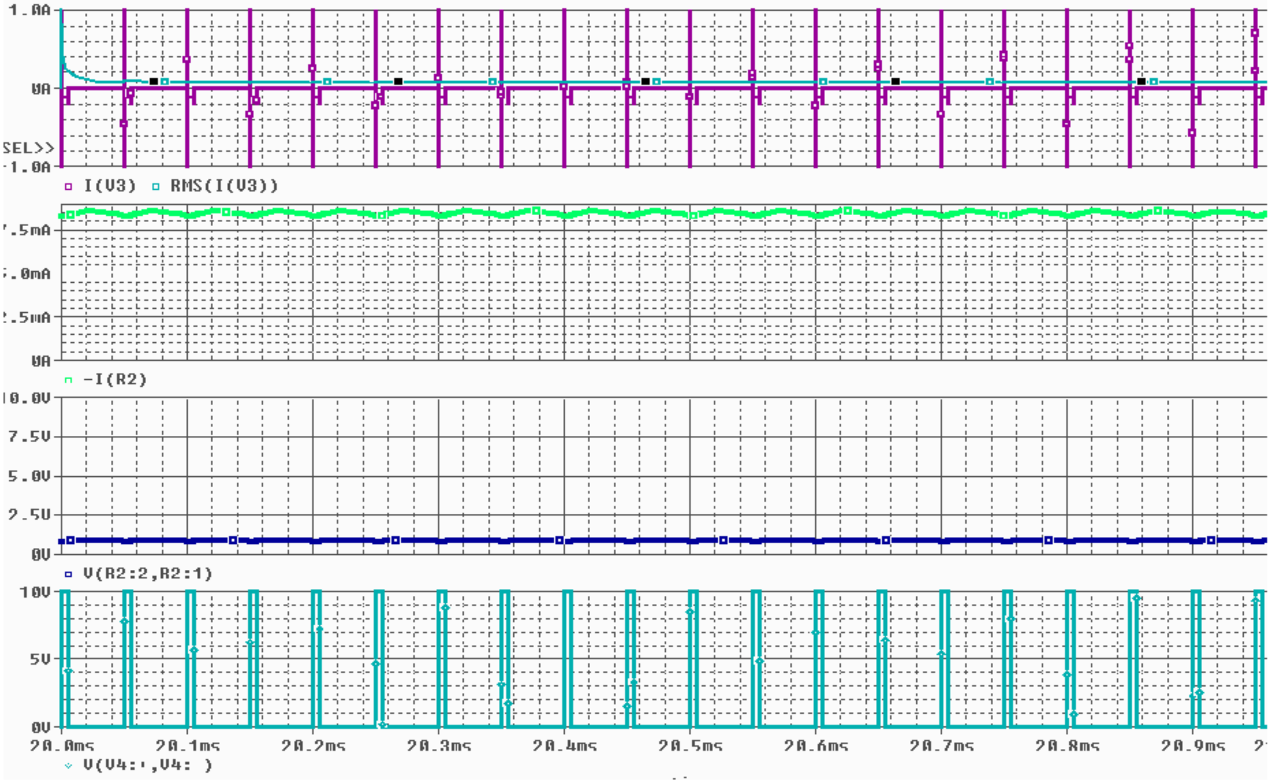
Here the simulation output for Buck converter is given below.

The first, second, third and fourth graph is for input RMS current, Output current at load, output voltage and Duty cycle respectively. These graphs are held as the benchmark for the next comparisons.

The following comparisons were done before implementing the original circuit and thus the actual load resistance was not known and assumed to be 100 ohm.

Here

L=2.8mh, C=5uF D=.1



For duty cycle D= 0.1

Input average current = 90mA

Input average voltage = 11V

Average input power = 0.99W

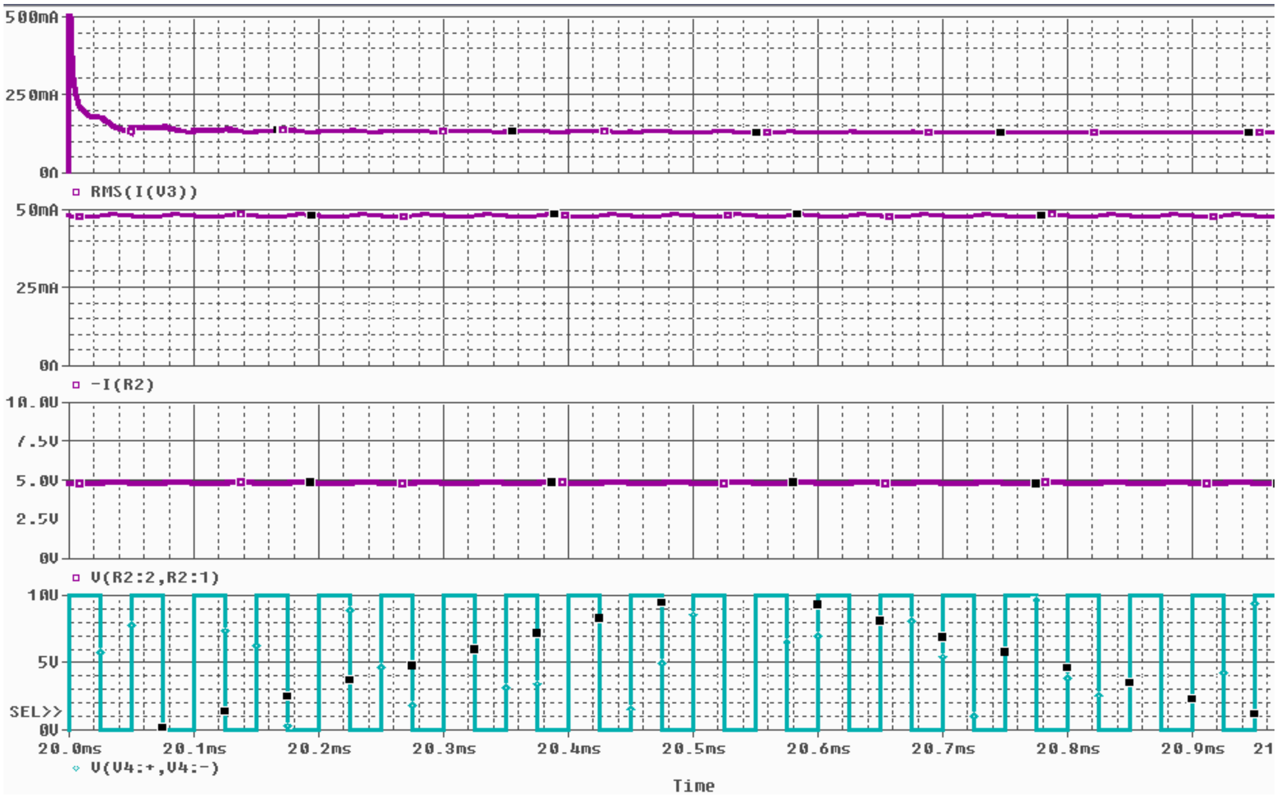
Average output current = 0.091A

Average output voltage = .08V

Average output power = 6.08mW

Efficiency = 0.89/2.75= 0.068

Now for L=2.8mh, C=5uF,
D=.5



For duty cycle D= 0.5

Input average current = 0.15A

Input average voltage = 11V

Average input power = 1.65W

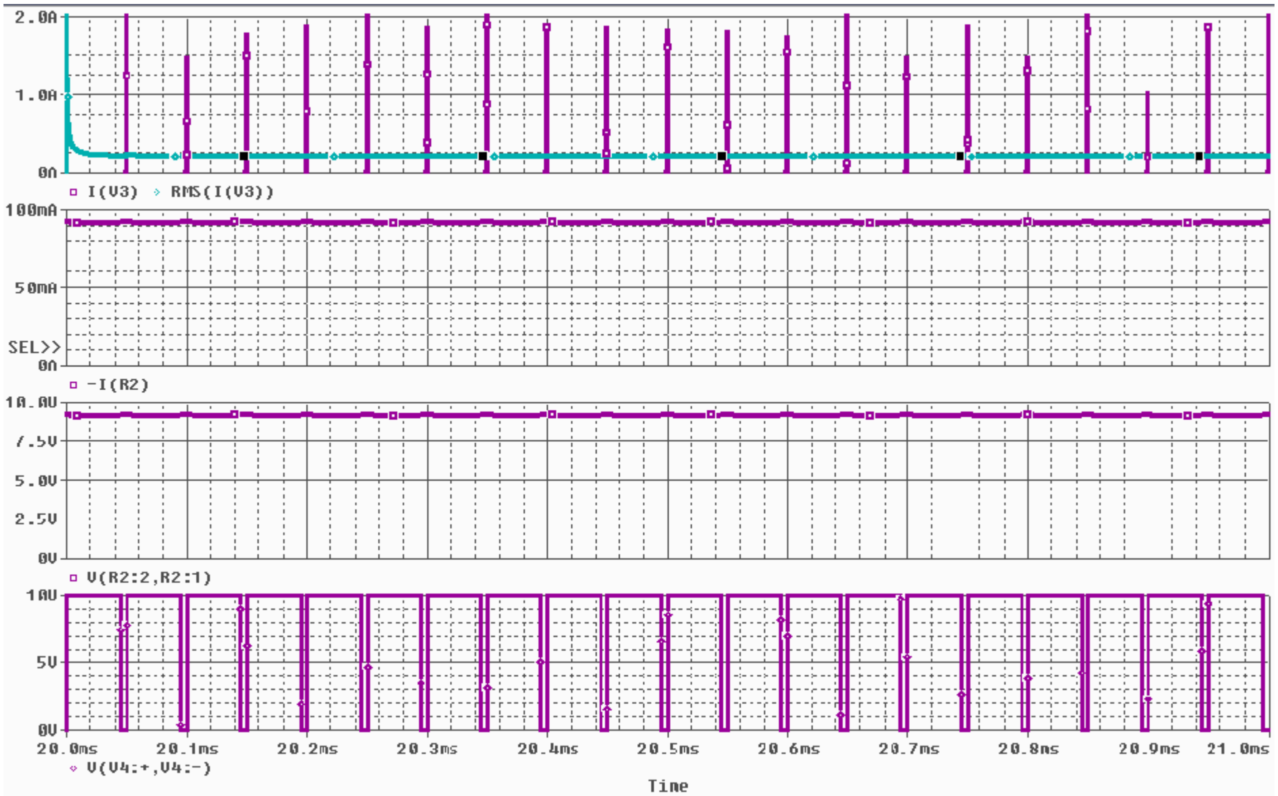
Average output current = 0.046A

Average output voltage = 5V

Average output power = 0.23W

Efficiency = 0.89/2.75= 0.13

L=2.8mh, C=5uF, D=.9



For duty cycle D= 0.9

Input average current = 0.25A

Input average voltage = 11V

Average input power = 2.75W

Average output current = 0.091A

Average output voltage = 9.9V

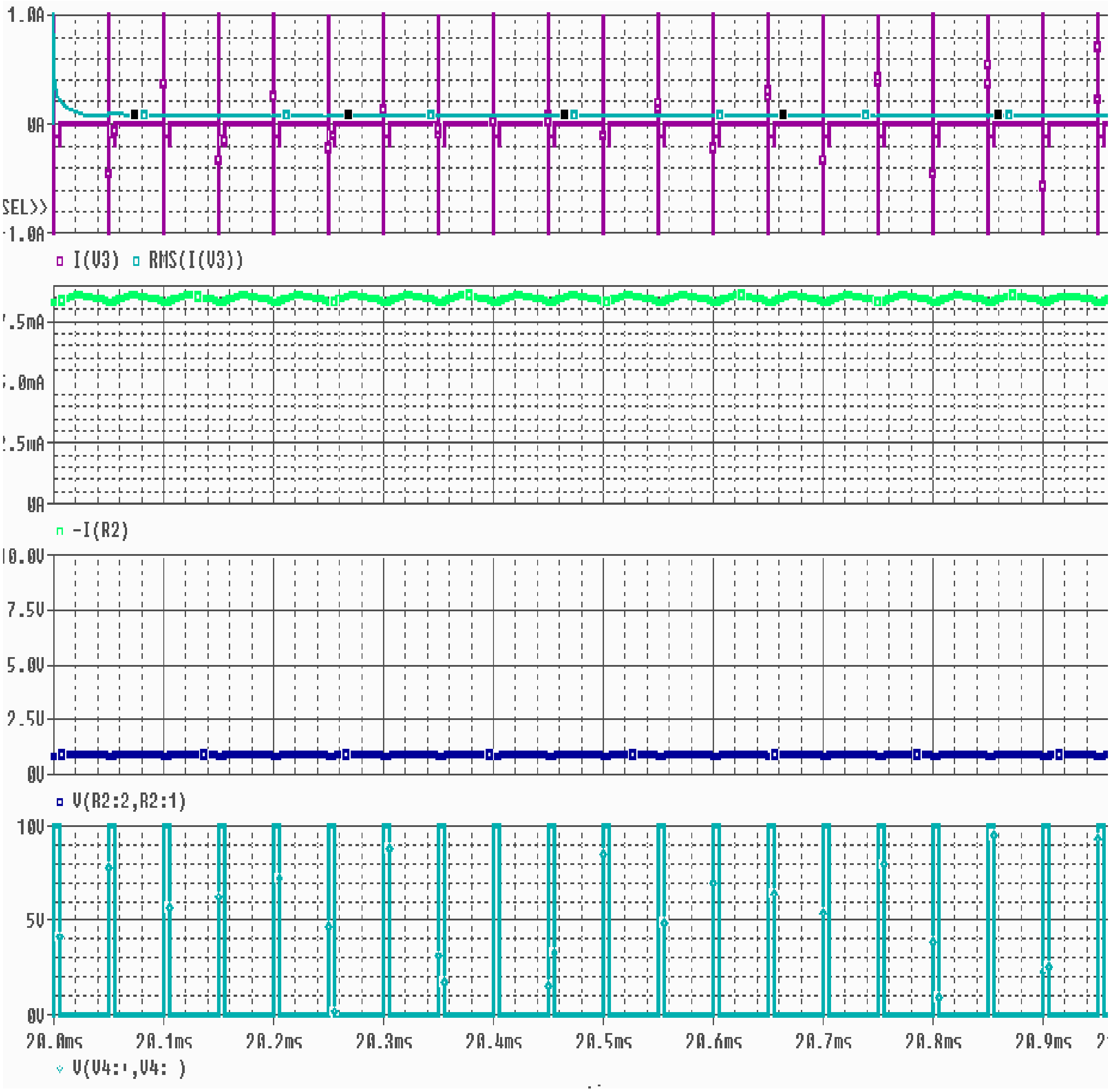
Average output power = 0.89W

Efficiency = 0.89/2.75= 0.32

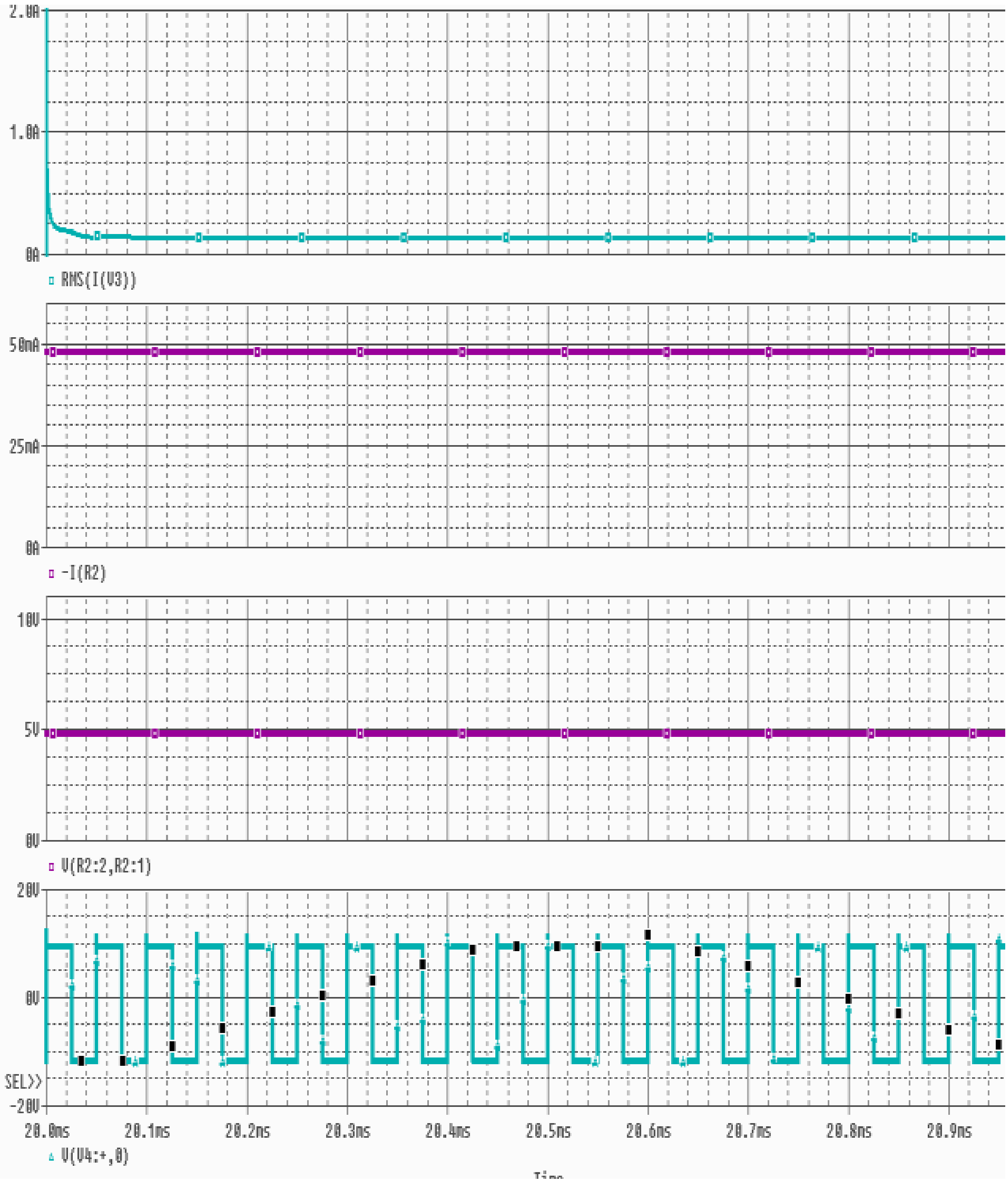
So, efficiency is increasing according to the increment of duty cycle.

Now, the circuit is re-designed for different values of inductor and capacitor and simulation output is checked

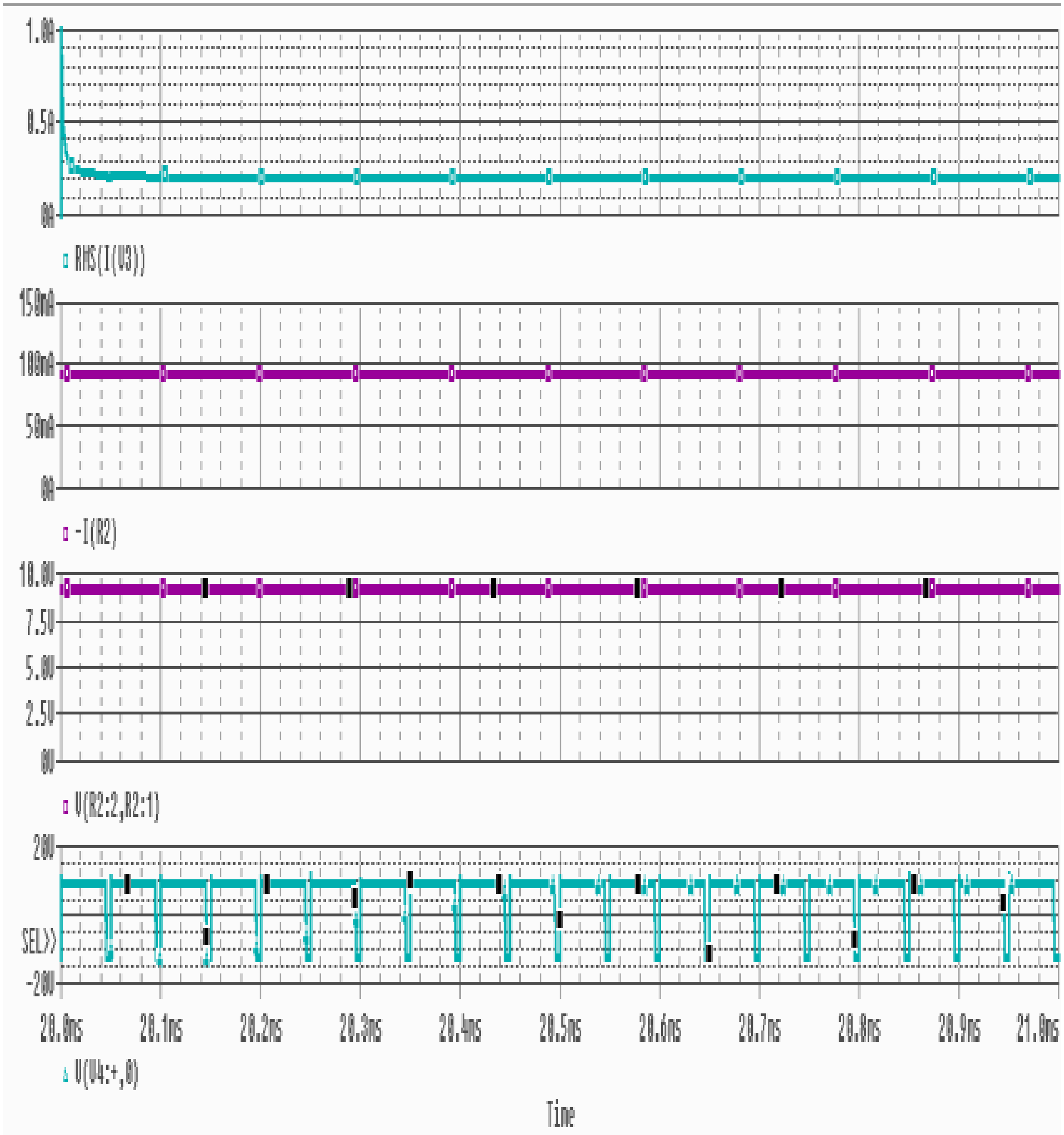
For, L=5mh, C=5uF, D=.1



L=5mh, C=5uF, D=.5

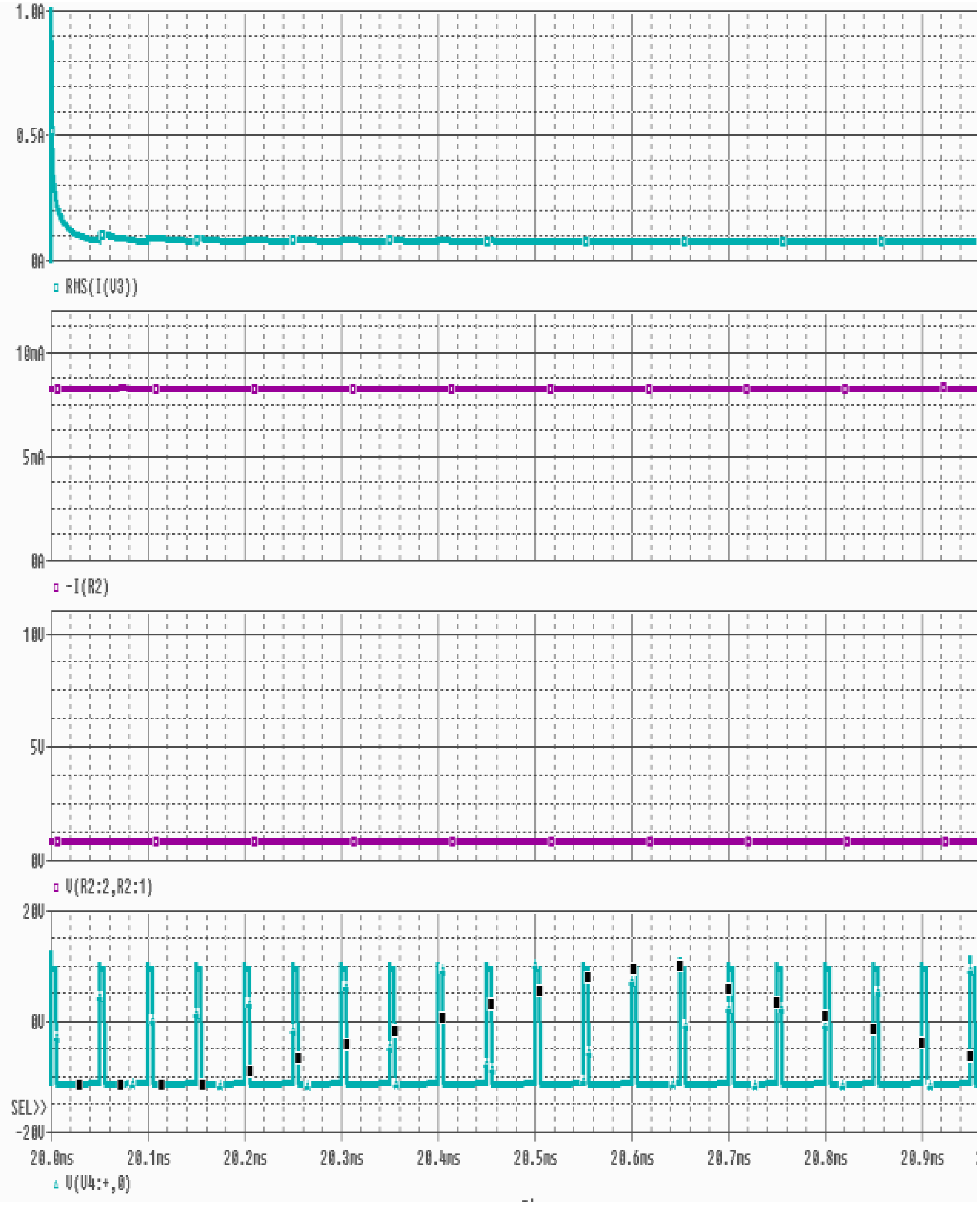

2.0A
1.0A
0A
RMS(I(V3))
50mA
25mA
0A
-I(R2)
10V
5V
0V
V(R2:2,R2:1)
20V
0V
SEL>>
-20V
20.0ms
20.1ms
20.2ms
20.3ms
20.4ms
20.5ms
20.6ms
20.7ms
20.8ms
20.9ms
V(V4:+,0)
Time

L=5mh, C=5uF, D=.9



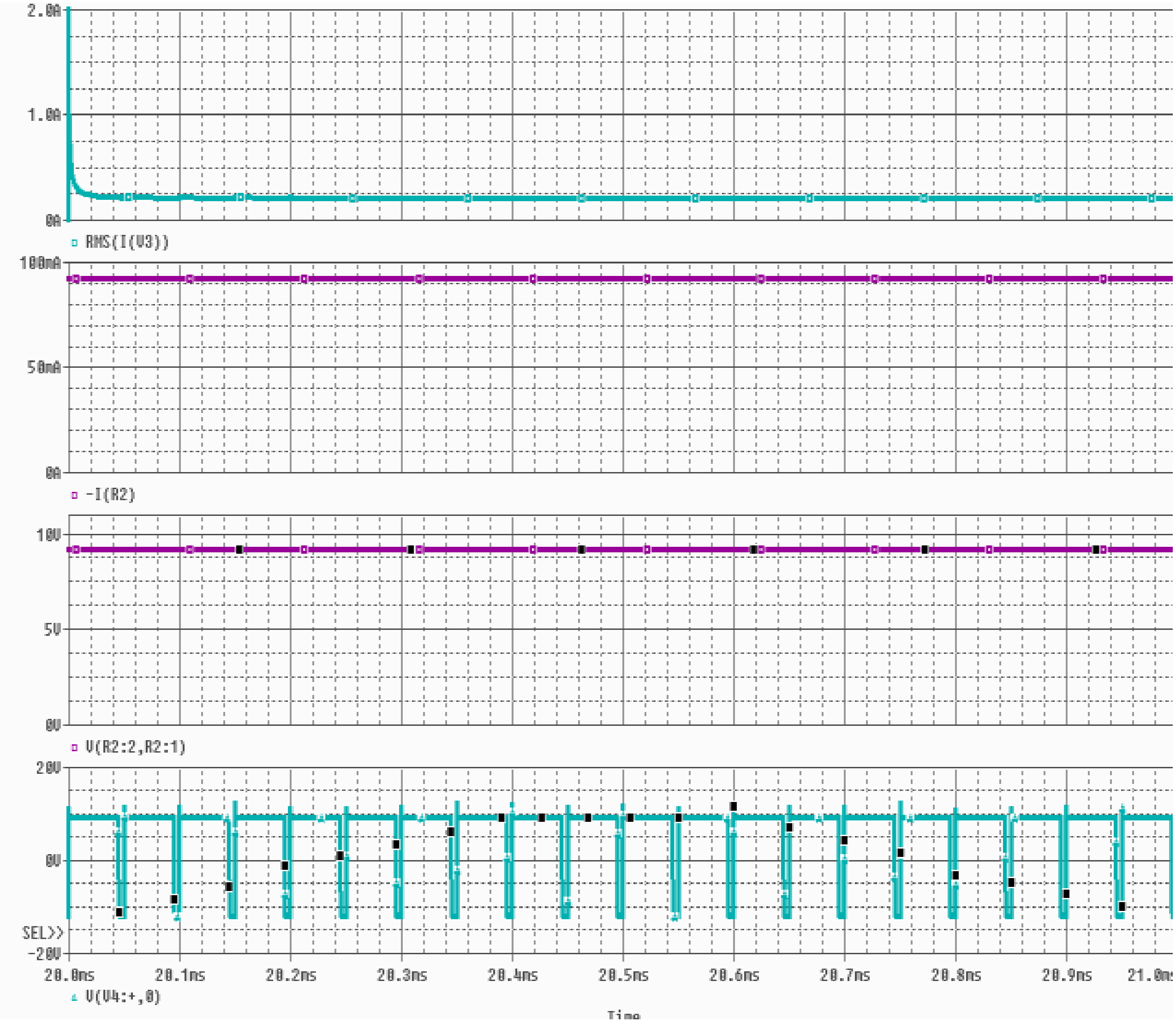
So, this time only by increasing the value of inductor (double) and keeping capacitor unchanged it has been observed that the changes of the values from the graph are not significant.

L=5mh, C=15uF, D=.1



L=5mh, C=15uF, D=.5

L=5mh, C=15uF,
D=.9



This time keeping the inductor value unchanged (5mh), by increasing the value of capacitor (10uF) no remarkable change of the graph is observed.

As the output current and voltage of the circuit didn't change significantly even though increasing the inductance by 100% and capacitance by 150%, and the expected output voltage and power has already been achieved to operate the guitar processor thus finally the base values for the parameters have been selected for the circuit construction.

Implementation of BOOST converter 3.2

The simulation results of Boost converter are given below in tabular form for different duty cycle considering the base value as

Minimum inductance L=.36mh

Capacitance C=46uF, for 1% ripple and the resistance R=100 ohm

Duty cycle	Avg Input current (mA)	Avg Output current(mA)	Output voltage
.1	132	100.89	10.08
.2	190	114.70	11.47
.3	258	140.20	14.02
.4	372	155.59	15.54
.5	526	187.72	18.72
.6	790	236.90	23.63
.7	1.33A	317.74	31.84
.8	2.83A	475.36	47.77
.9	10.87A	918.05	91.63

Simulation Results

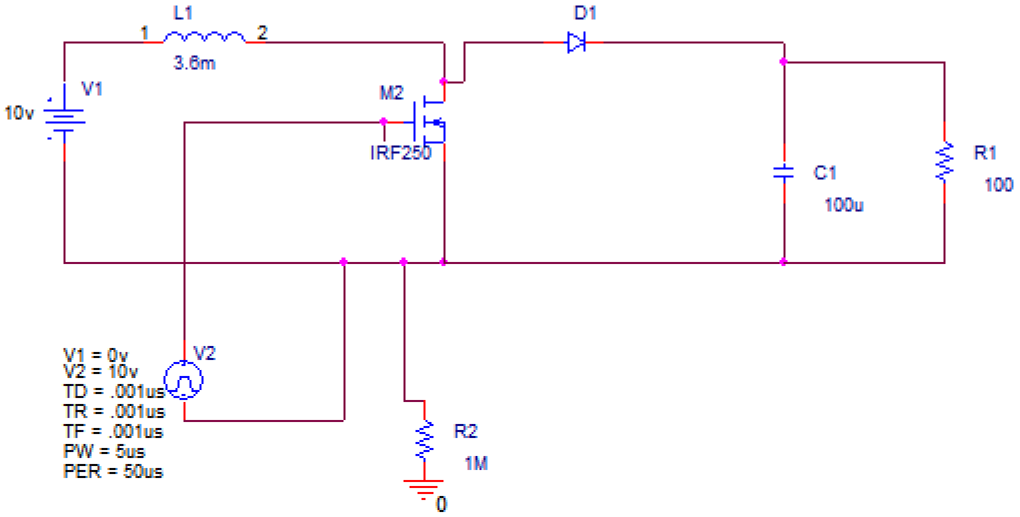
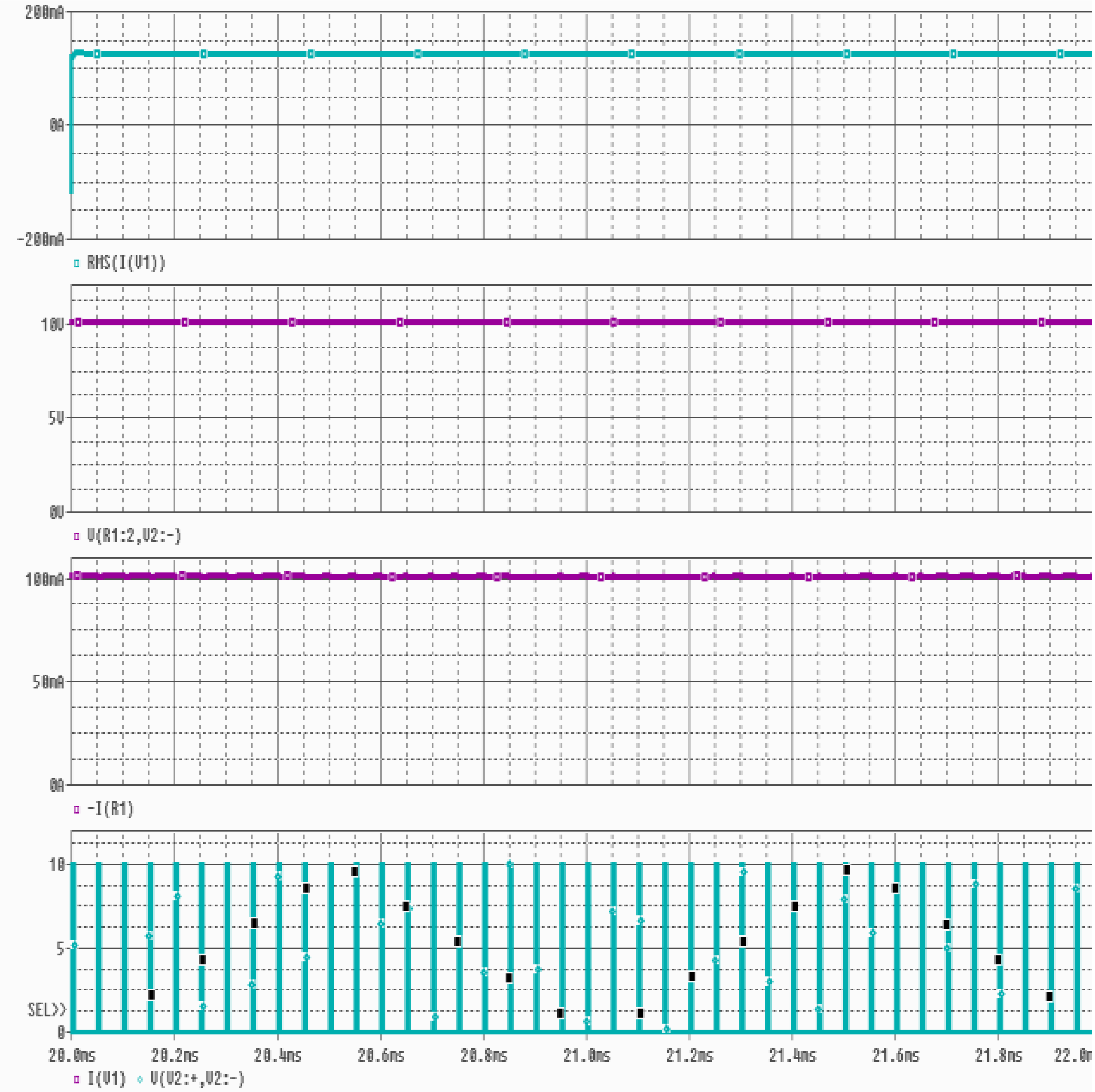


Figure 3.2.1 : Construction of BOOST converter

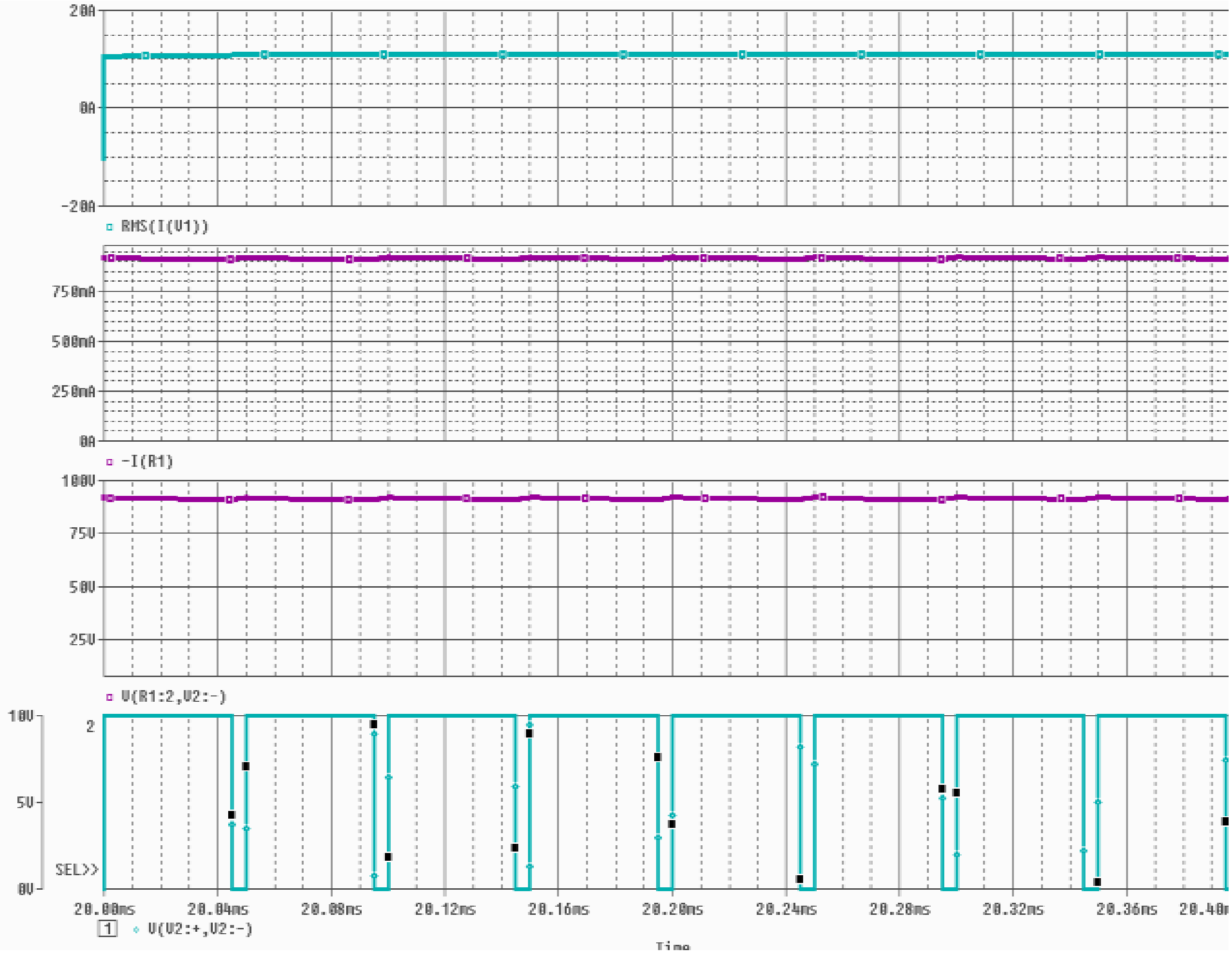
The simulation outputs for Boost converter are given below.

L=.36mH, C=46uF, R=100 ohm, D=.1



For L=.36mH, C=46uF, R=100 ohm, D=.5

L=.36mH, C=46uF, R=100 ohm, D=.9



The output power for this configuration is 76.5W

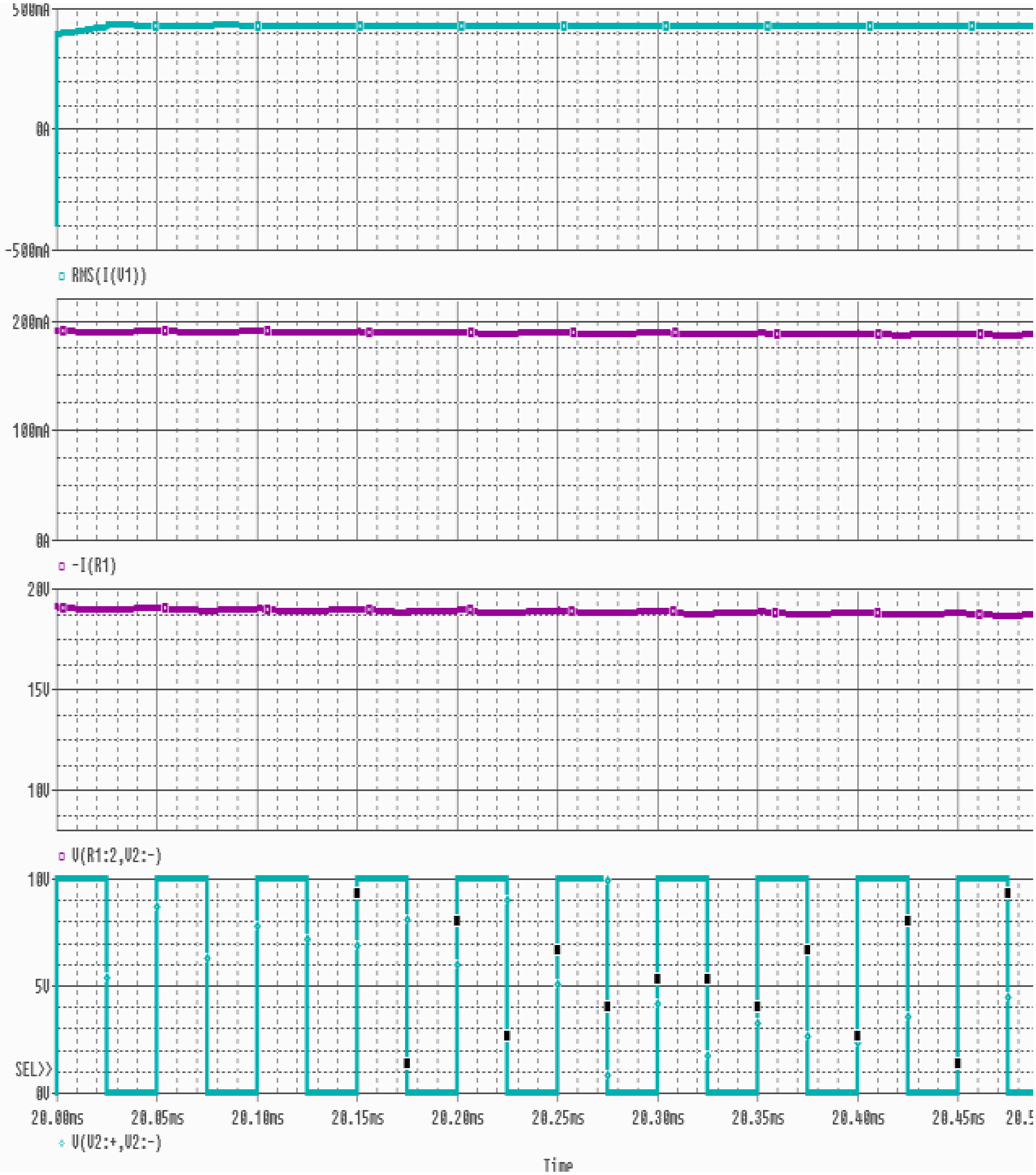
The input power is 11V*10A=110W

Efficiency = 76.5/110=0.695

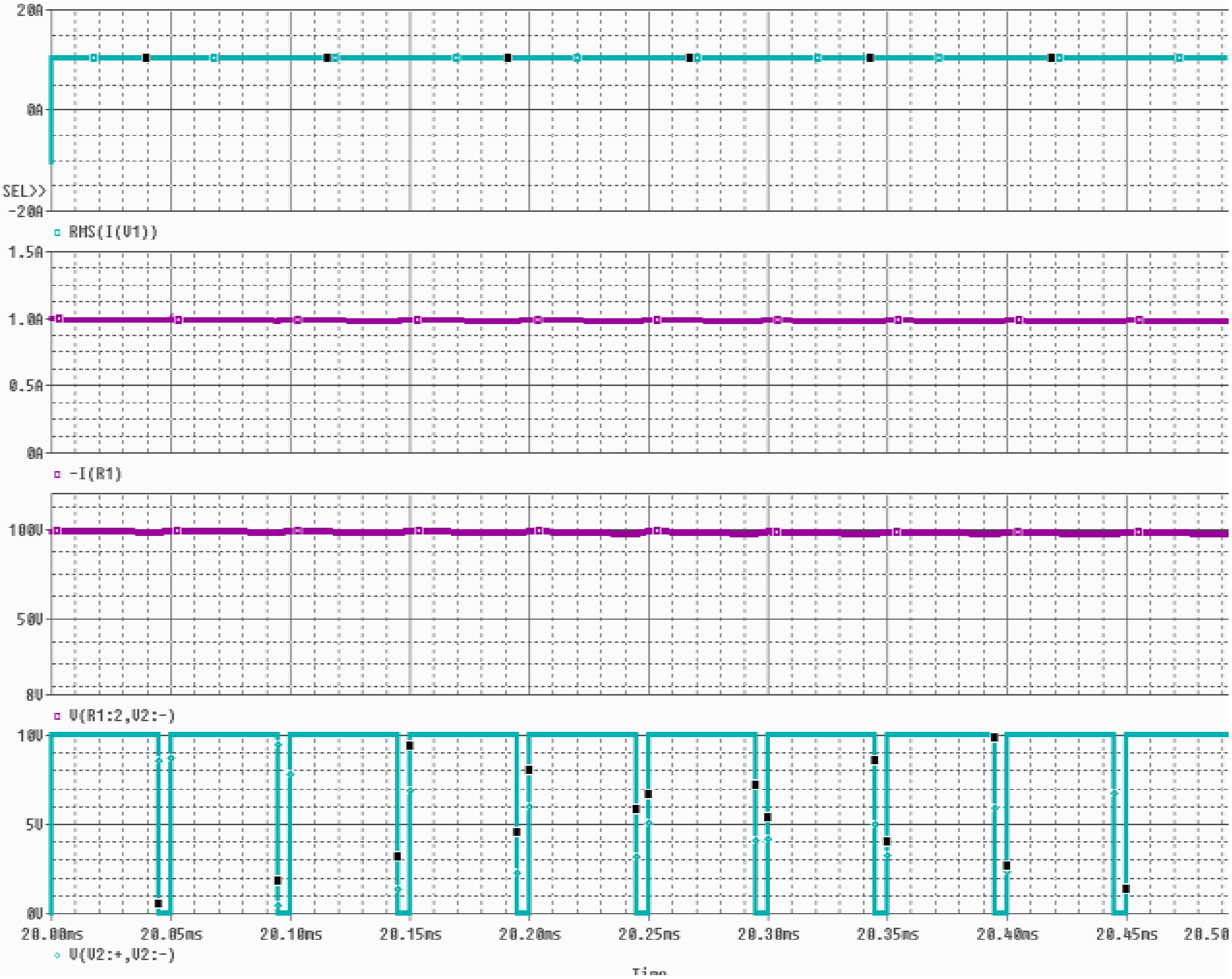
Now, only by increasing the inductor value and keeping the other parameters same the simulations outputs are given below

L=3. 6mH, C=46uF, R=100 ohm,
D=.1

L=3.6mH, C=46uF, R=100 ohm, D=.5



L=3.6mH, C=46uF, R=100 ohm, D=.9



.

The output power in this case is 100W

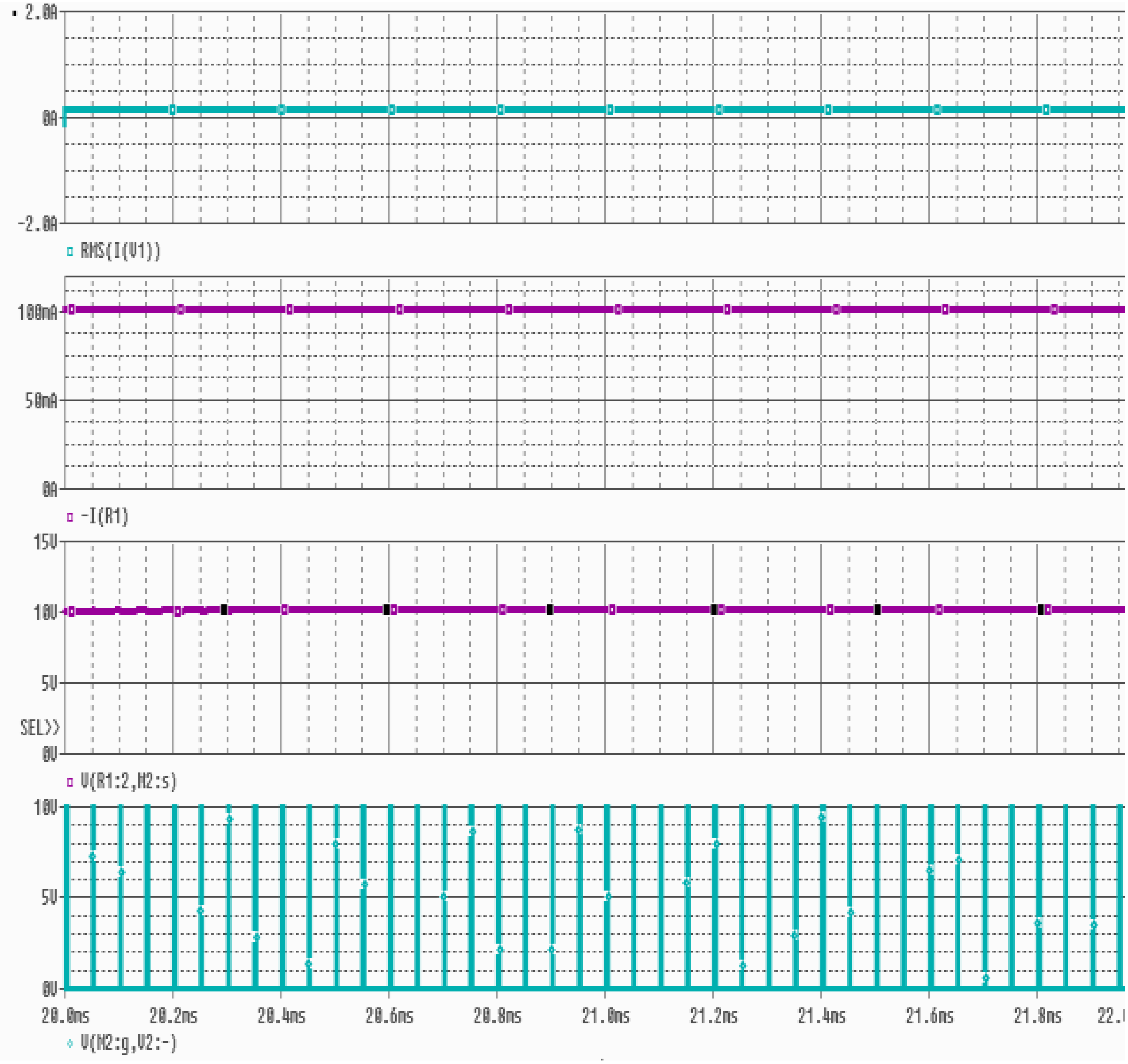
The input power here is = 11*10=110W

Efficiency= 100/110= 0.91

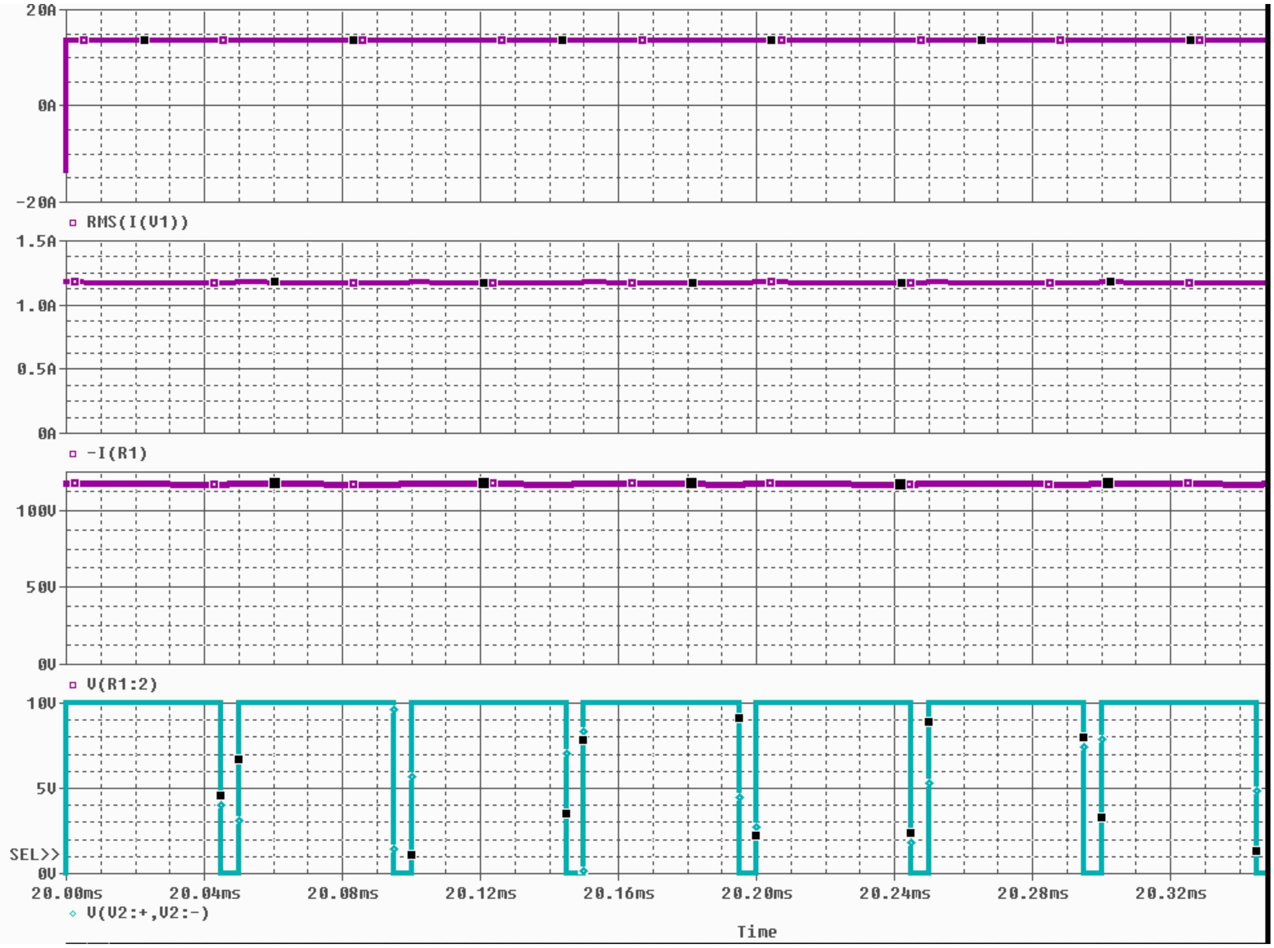
The efficiency seems to have increased.

Now, again the circuit is re-designed by keeping the inductor value unchanged and increasing the value of capacitor. The output of the simulations is given below.

L=3.6mH, C=100uF, R=100 ohm, D=.1



L=3.6mH, C=100uF, R=100 ohm,
D=.9



Here, (considering duty cycle .9)

The output voltage = 115v

The output current = 1.15A

The output power is = 132.25W

The input current (in RMS) = 14A

As the input voltage is known, the input power= 14*11= 154W

The efficiency= 132.25/154 =.86

Judging the output for these parameters (L=3.6mH, C=100uF, for 100 ohm load) comparing with the others it has been established that input current rises around 4A maximum. Output current at the load also increase. And the output voltage this time stepped up to around 115v (maximum) for

D=.9 where as for other parameters the maximum output voltage was 100v. the overall efficiency drops in comparison with the previous circuit.

So, considering all the output listed above the parameters that give better output for a Boost converter are

Inductance L= 3.6mH

Capacitance C=46uF

For load R=100ohm

3.3 Implementation of BUCK-BOOST converter

Lmin= R(*1-D)^2/2f = .30mH

Considering 25% larger value for continuous current Lmin=.379mH

For ripple 2%,

.02=D/RCf

Or, C=.9/.02*15*20kz =150uF

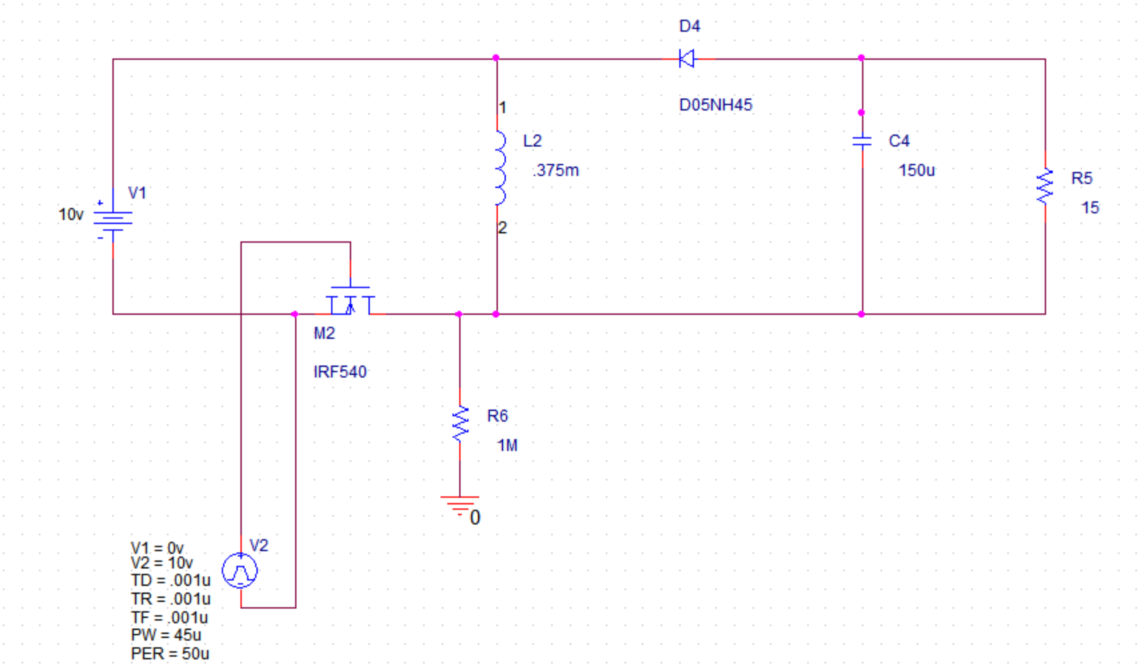
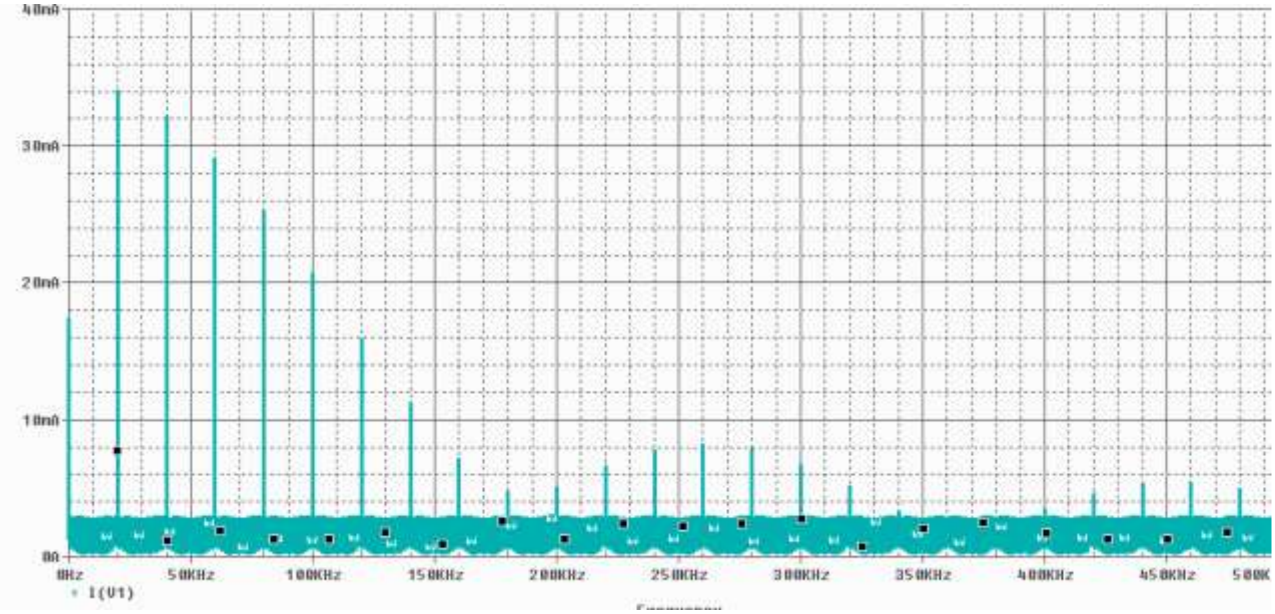


Fig 3.3.1: Construction of BUCK-BOOST converter

The output results after simulation are given below

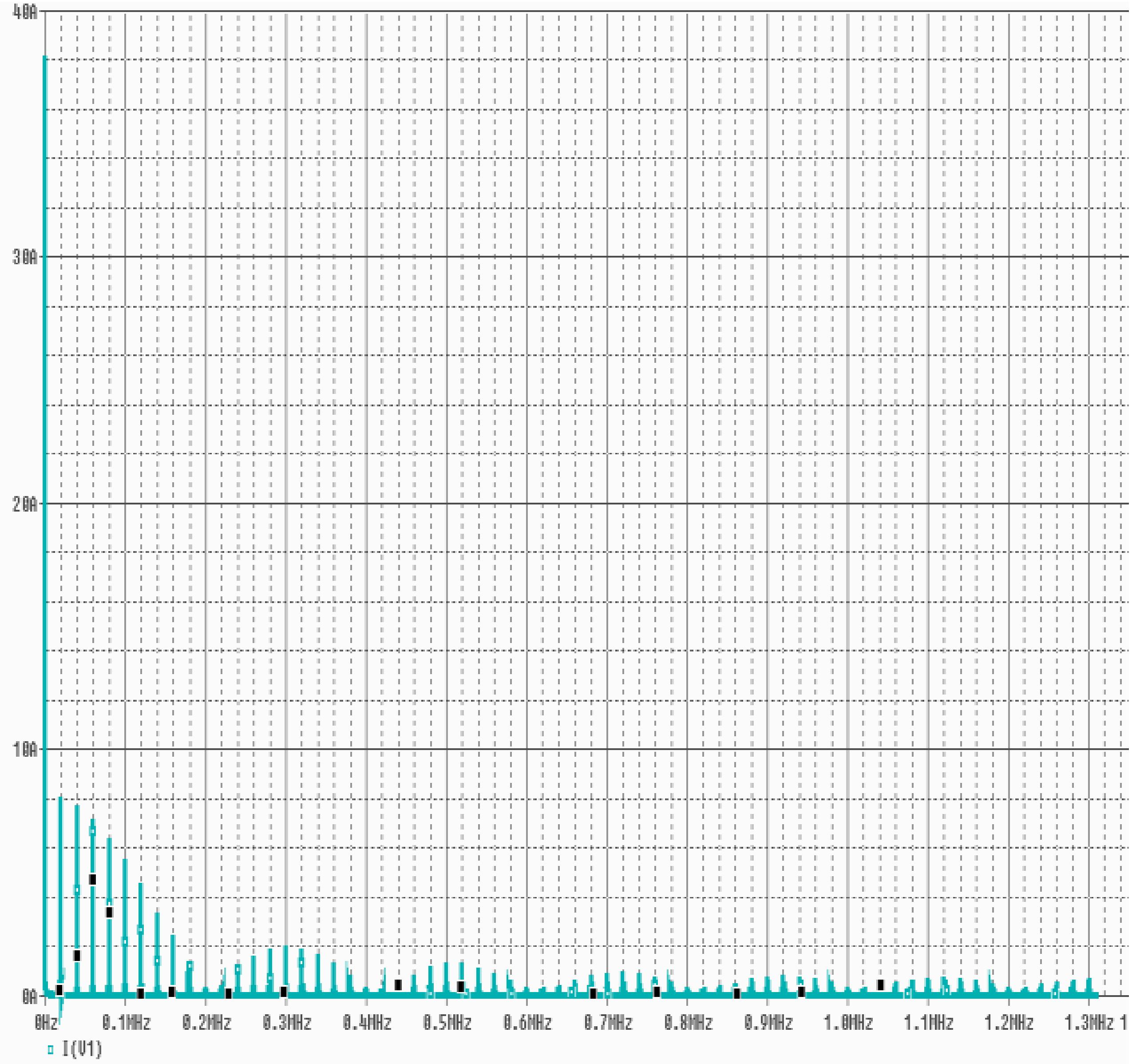
Output voltage and output current for D=.1

Input current for D=.1



Output voltage and output current for D=.9

Input current for D=.9



Input power=420.14W

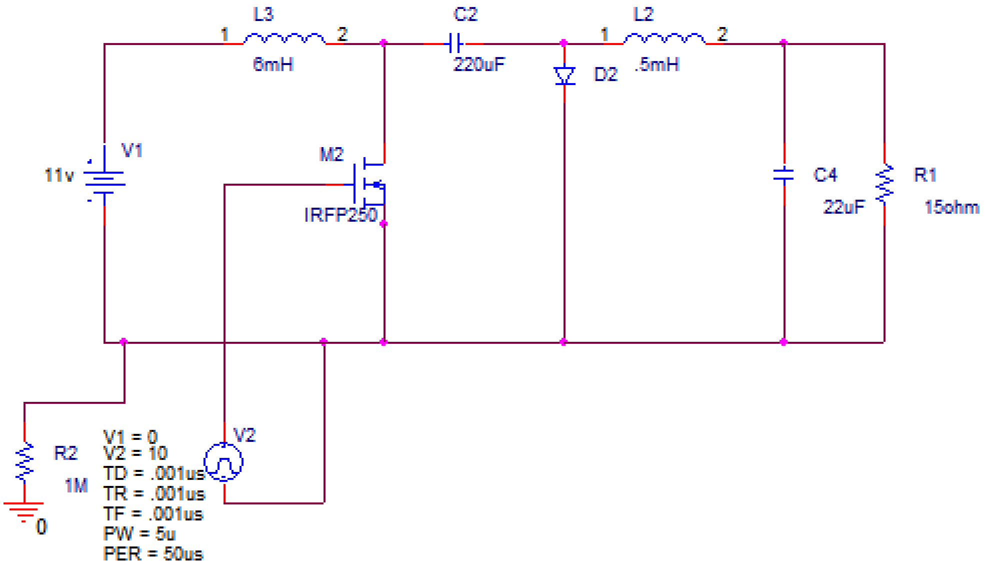
Output power=284.2

Efficiency 67%

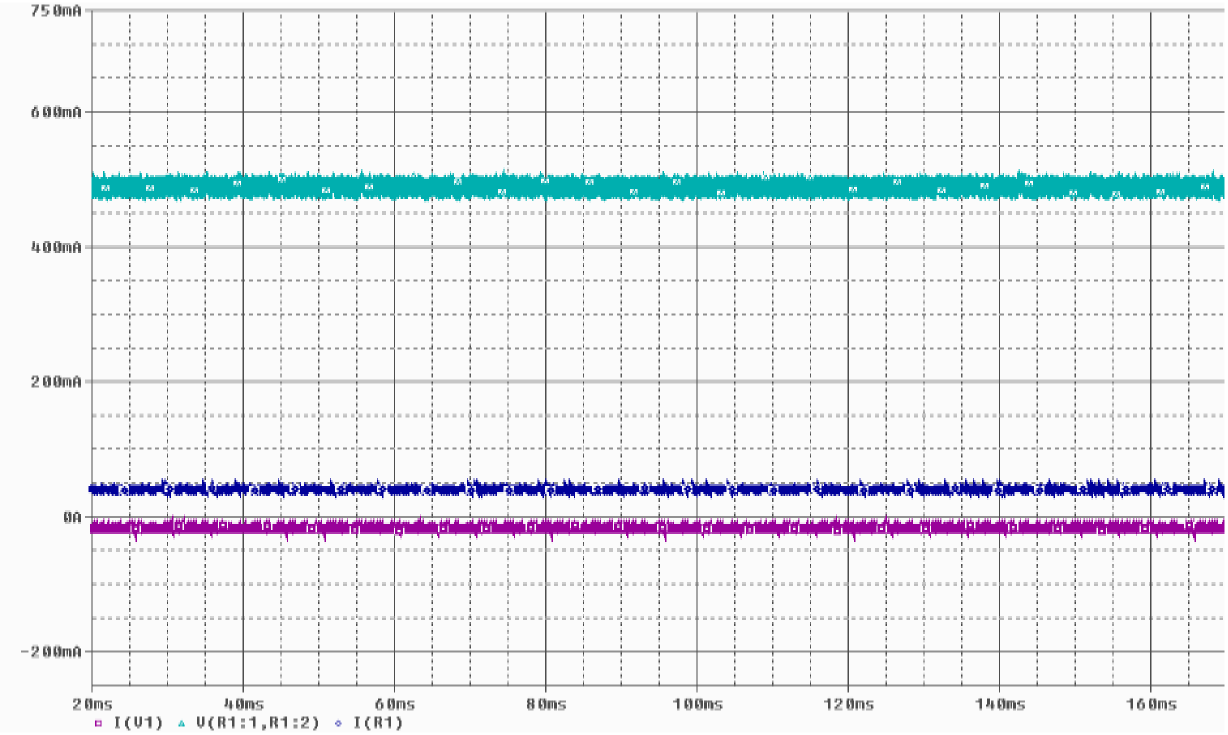
For a duty cycle of 0.9 the harmonic content of the input current is very high.

Thd = 46.53

3.4 Implementation of the Cuk Converter:



For D=.1

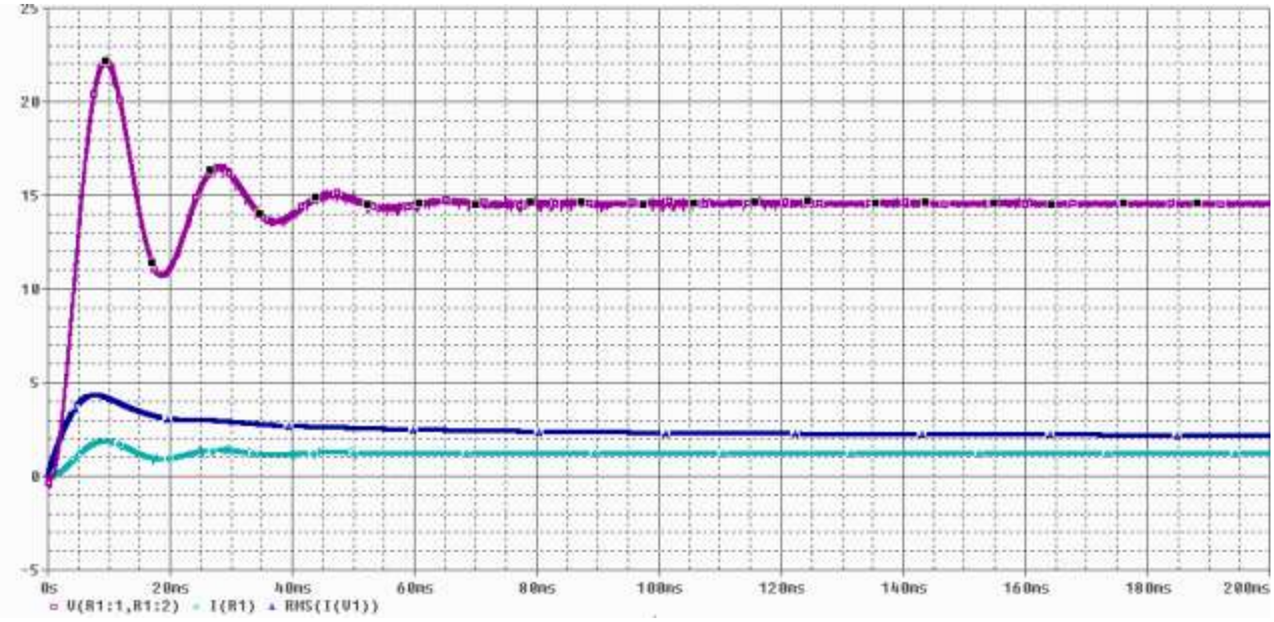


Input power = 11V*15mA =0.165W (from graph)

Output power = 0.5V*40mA=0.02W

Efficiency = 0.02/0.165 = 0.12

For D=.6



Input power=40W

Output power=14W

The inductor in the input side is acting as a filter for the higher frequency current. Thus the harmonic content of the input current is suppressed highly. The output voltage can be stepped up and down both.

The simulation comparisons are given below

Input power = 11V*2A = 22W

Output power = 15V*0.5A= 7.5W

Efficiency = 0.34

The efficiency of the circuit increases with duty cycle. But the required efficiency is not reached.

4. Conclusion

The required output voltage and power from a 12 V battery is gained from the buck converter. Though it is inefficient it meats the primary target of the thesis of achieving 6W and 9 volt supply for Guitar processor Boss-ME-50. Parameters for each converters were calculated approximately. Besides the properties of other converters were verified by simulations and their output results were shown for different duty cycle and different parameters. Efficiency was calculated for each converter as well. A PWM circuit was constructed for the switching frequency to drive the switch gate.

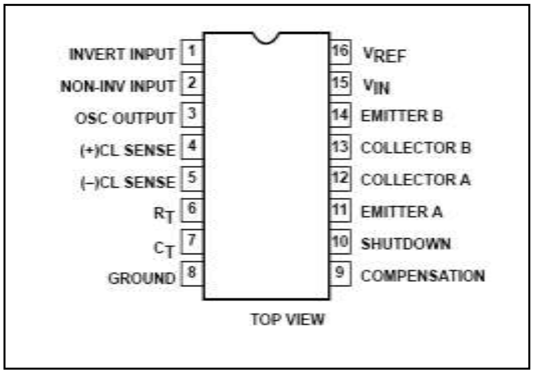
5. Appendix:

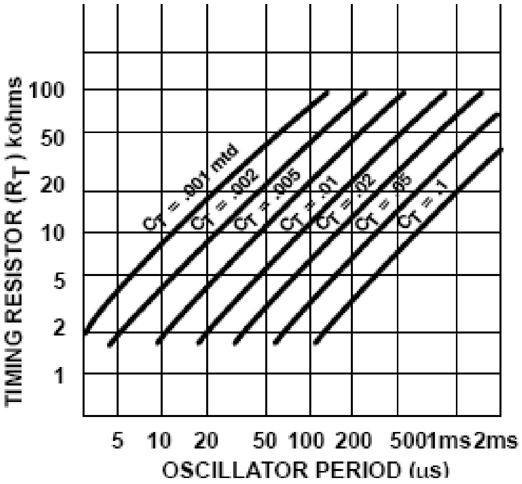
In our circuit we have used the ICs:

SG3524 for PWM

MOSFET IRF 540n

SG3524





Absolute maximum ratings

Vcc= 40V

Iout= 100mA

Pdissipation=1W

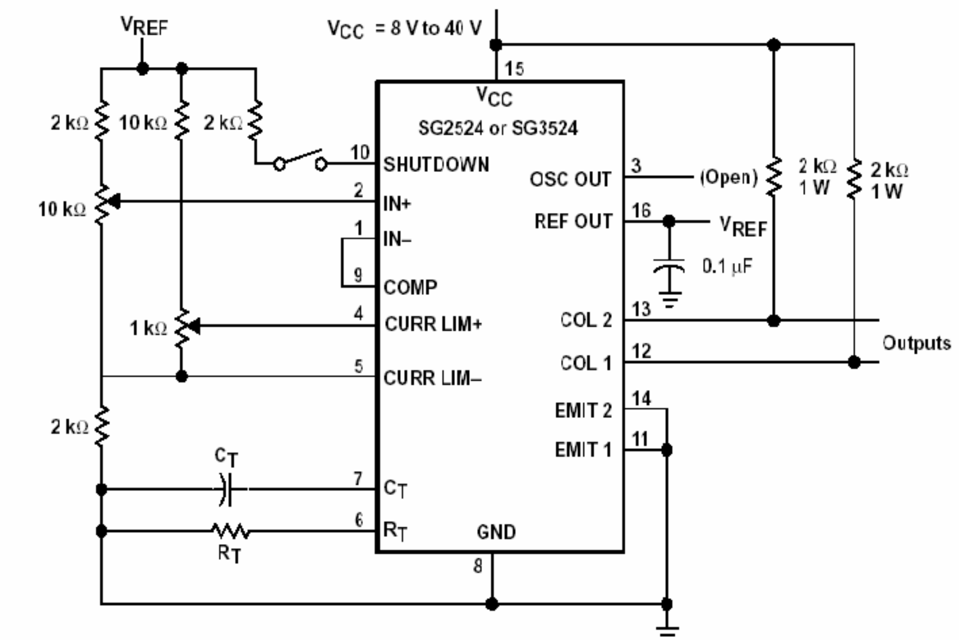
Fmax=300kHz

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

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

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

Circuit construction SG3524 :



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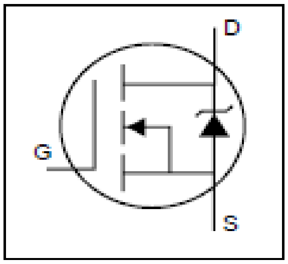


V_{DSS} = 100V

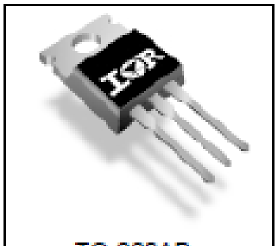
$R_{DS(on)}$ = 44mΩ

I_D = 33A

Description

Advanced HEXFET® Power MOSFETs from International Rectifier utilize advanced processing techniques to achieve extremely low on-resistance per silicon area. This benefit, combined with the fast switching speed and ruggedized device design that HEXFET power MOSFETs are well known for, provides the designer with an extremely efficient and reliable device for use in a wide variety of applications.

The TO-220 package is universally preferred for all commercial-industrial applications at power dissipation levels to approximately 50 watts. The low thermal resistance and low package cost of the TO-220 contribute to its wide acceptance throughout the industry.



TO-220AB

Absolute Maximum Ratings

	Parameter	Max.	Units
I_D @ T_C = 25°C	Continuous Drain Current, V_{GS} @ 10V	33	A
I_D @ T_C = 100°C	Continuous Drain Current, V_{GS} @ 10V	23	
I_{DM}	Pulsed Drain Current ①	110	
P_D @T_C = 25°C	Power Dissipation	130	W
	Linear Derating Factor	0.87	W/°C
V_{GS}	Gate-to-Source Voltage	± 20	V
I_{AR}	Avalanche Current①	16	A
E_{AR}	Repetitive Avalanche Energy①	13	mJ
dv/dt	Peak Diode Recovery dv/dt ③	7.0	V/ns
T_J T_{STG}	Operating Junction and Storage Temperature Range	-55 to + 175	°C
	Soldering Temperature, for 10 seconds	300 (1.6mm from case)	
	Mounting torque, 6-32 or M3 srew	10 lbf•in (1.1N•m)	

Thermal Resistance

	Parameter	Typ.	Max.	Units
$R_{\theta JC}$	Junction-to-Case	——	1.15	°C/W
$R_{\theta CS}$	Case-to-Sink, Flat, Greased Surface	0.50	——	
$R_{\theta JA}$	Junction-to-Ambient	——	62	

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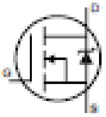
Electrical Characteristics @ T_J = 25°C (unless otherwise specified)

	Parameter	Min.	Typ.	Max.	Units	Conditions
$V_{(BR)DSS}$	Drain-to-Source Breakdown Voltage	100	—	—	V	V_{GS} = 0V, I_D = 250μA
$\Delta V_{(BR)DSS}/\Delta T_J$	Breakdown Voltage Temp. Coefficient	—	0.12	—	V/°C	Reference to 25°C, I_D = 1mA
$R_{DS(on)}$	Static Drain-to-Source On-Resistance	—	—	44	mΩ	V_{GS} = 10V, I_D = 16A ④
$V_{GS(th)}$	Gate Threshold Voltage	2.0	—	4.0	V	V_{DS} = V_{GS}, I_D = 250μA
g_{fs}	Forward Transconductance	21	—	—	S	V_{DS} = 50V, I_D = 16A④
I_{DSS}	Drain-to-Source Leakage Current	—	—	25	μA	V_{DS} = 100V, V_{GS} = 0V
		—	—	250		V_{DS} = 80V, V_{GS} = 0V, T_J = 150°C
I_{GSS}	Gate-to-Source Forward Leakage	—	—	100	nA	V_{GS} = 20V
	Gate-to-Source Reverse Leakage	—	—	-100		V_{GS} = -20V
Q_g	Total Gate Charge	—	—	71	nC	I_D = 16A
Q_{gs}	Gate-to-Source Charge	—	—	14		V_{DS} = 80V
Q_{gd}	Gate-to-Drain ("Miller") Charge	—	—	21		V_{GS} = 10V, See Fig. 6 and 13
$t_{d(on)}$	Turn-On Delay Time	—	11	—	ns	V_{DD} = 50V
t_r	Rise Time	—	35	—		I_D = 16A
$t_{d(off)}$	Turn-Off Delay Time	—	39	—		R_G = 5.1Ω
t_f	Fall Time	—	35	—		V_{GS} = 10V, See Fig. 10 ④
L_D	Internal Drain Inductance	—	4.5	—	nH	Between lead, 6mm (0.25in.) from package and center of die contact 
L_S	Internal Source Inductance	—	7.5	—		
C_{iss}	Input Capacitance	—	1960	—	pF	V_{GS} = 0V
C_{oss}	Output Capacitance	—	250	—		V_{DS} = 25V
C_{rss}	Reverse Transfer Capacitance	—	40	—		ƒ = 1.0MHz, See Fig. 5
E_{AS}	Single Pulse Avalanche Energy②	—	700⑤	185⑥	mJ	I_{AS} = 16A, L = 1.5mH

Source-Drain Ratings and Characteristics

	Parameter	Min.	Typ.	Max.	Units	Conditions
I_S	Continuous Source Current (Body Diode)	—	—	33	A	MOSFET symbol showing the integral reverse p-n junction diode. 
I_{SM}	Pulsed Source Current (Body Diode)①	—	—	110		
V_{SD}	Diode Forward Voltage	—	—	1.2	V	T_J = 25°C, I_S = 16A, V_{GS} = 0V ④
t_{rr}	Reverse Recovery Time	—	115	170	ns	T_J = 25°C, I_F = 16A
Q_{rr}	Reverse Recovery Charge	—	505	760	nC	di/dt = 100A/μs ④
t_{on}	Forward Turn-On Time	Intrinsic turn-on time is negligible (turn-on is dominated by L_S+L_D)				

Notes:

① Repetitive rating; pulse width limited by max. junction temperature. (See fig. 11)

② Starting T_J = 25°C, L =1.5mH
R_G = 25Ω, I_{AS} = 16A. (See Figure 12)

③ $I_{SD} \leq$ 16A, di/dt ≤ 340A/μs, $V_{DD} \leq V_{(BR)DSS}$,
$T_J \leq$ 175°C

④ Pulse width ≤ 400μs; duty cycle ≤ 2%.

⑤ This is a typical value at device destruction and represents operation outside rated limits.

⑥ This is a calculated value limited to T_J = 175°C .

6. Problems faced:

1. The required value of inductor was not available in the lab. So, it was a tough task to make the inductor value appropriate by maintaining the turns of the wire in the core.

2. Setting the switching frequency at PWM was another trouble.

7. Further work:

1. Designing a filter along with the converter to reduce the harmonic content as well as to increase the efficiency.
2. Establishing a feedback system so that if the input voltage is changed causing a change in output voltage, it rectifies automatically.

8. Reference:

- http://www.ee.iitb.ac.in/vlsi/wb/pages/slides/MSB-BC.pdf

- http://en.wikipedia.org/wiki/DC-to-DC_converter

- **Ref Book: "power electronics" by William hart**